Review of Polarized Ion Sources

Anatoli Zelenski, BNL

- Polarization techniques.
- Polarized proton (deuteron) $H^-(D^-)$ sources.
- Polarized $^3He^{++}$ ion sources.

Summary.

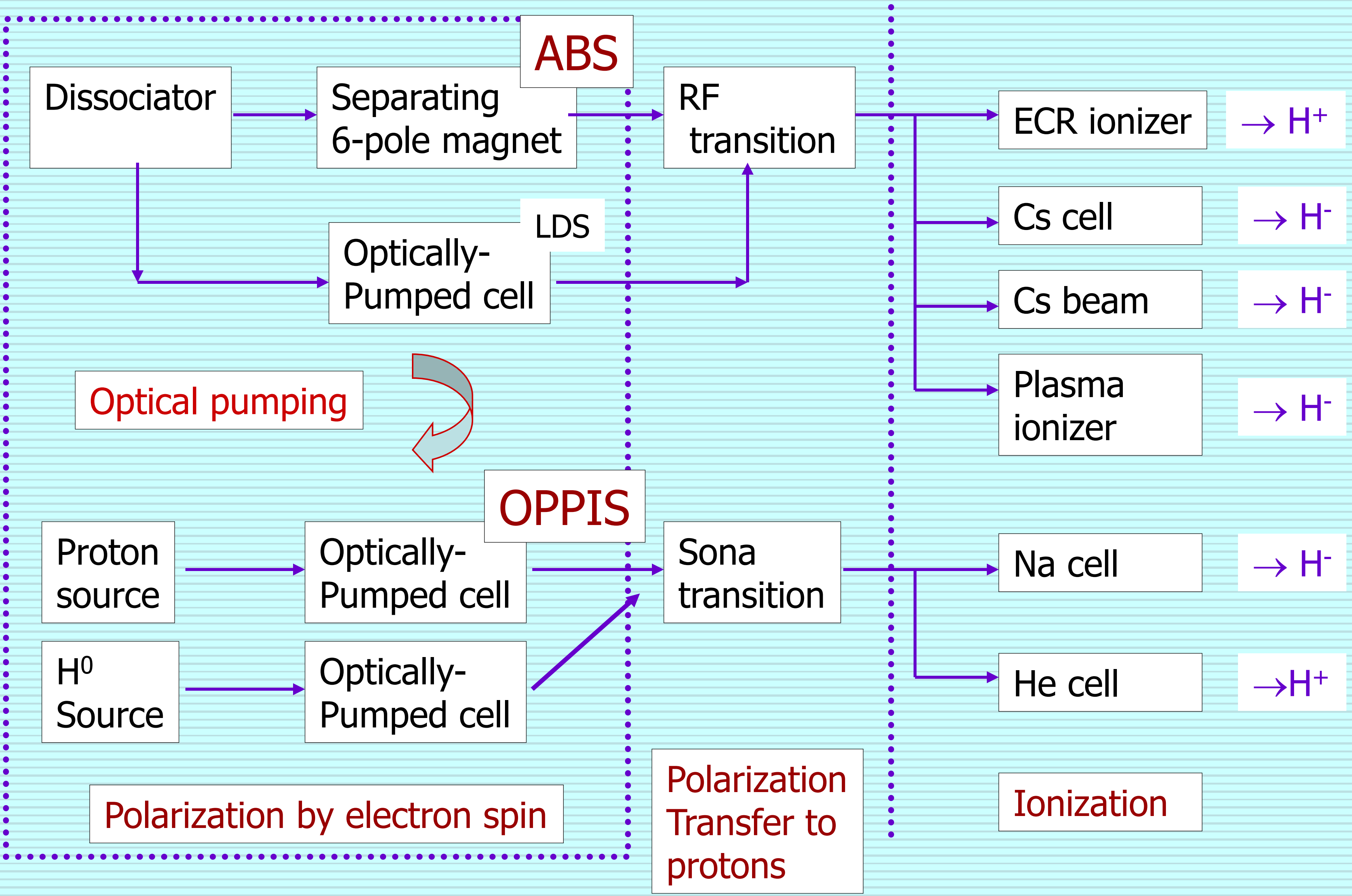
SPIN 2014, October 22, 2014

北京大学物理学院
School of Physics, Peking University

Polarized proton beams in high-energy accelerators and colliders

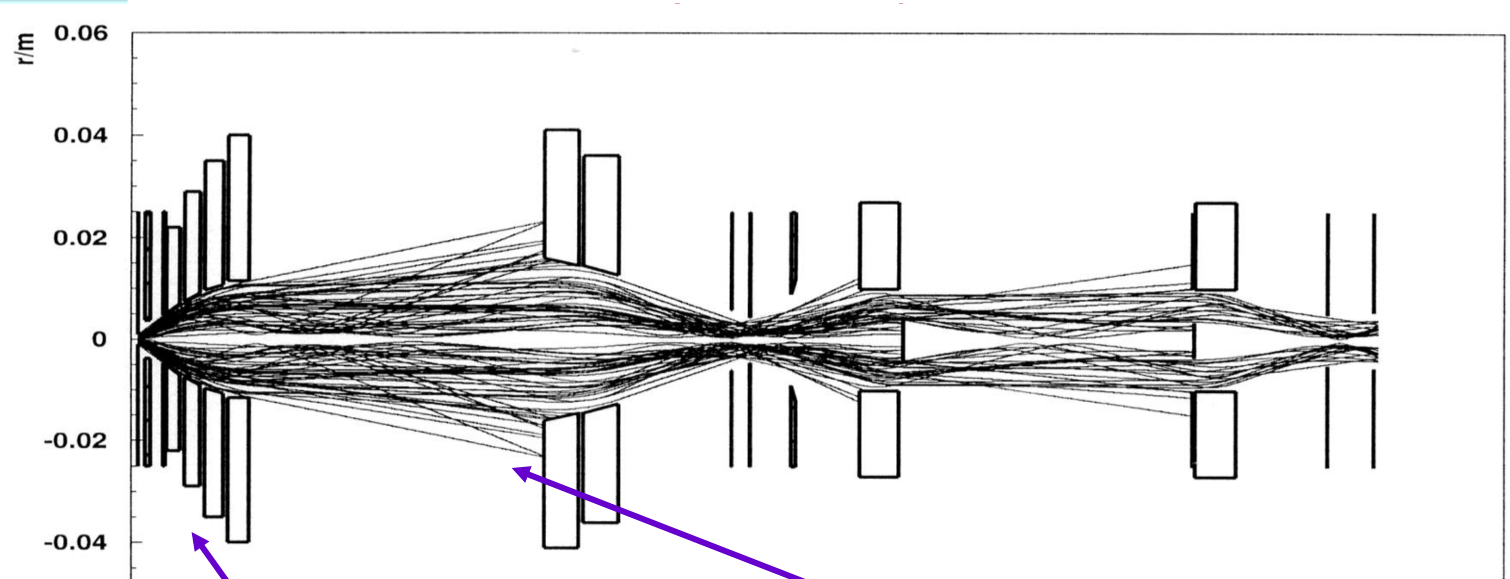
- High intensity polarized negative H^-, D^- sources.
- Optically Pumped Polarized Ion Source (OPPIS) for RHIC and Atomic Beam Source (ABS) with charge exchange ionizer at COSY, IUCF and NICA (Dubna).
- Charge-exchange (strip) injection.
- Equal (maximum possible) intensity of polarized and un-polarized beams in RHIC and COSY.

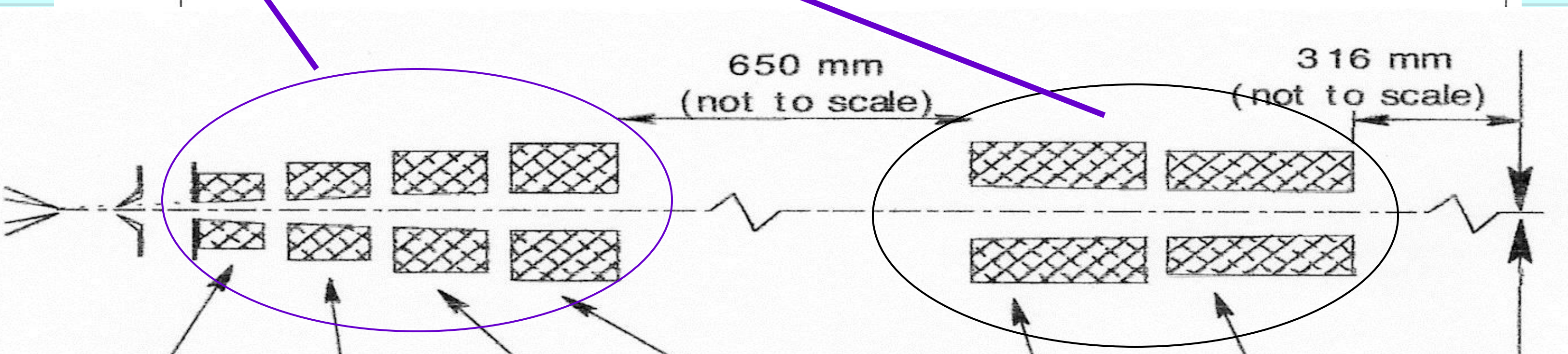
$H^{\pm}$, $D^{\pm}$ - Polarization techniques



Atomic Beam Sources

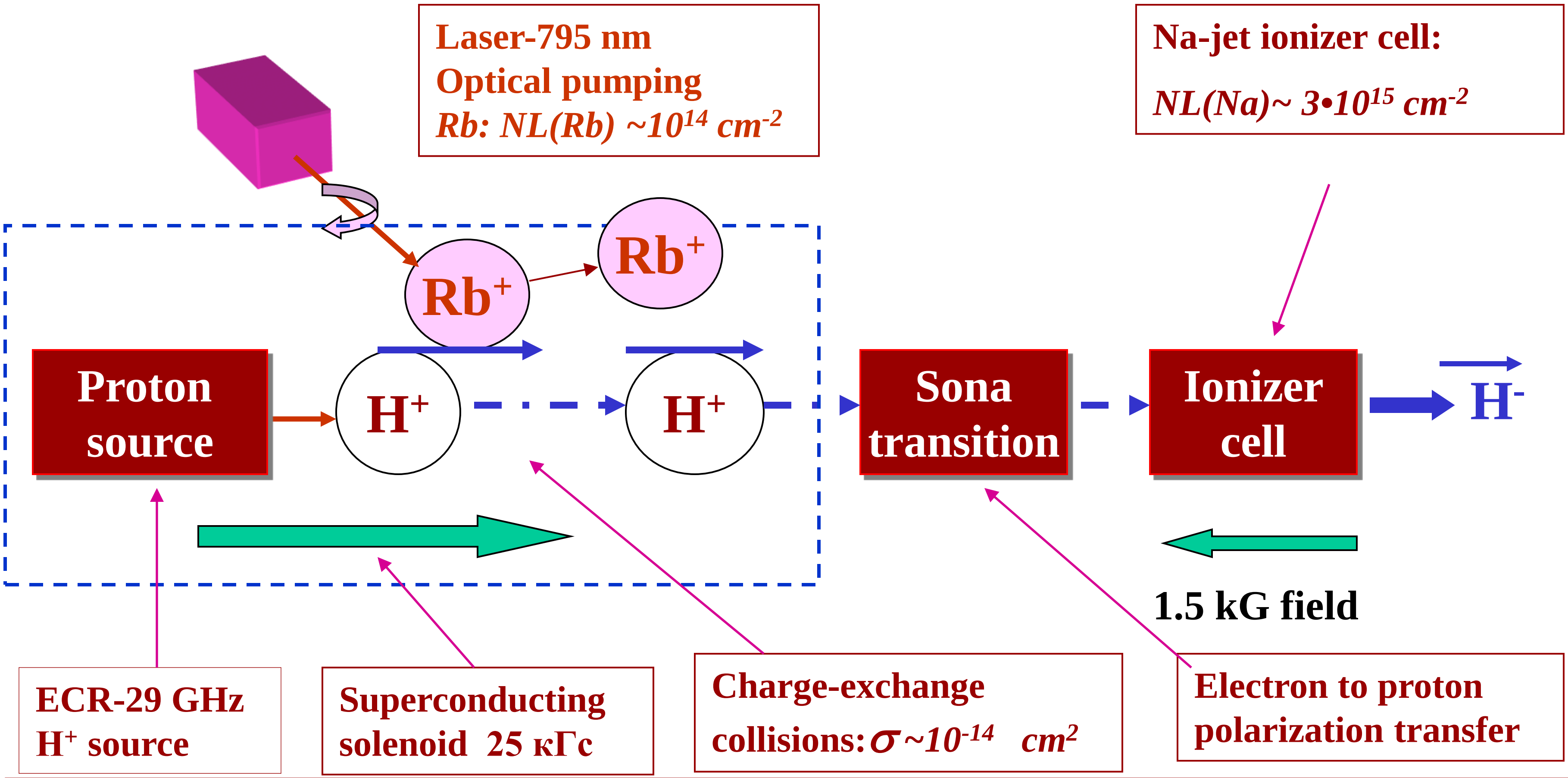
Separating sextupole magnet system.





Basic limitation on the polarized atomic beam intensity ~10^{17} atoms/sec (~30 mA equivalent)

SPIN -TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS.



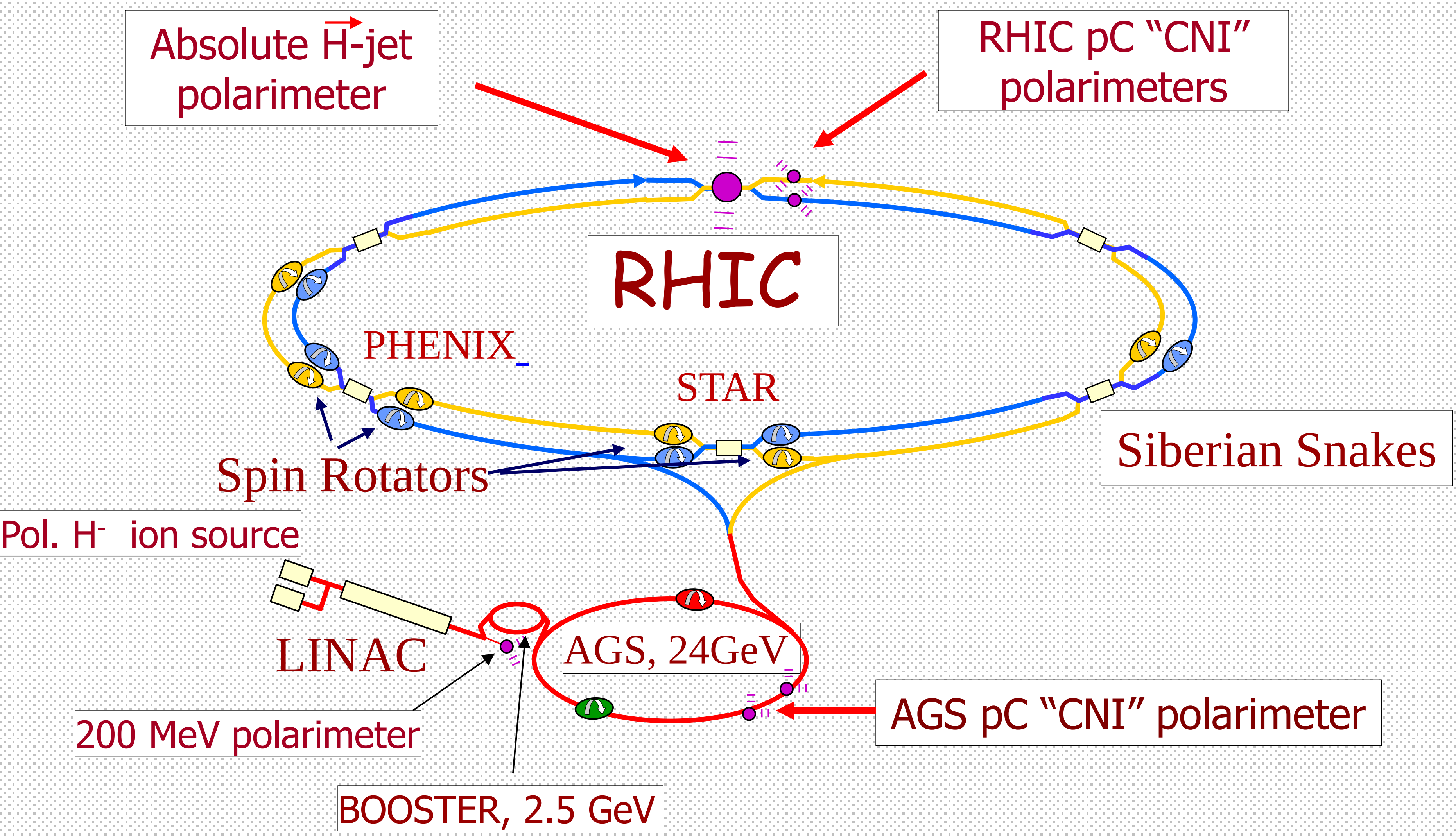
Laser beam is a powerfull primary source of angular momentum:

10 W (795 nm) → $4 \cdot 10^{19}$ hν/sec → 2 A, $\vec{H^0}$ equivalent intensity.

Feasibility of Multi-ampere polarized beams.

Polarization facilities at RHIC

$L_{max} = 1.6 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 510$ GeV



The RHIC OPPIS after upgrade (2011-12)with atomic hydrogen injector. Completed for 2013 Run.

RHIC Polarized beam in Run 2013

OPPIS → 1.0-2.0 mA

LINAC

(6.0-9.0) $\cdot 10^{11}$ polarized H^- /pulse at 200 MeV

Booster

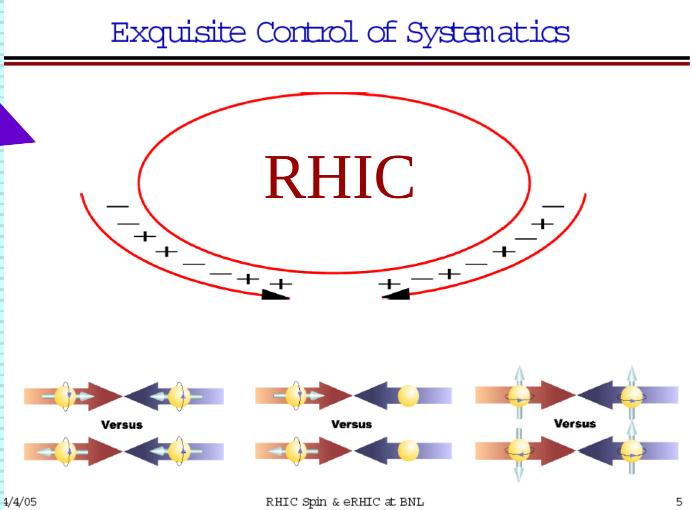
(2.5-3.0) $\cdot 10^{11}$ protons /pulse at 2.3 GeV

AGS

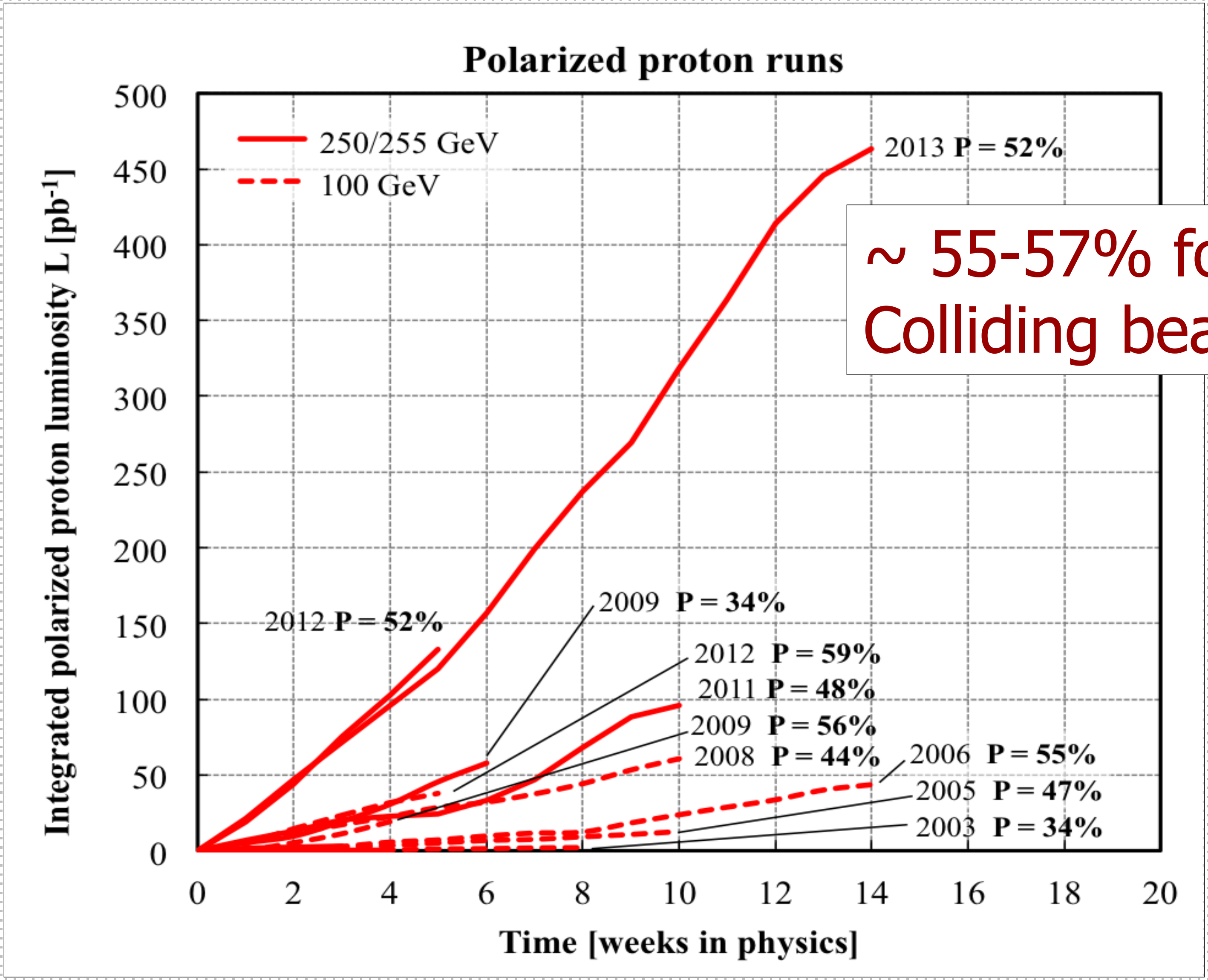
(2.0-2.5) $\cdot 10^{11}$ p/bunch

~2.0$\cdot 10^{11}$ p/bunch, P~60-65% at 100 GeV
P ~ 58% at 255 GeV

It is expected, that use of Electron Lens will allow increase of the bunch intensity to ~2.5$\cdot 10^{11}$ p/bunch.

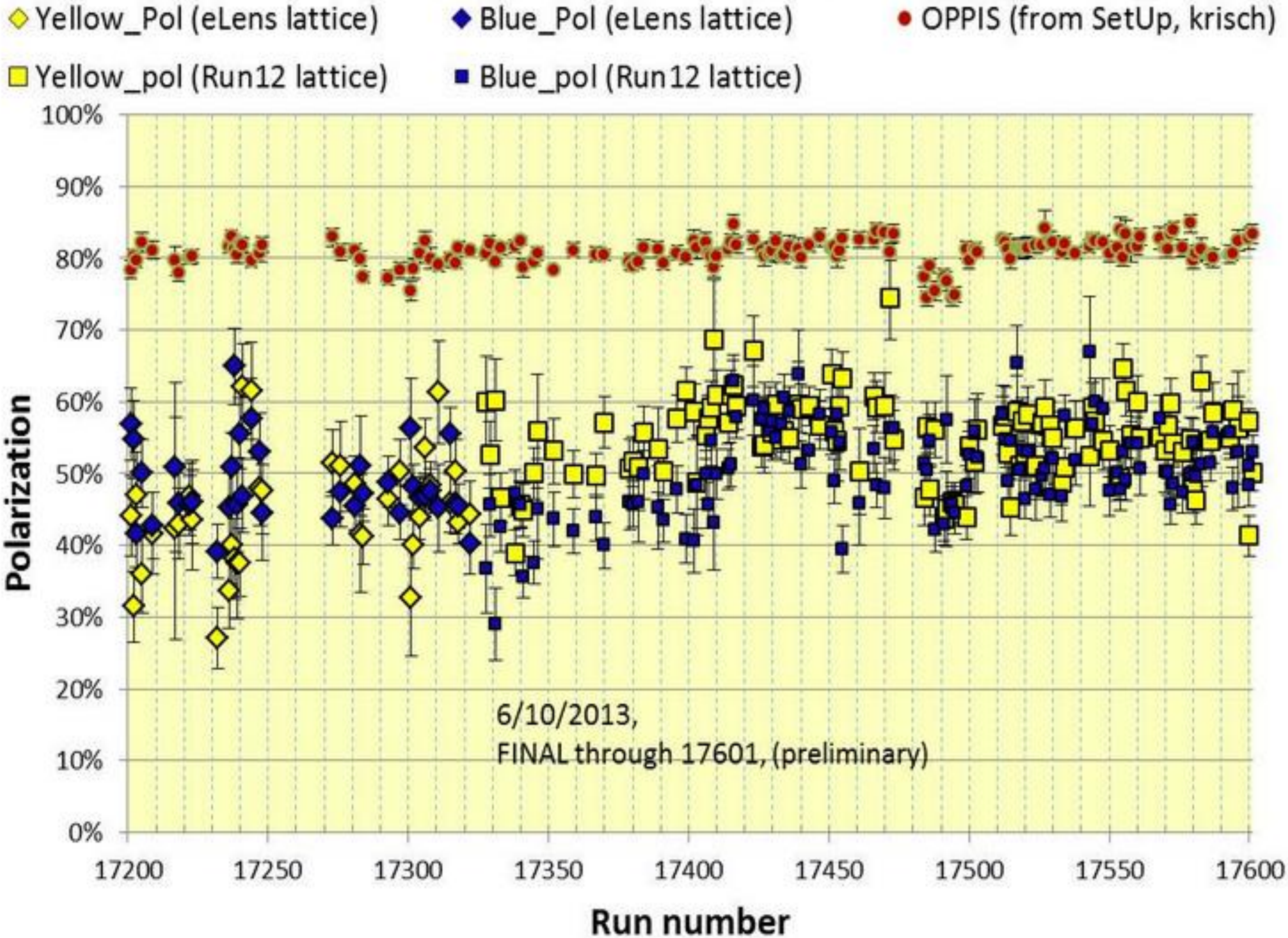


Luminosity from Run-13 exceeds all previous p+p runs combined

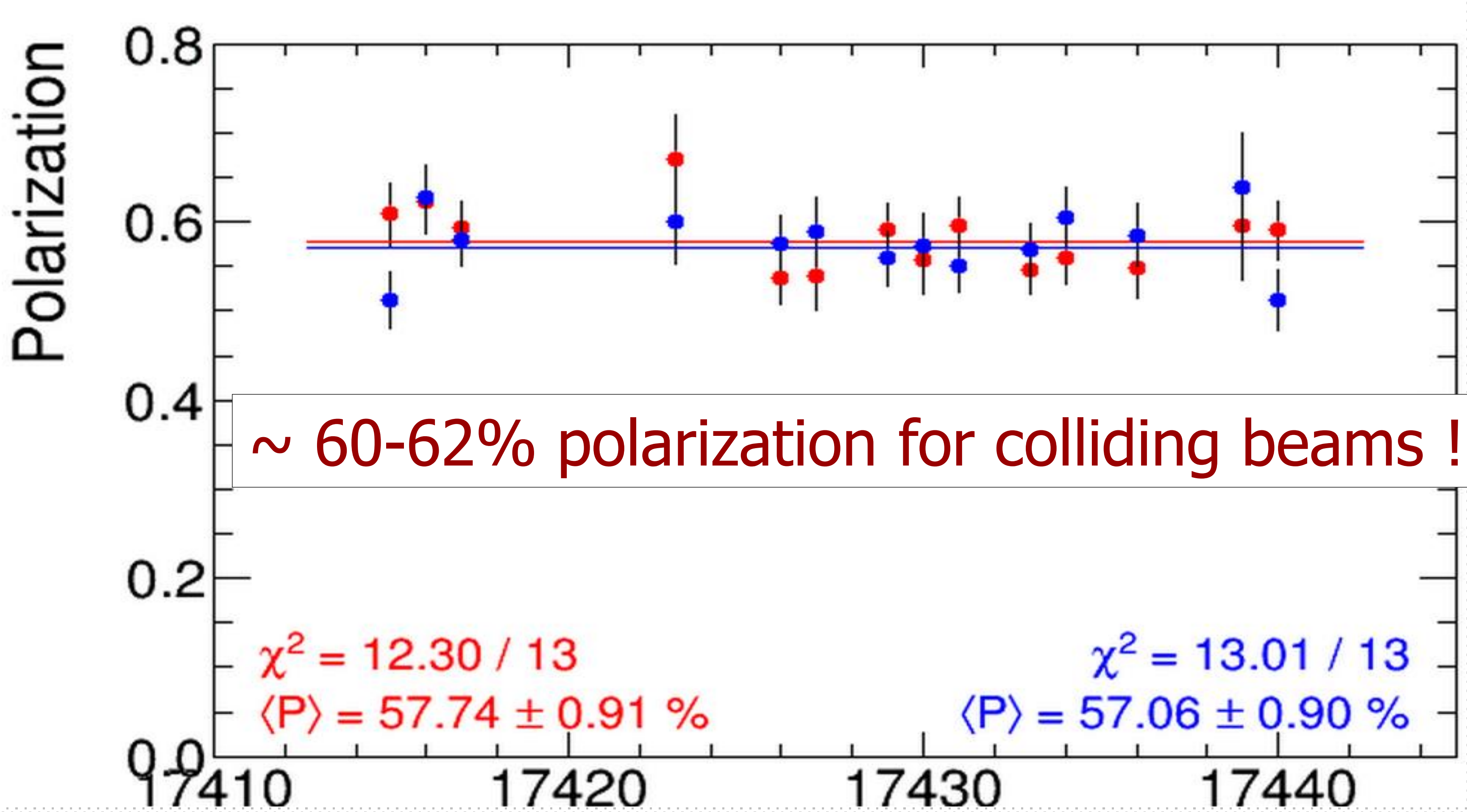


~ 55-57% for Colliding beams

Run 13 H-jet polarimeter, physics stores

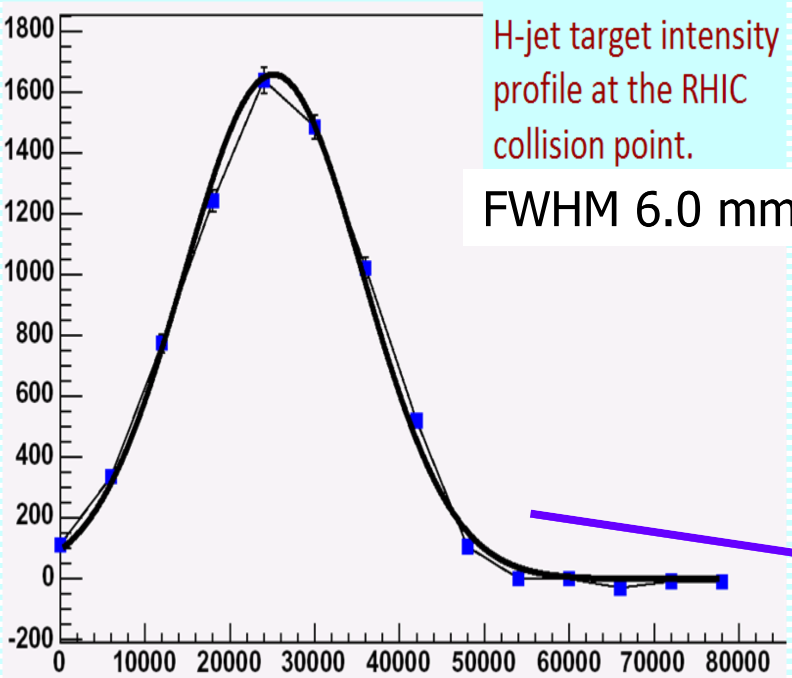


Polarization measurements at 255 GeV in H-jet polarimeter, Run-2013, April-25-30



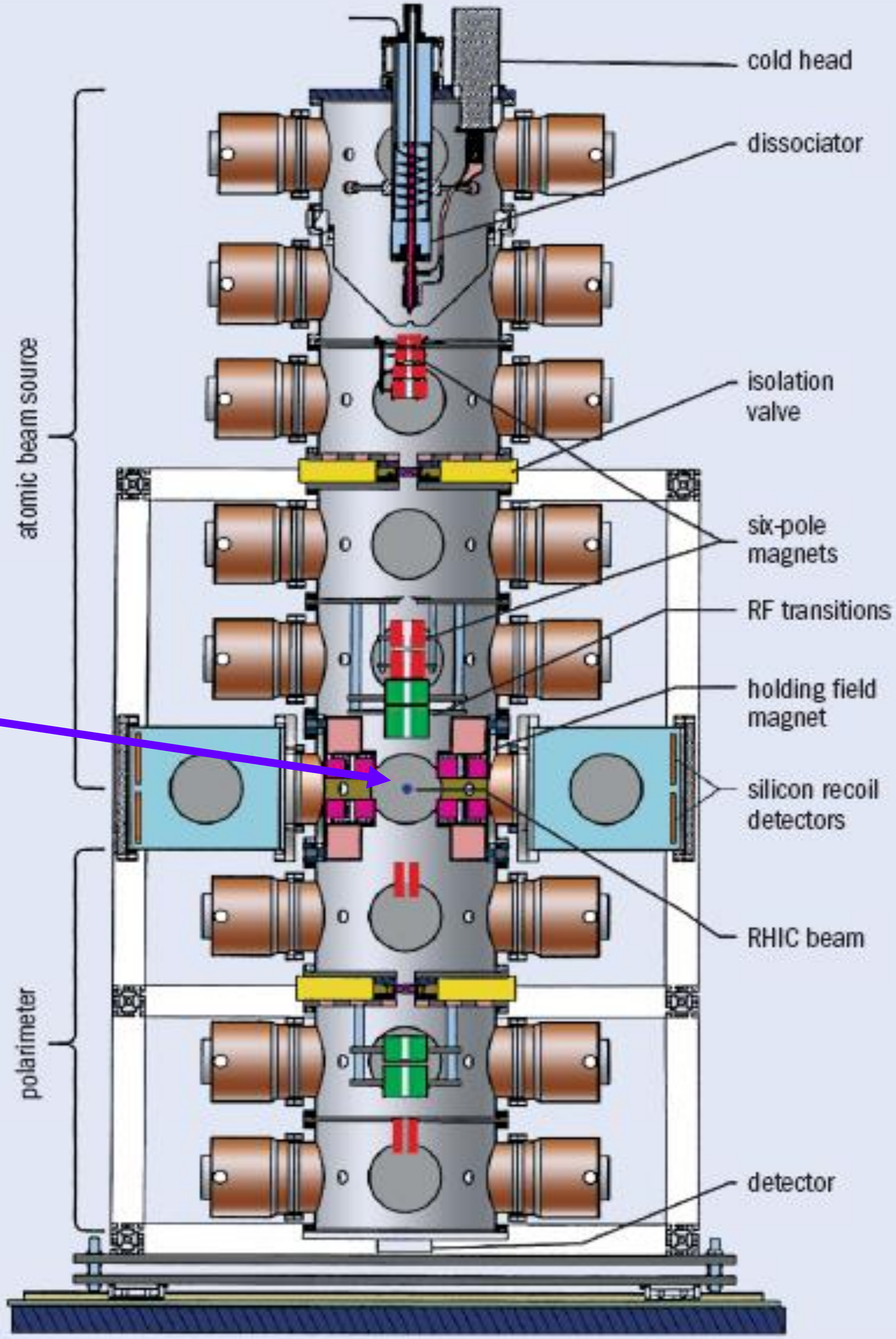
~ 60-62% polarization for colliding beams !

H -jet polarimeter



H-jet target intensity profile at the RHIC collision point.

FWHM 6.0 mm



Record $12.6 \cdot 10^{16}$ atoms/s Atomic Beam intensity.

H-jet target thickness at the collision point $\sim 1.2 \cdot 10^{12}$ atoms /cm^2

ABS: colliding beam ionizer and nearly resonant charge-exchange

Direct conversion of polarized atoms into polarized negative ions: **(Haeberli, 1968)**

- **Colliding beam ionizer:**

$$H^0\uparrow + Cs^0 \Rightarrow H^-\uparrow + Cs^+$$

(conversion efficiency ~ $5\cdot10^{-3}$)

50 μA pulsed $H^-\uparrow$ beam (R. Gebel et. al. , COSY)

- **Resonant charge-exchange plasma ionizer:**

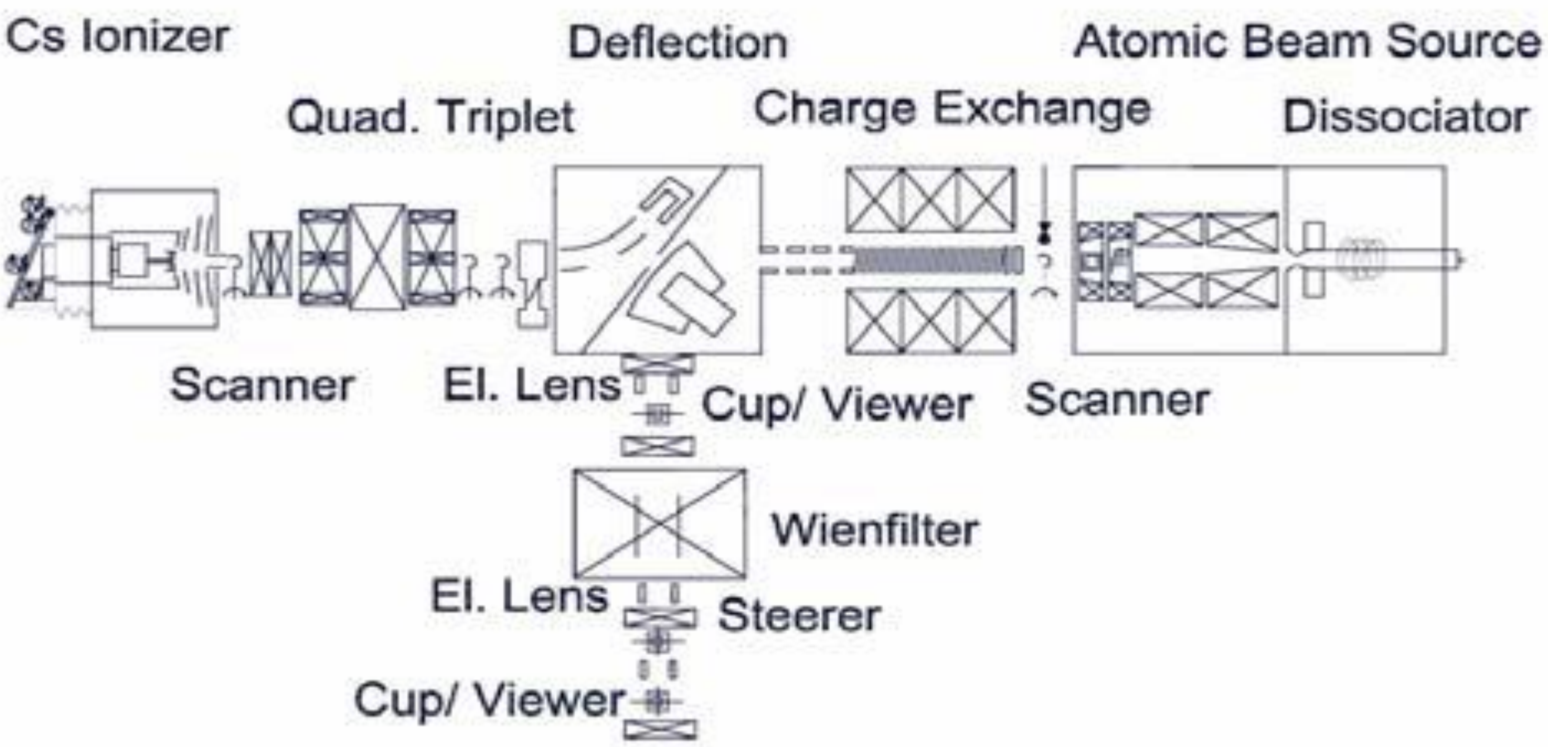
$$H^0\uparrow + D^- \Rightarrow H^-\uparrow + D^0$$

(conversion efficiency ~ 0,12)

4 mA of pulsed $H^-\uparrow$ (Belov et. al., INR RAS)

COSY/Julich polarized H-/D- Atomic Beam ion source with Cs colliding beam ionizer

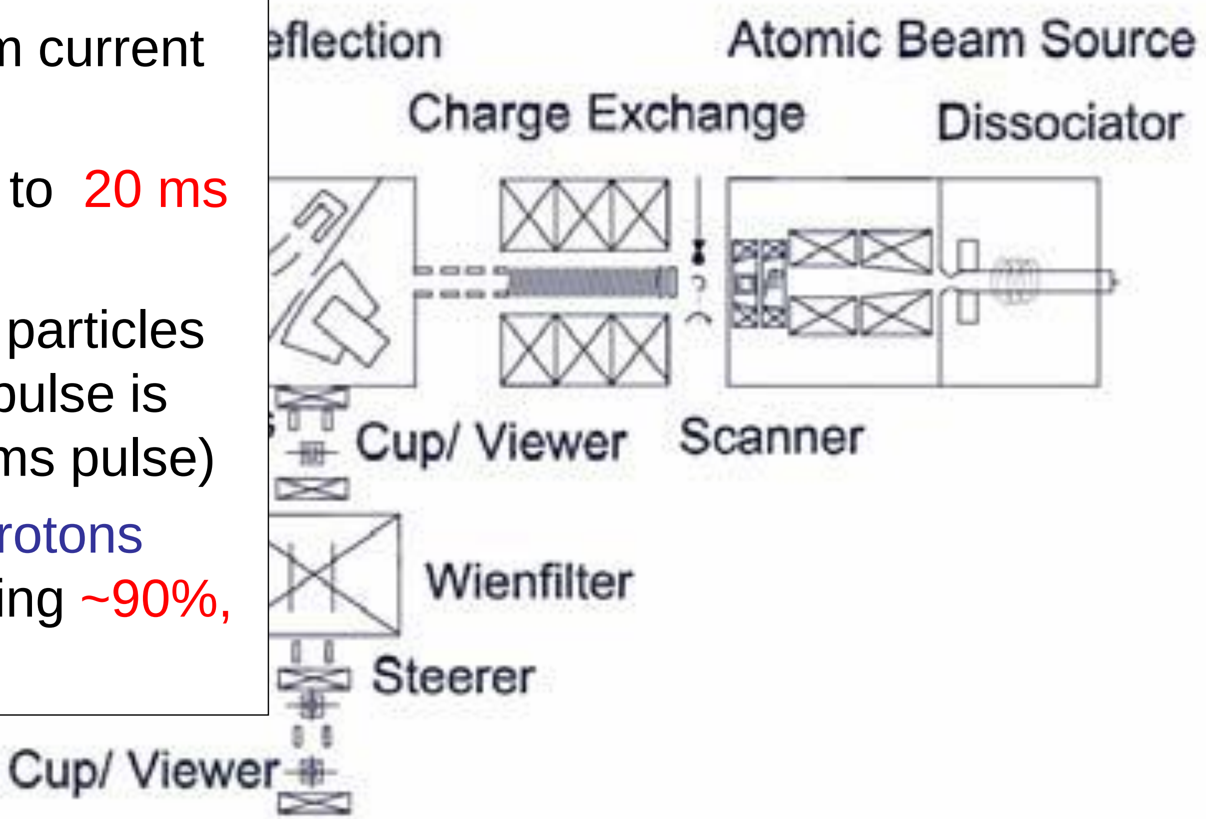
R.Gebel



COSY/Julich polarized H-/D- ion source

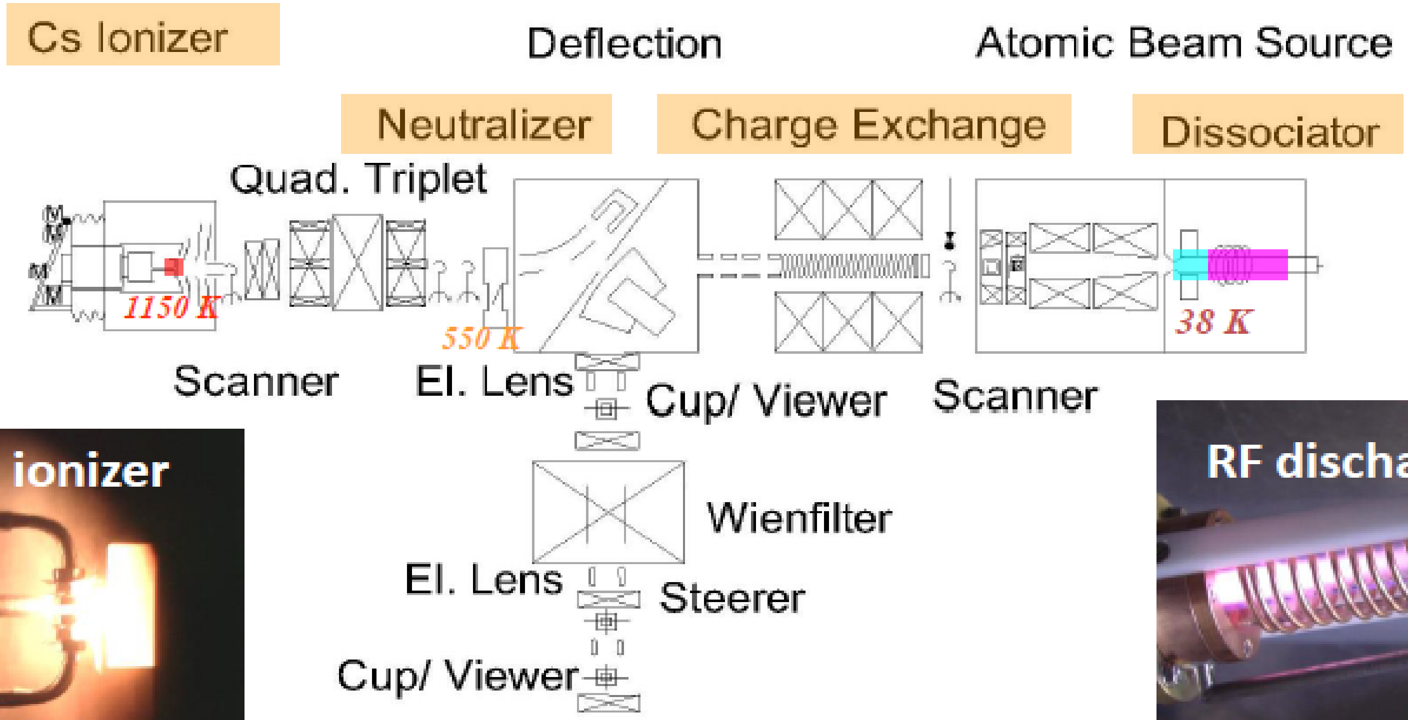
R.Gebel

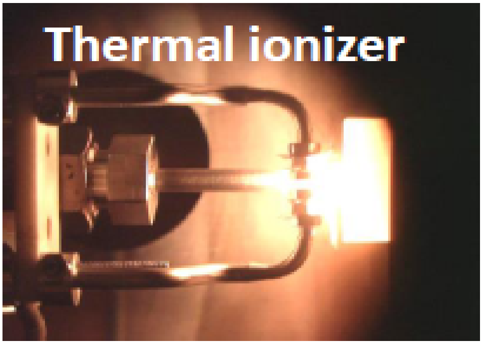
- $H^0\uparrow + Cs^0 \Rightarrow \mathbf{H^-}\uparrow + Cs^+$
- $D^0\uparrow + Cs^0 \Rightarrow \mathbf{D^-}\uparrow + Cs^+$
- Polarized H^-/D^- beam current up to 50 μA
- Pulse duration is up to 20 ms (injector - cyclotron)
- Number of polarized particles from the source per pulse is $5{,}5\cdot10^{12}$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

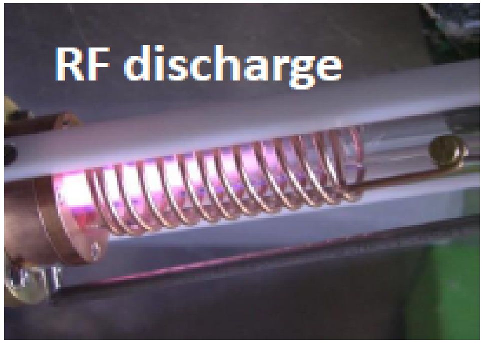


COSY's Polarized Ion Source

R.Gebel







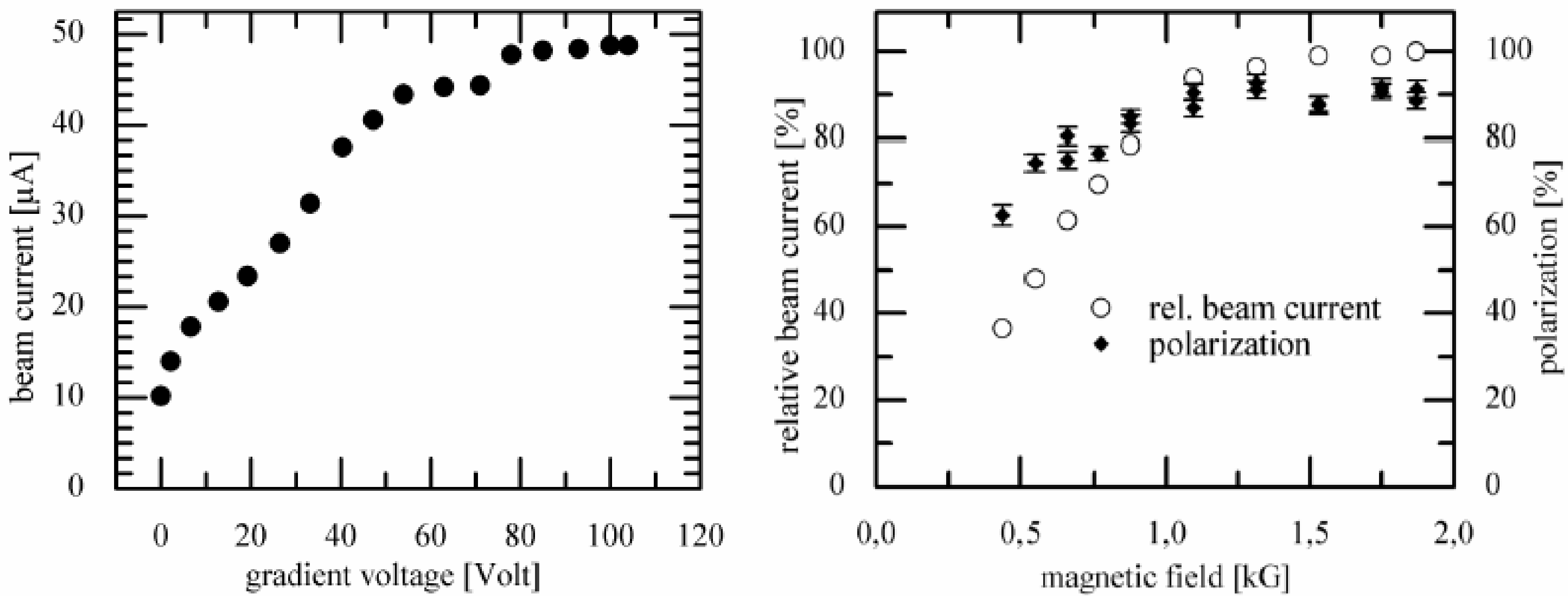
<u>Charge exchange reaction</u>

$$\vec{H}^0(\vec{D}^0) + Cs^0 \rightarrow \vec{H}^-(\vec{D}^-) + Cs^+$$

Ref.: Haeberli , NIM **62**(1968)

Ion Source Performance

R.Gebel

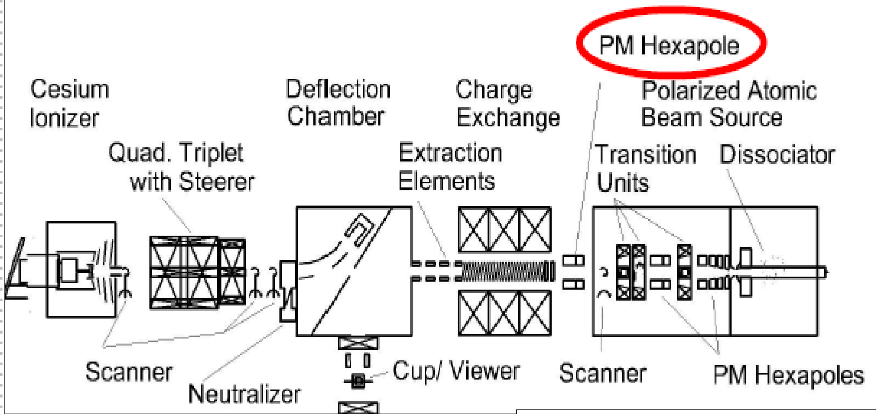


- With 6 pmA Cs @ 50 kV
- Gradient voltage -> energy spread
- High polarization is preferred
- Magnetic field -> emittance growth

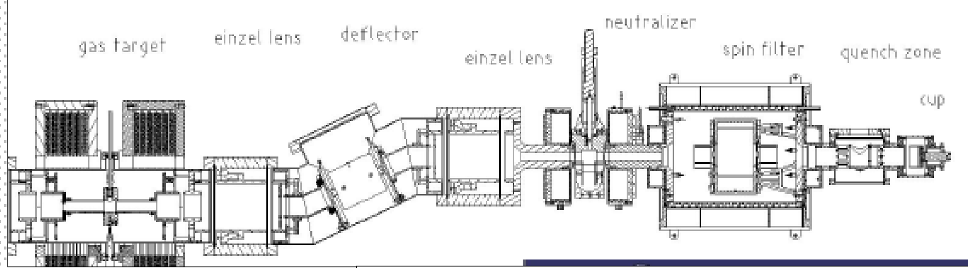
Polarimetry

R.Gebel

Breit Rabi-Polarimeter



Lambshift-Polarimeter



JÜLICH
FORSCHUNGSZENTRUM

45 MeV Polarimeter

- **pC elastic**
- **NaI scintillator @ 52.5° (Lab)**
- **Amplifier & TSCA for MHz Counter**
- **Pulse height analysis**

Carbon targets (C, CH_2)

Chromox viewer

Polarized source of H-/D- and H+/D+ ions with nearly resonant charge-exchange plasma ionizer. INR Moscow

Peak H^- ion current - 4 mA

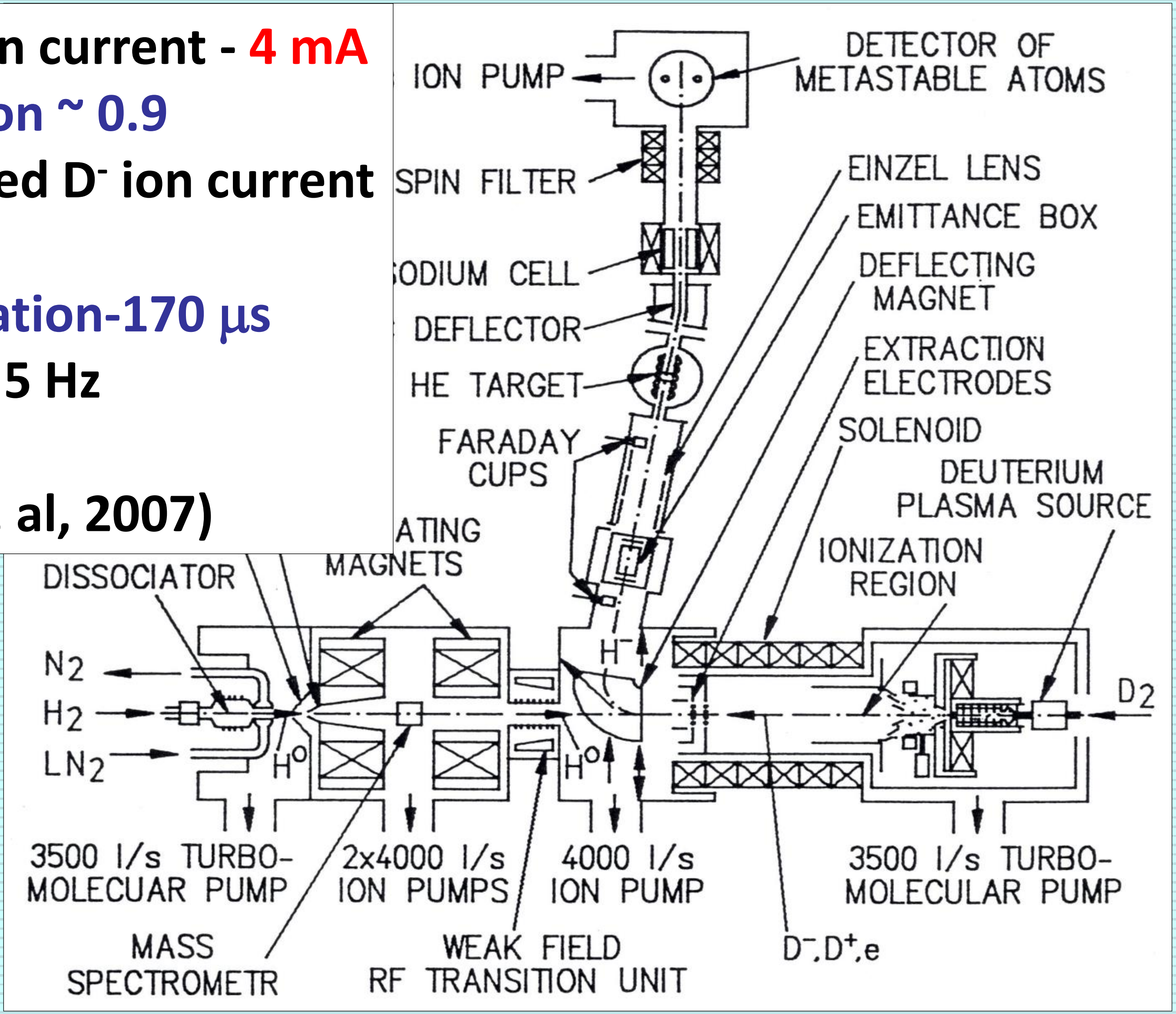
Polarization ~ 0.9

Unpolarized D^- ion current - 60 mA

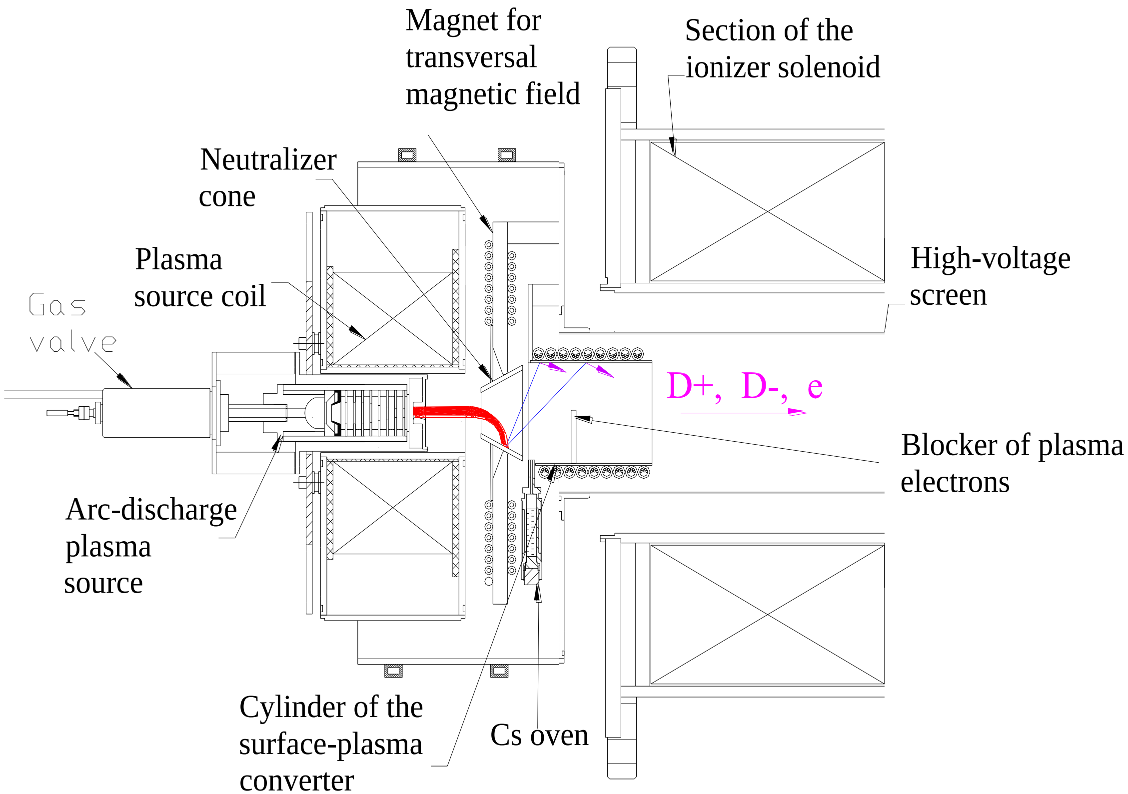
Pulse duration-170 μs

Rep. Rate 5 Hz

(Belov et. al, 2007)



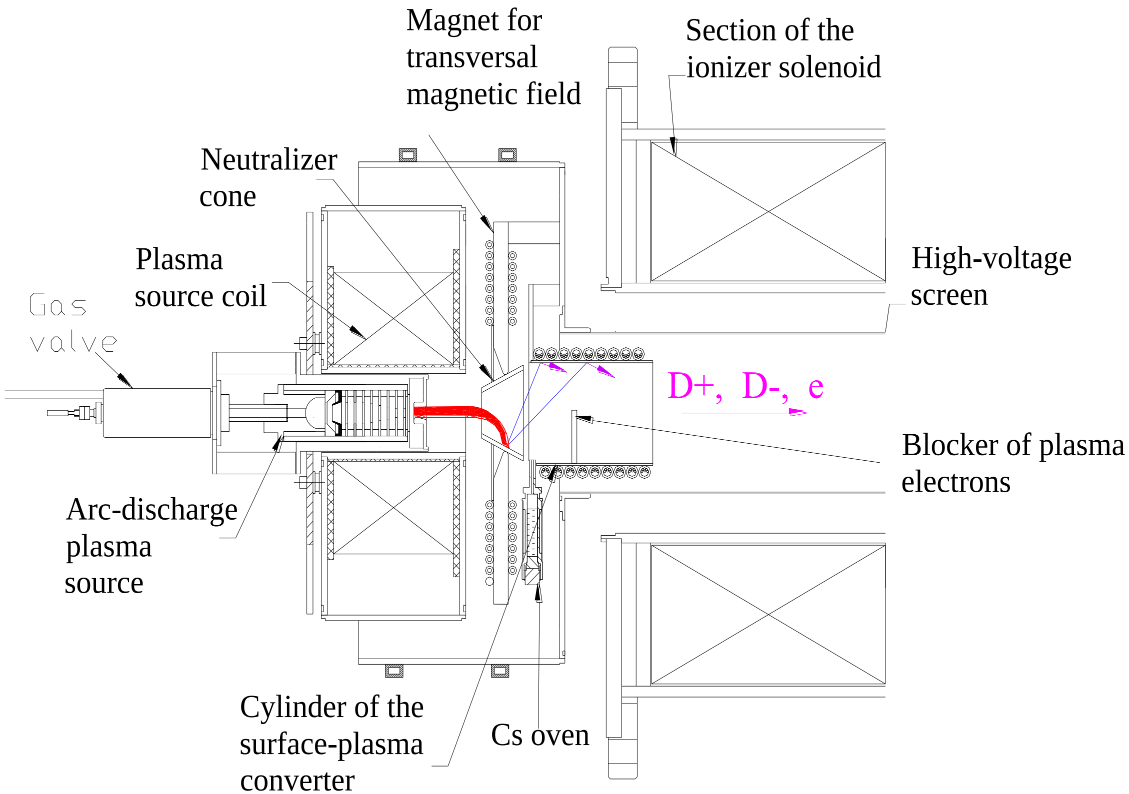
Plasma generator for resonant charge-exchange ionizer



- 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 easily destroyed in collisions with plasma electrons.

- Plasma injector producing deuterium plasma enriched by D^- ions with surface-plasma converter has been developed at INR.

Plasma generator for resonant charge-exchange ionizer



INR ionizer was successfully implemented at IUCF, where ~ 1.0 mA H^-/D^- beam intensity was obtained with 80-85% polarization

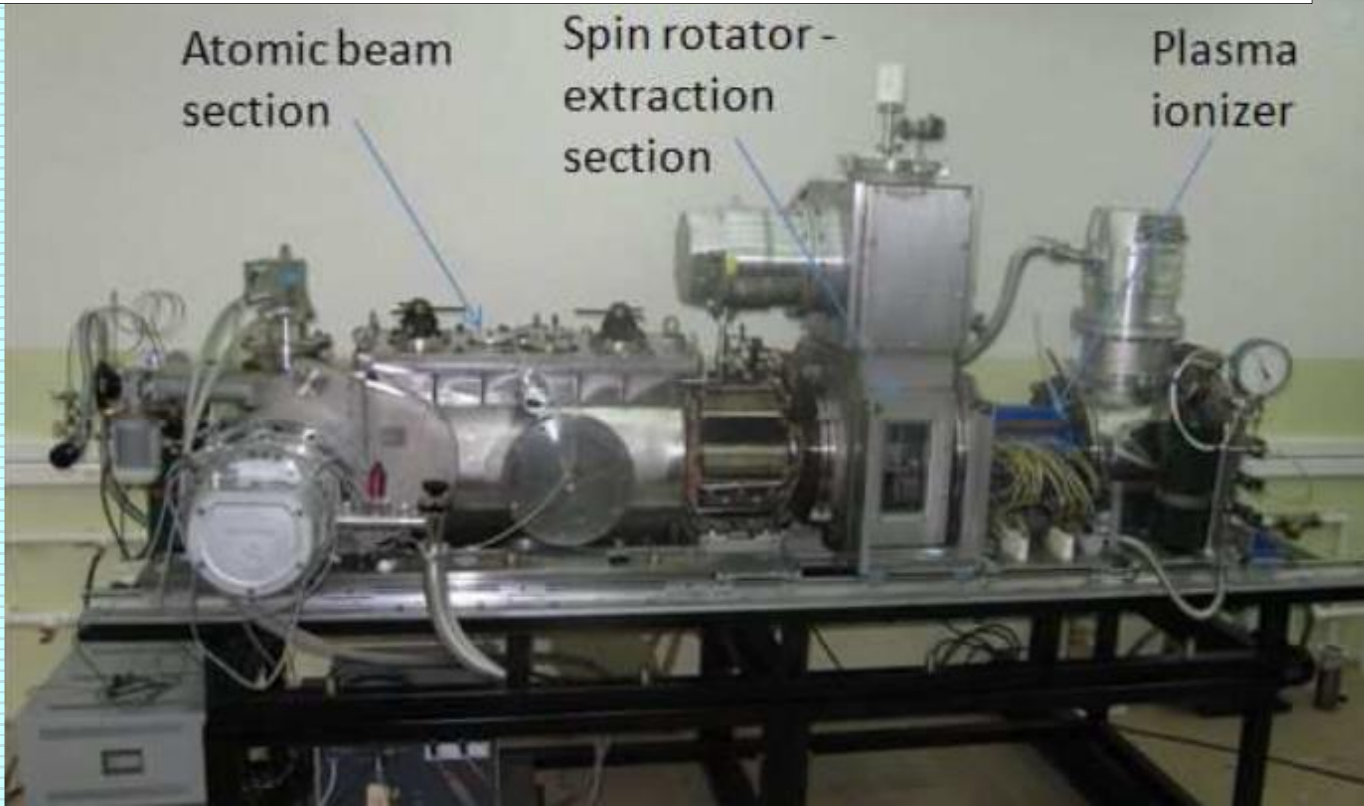
surface-plasma converter has been developed at INR.

Polarized ion source for Dubna NICA project. (V.Fimushkin in this session)

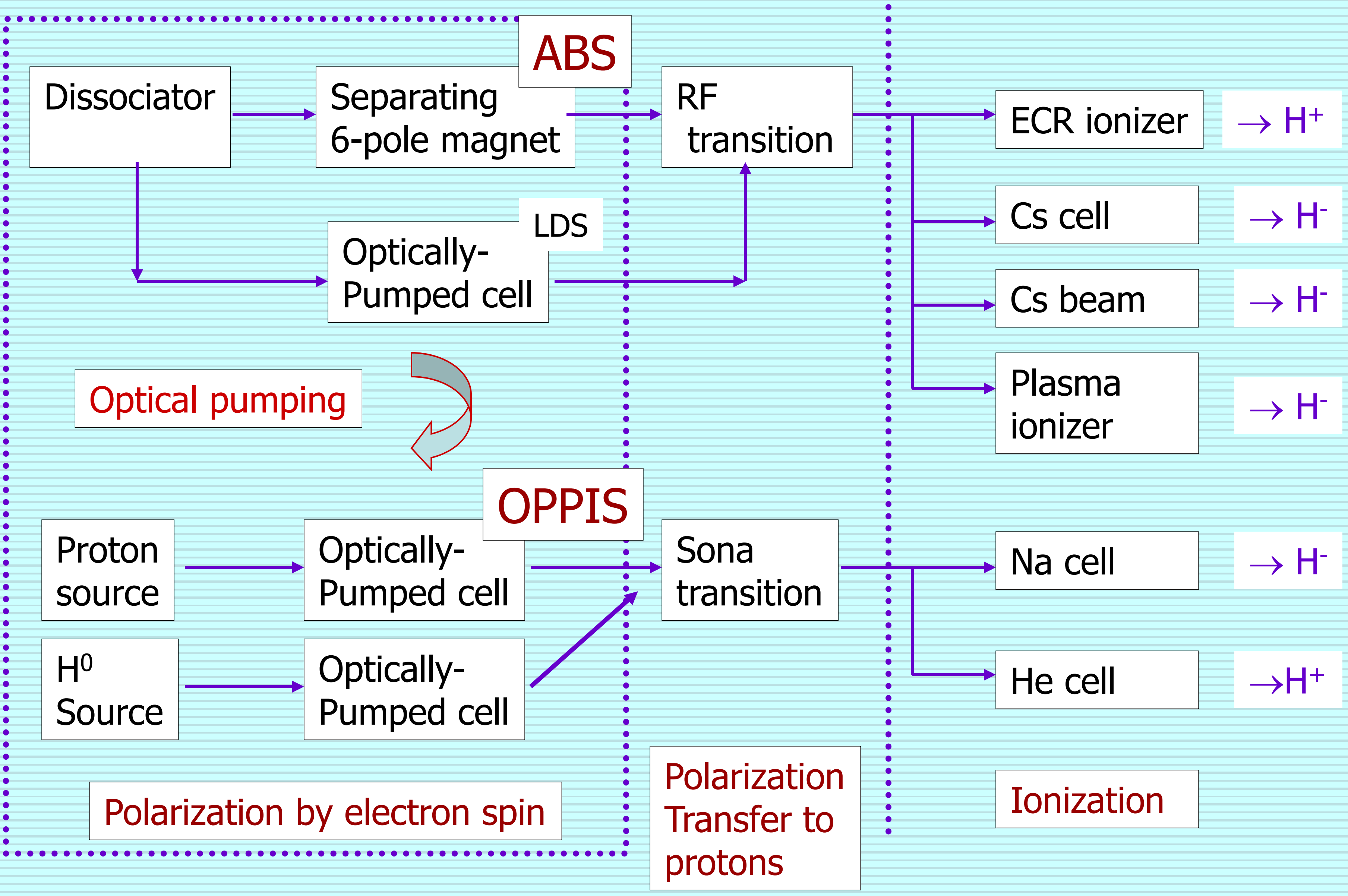
- New atomic beam-type source with nearly resonant charge-exchange plasma ionizer is developed for NUCLOTRON
- Motivation: high intensity pulsed polarized ion beam is necessary due to use of one turn injection into the NUCLOTRON (8 μs pulse duration)
- Project goal:
  - 10 mA D^+/H^+
  - polarization ~ 90 % from nominal vector polarization + (-) 1 and tensor polarization + 1,-2

The polarized ions source for the JINR accelerator complex

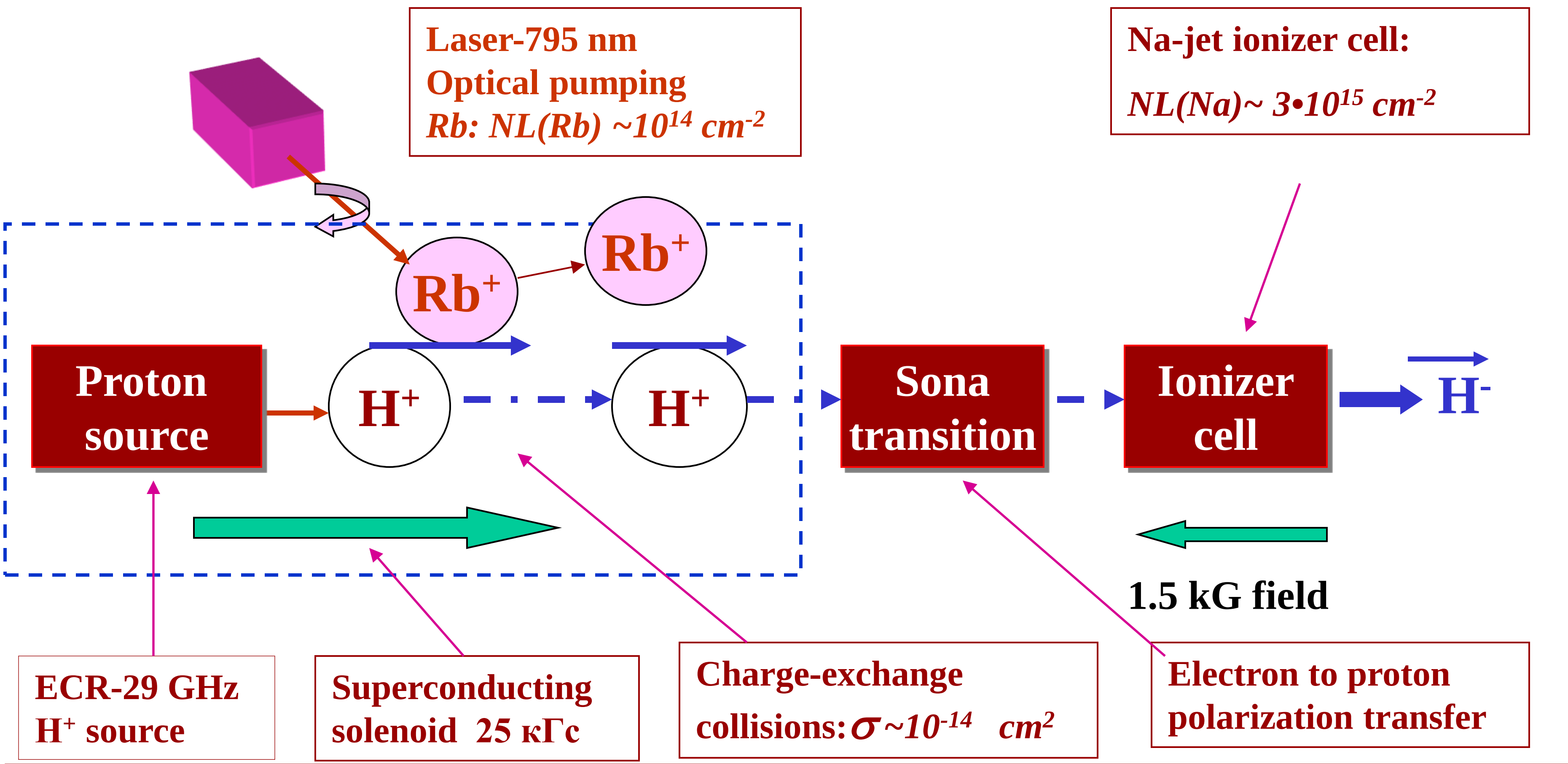
The project assumes the design and construction of a universal high-intensity source of polarized deuterons (protons) using a charge-exchange plasma ionizer. The output D+↑(H+↑) current of the source is expected to be at a level of 10mA. The polarization will be up to 90% of the maximal vector (±1) for D+↑ (H+↑) and tensor (+1, -2) for D+↑ polarization. Realization of the project is carried out in close cooperation with INR of the RAS (Moscow).



$H^{\pm}$, $D^{\pm}$ - Polarization techniques



SPIN -TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS.



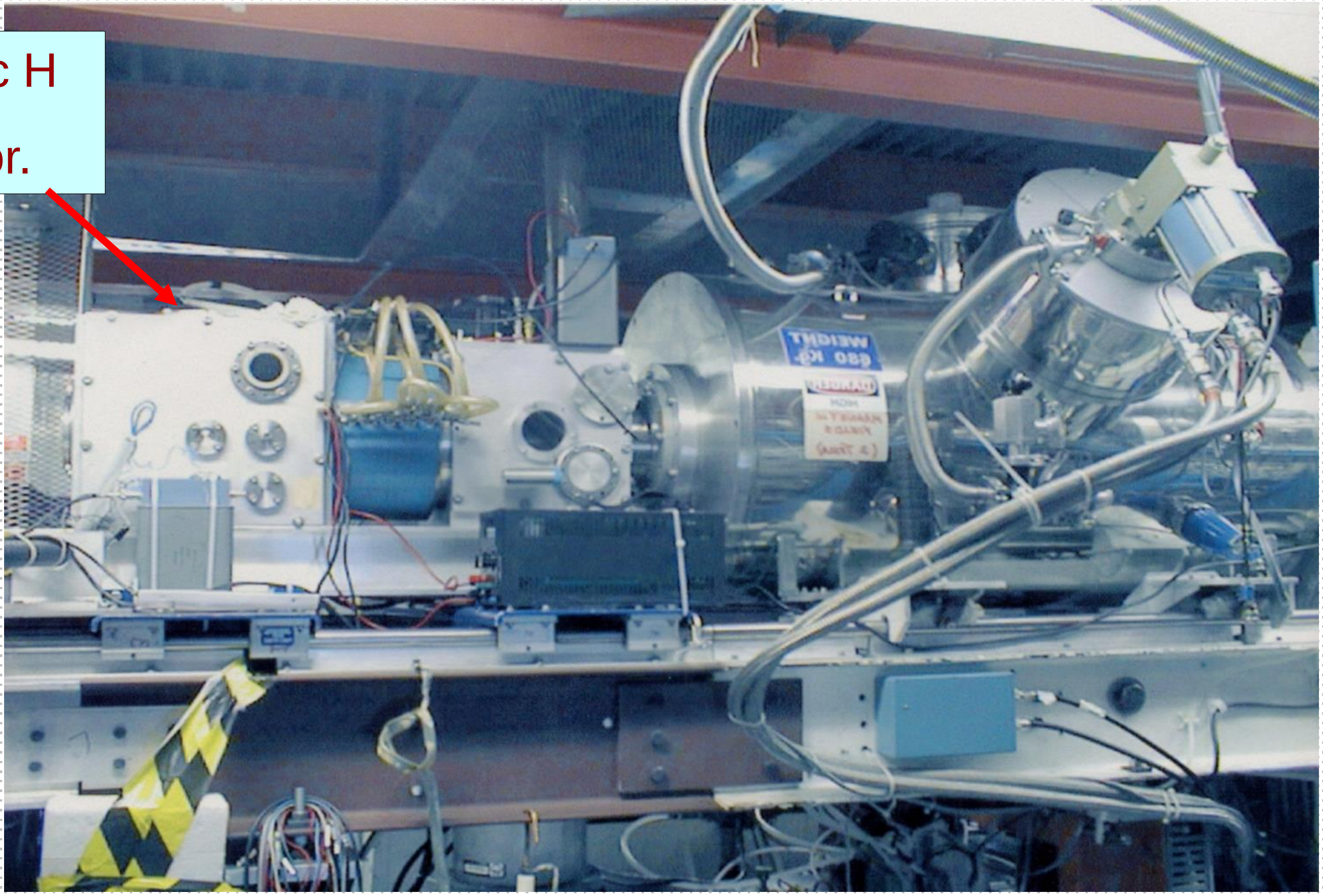
Laser beam is a powerfull primary source of angular momentum:

10 W (795 nm) → 4•10^{19} hν/sec → 2 A, $\vec{H}^0$ equivalent intensity.

Feasibility of Multi-ampere polarized beams.

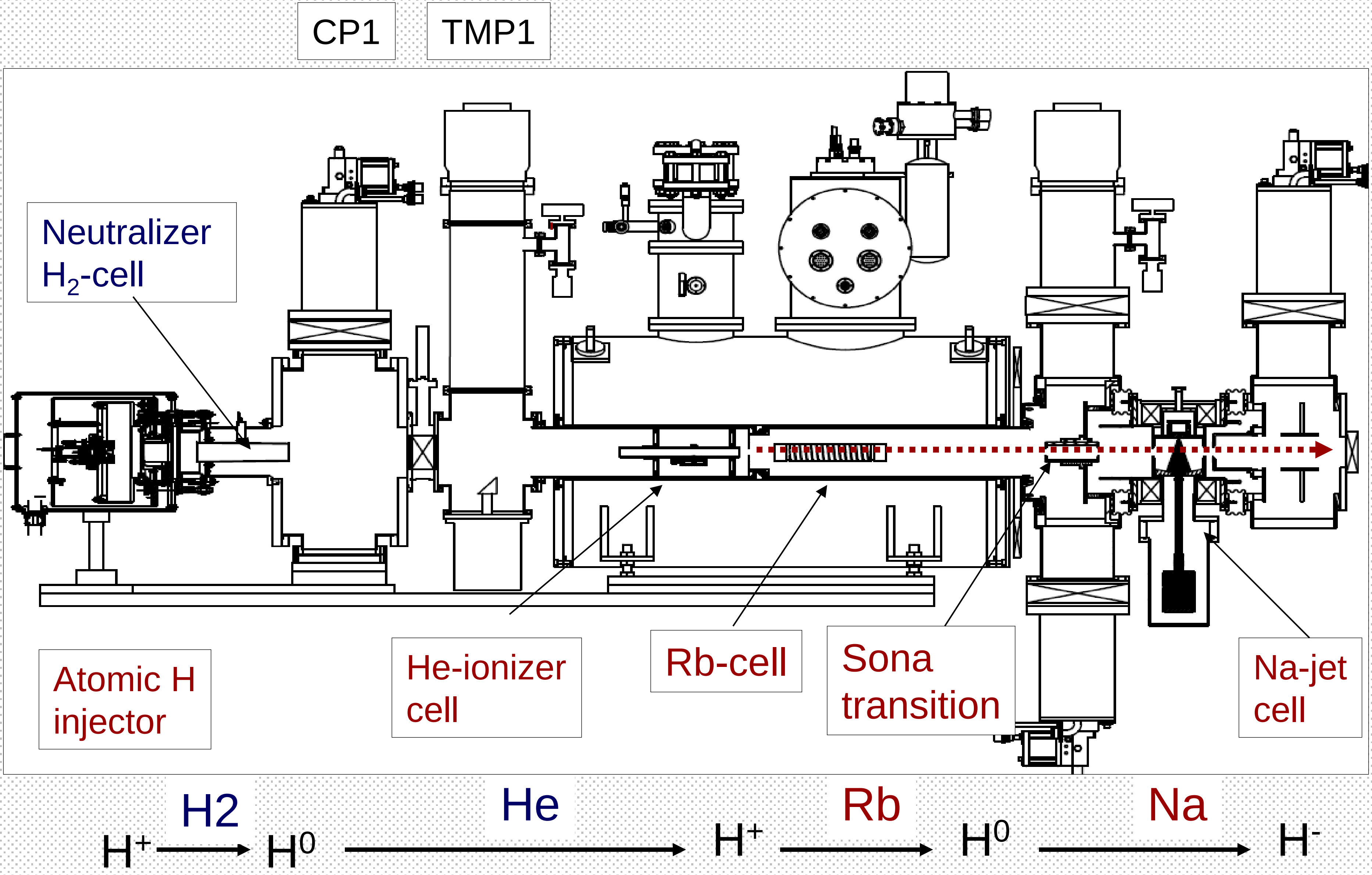
Pulsed OPPIS at TRIUMF, 1997-99. Second generation.

Atomic H Injector.



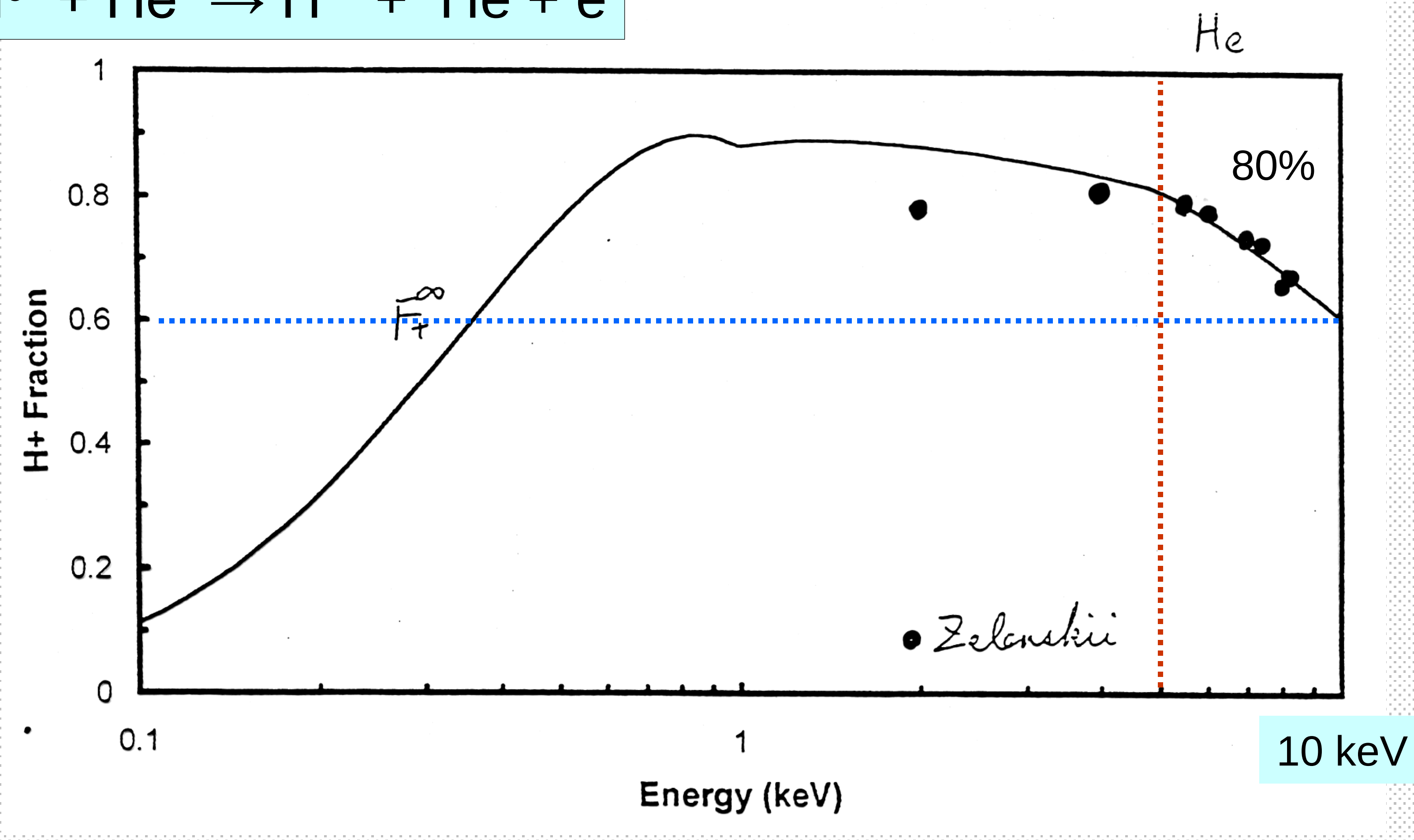
A pulsed H^- ion current of a 10 mA was obtained in 1999.

New OPPIS with atomic H^0 injector layout

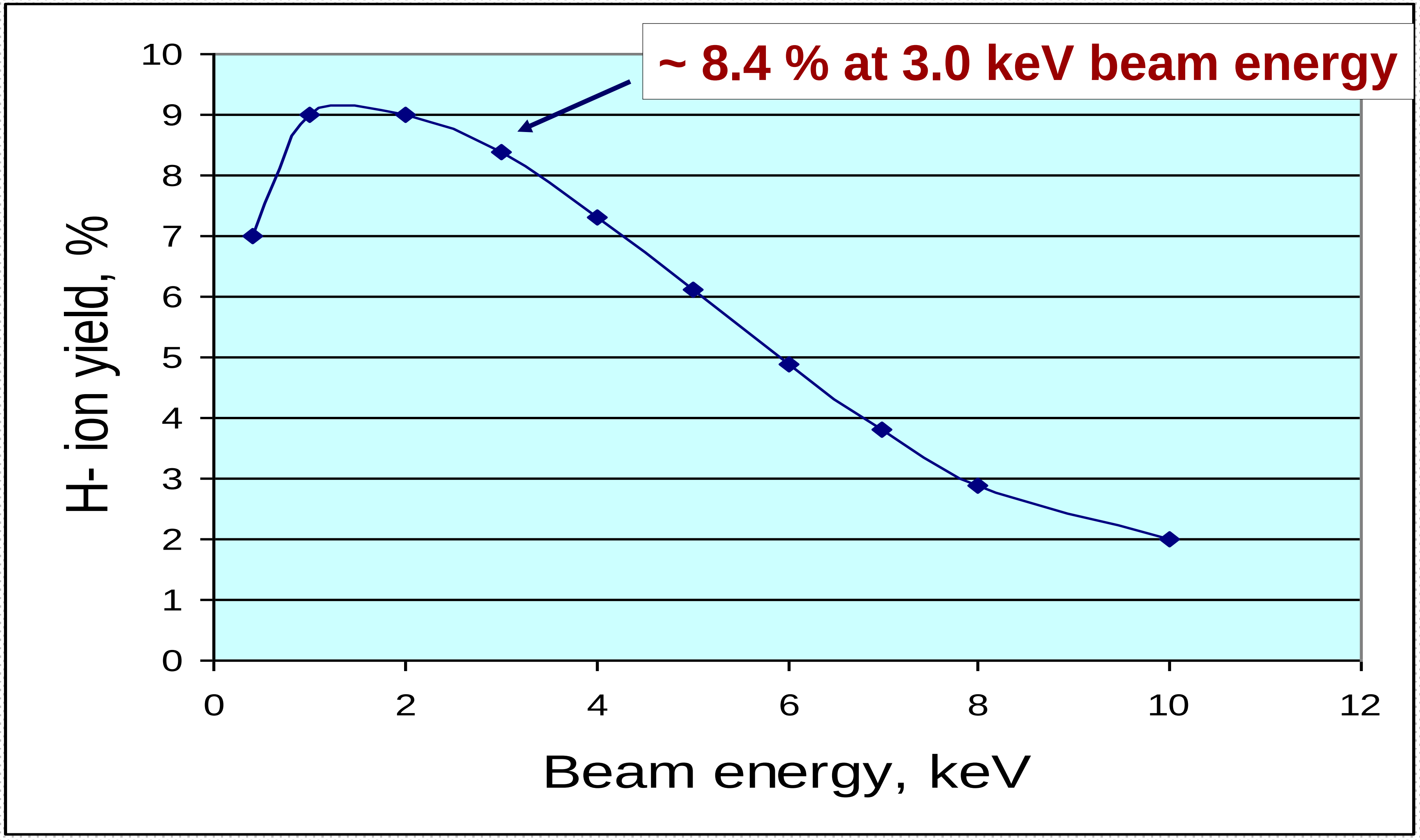


Hydrogen atomic beam ionization efficiency in the He- cell.

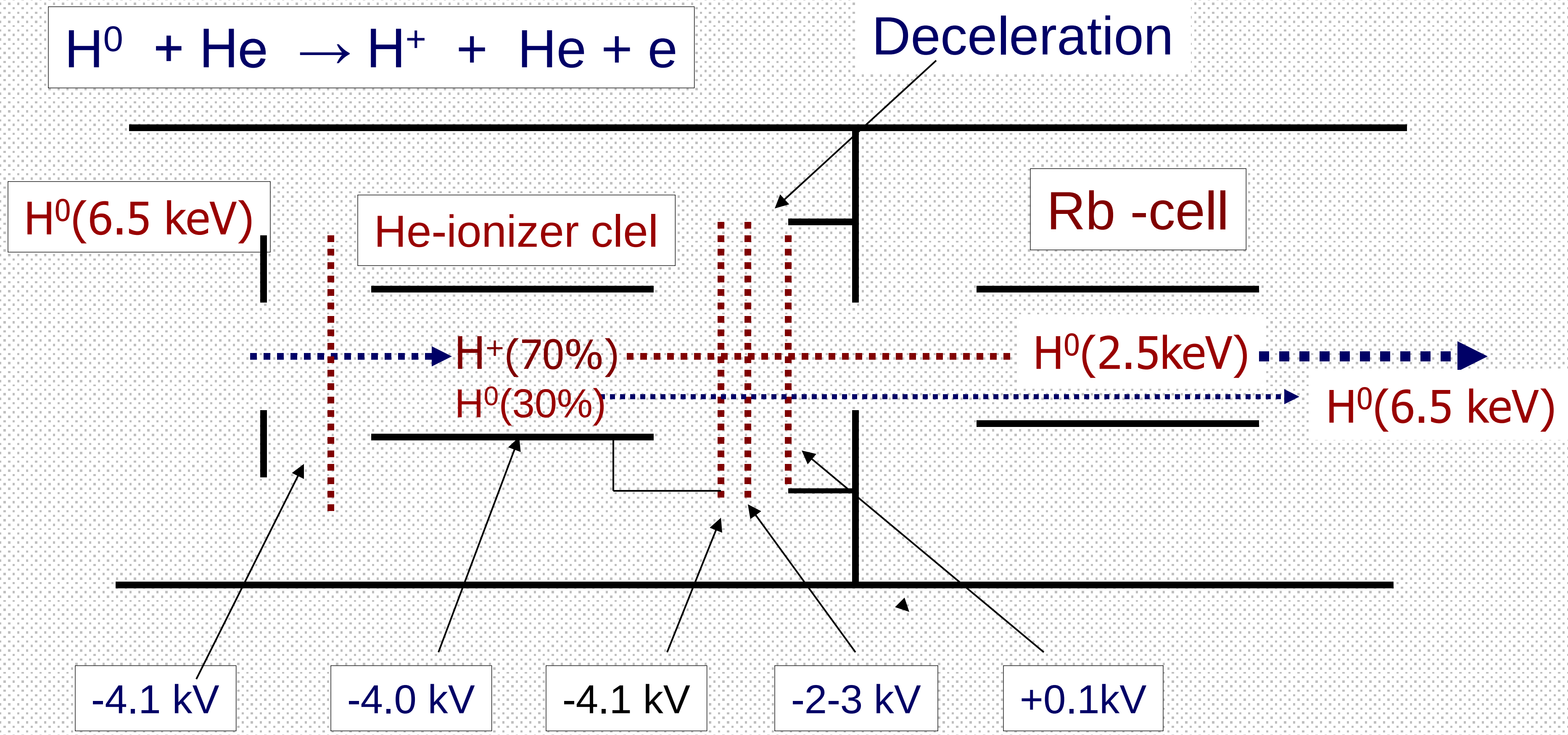
$H^0 + He \rightarrow H^+ + He + e$



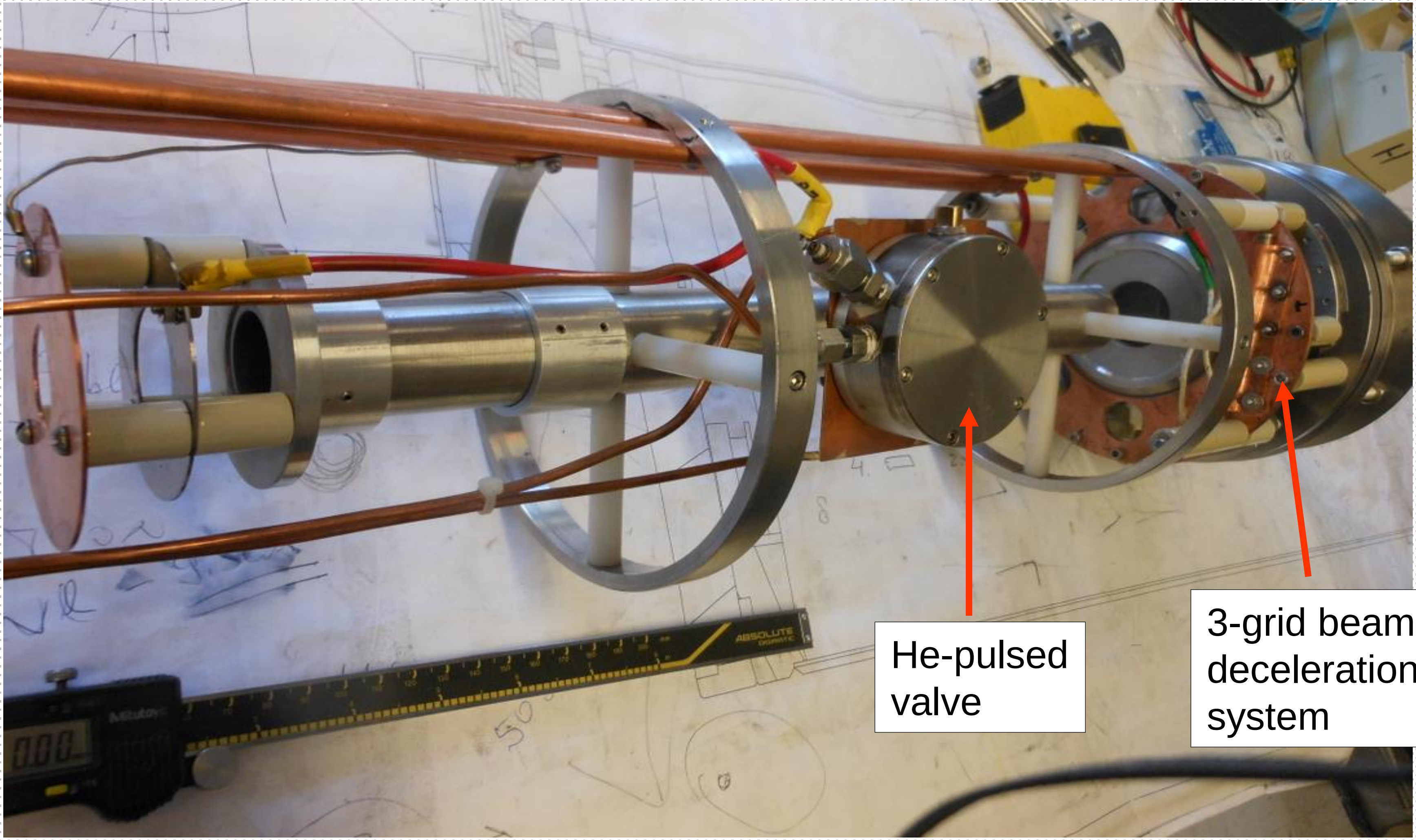
H^- yield vs. H^0 beam energy



Residual un-polarized H^0 beam component suppression by the energy separation



He-ionizer cell and three-grid energy separation system

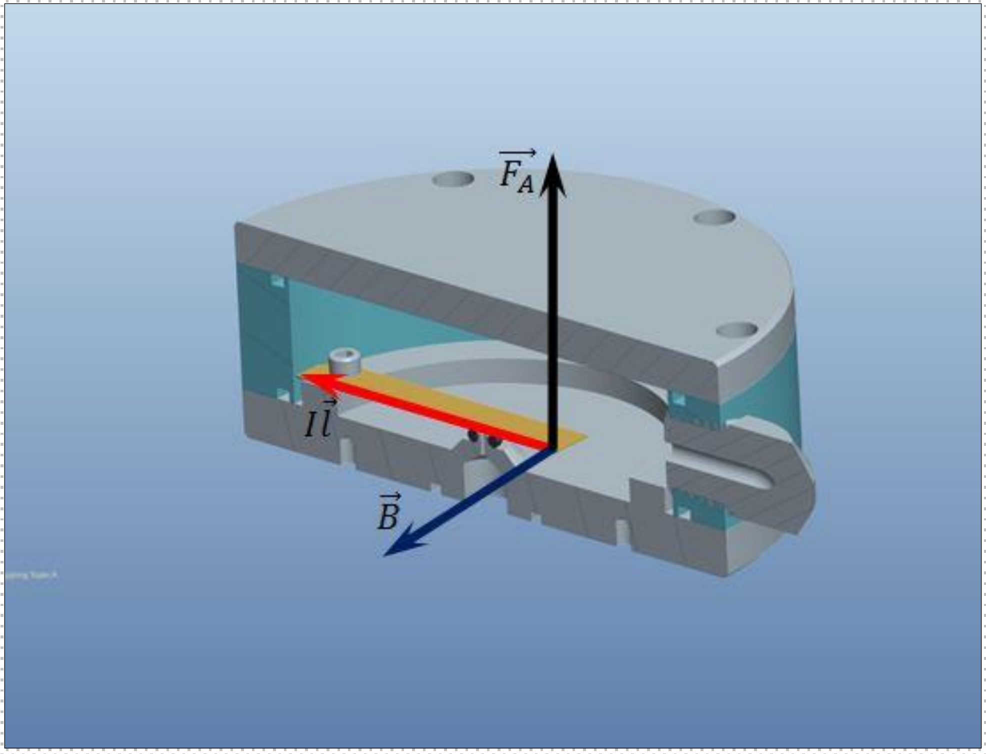


"Electro-dynamic" valve operation principle.

Force to the conducting plate in the (high ~ 3 T) magnetic field.

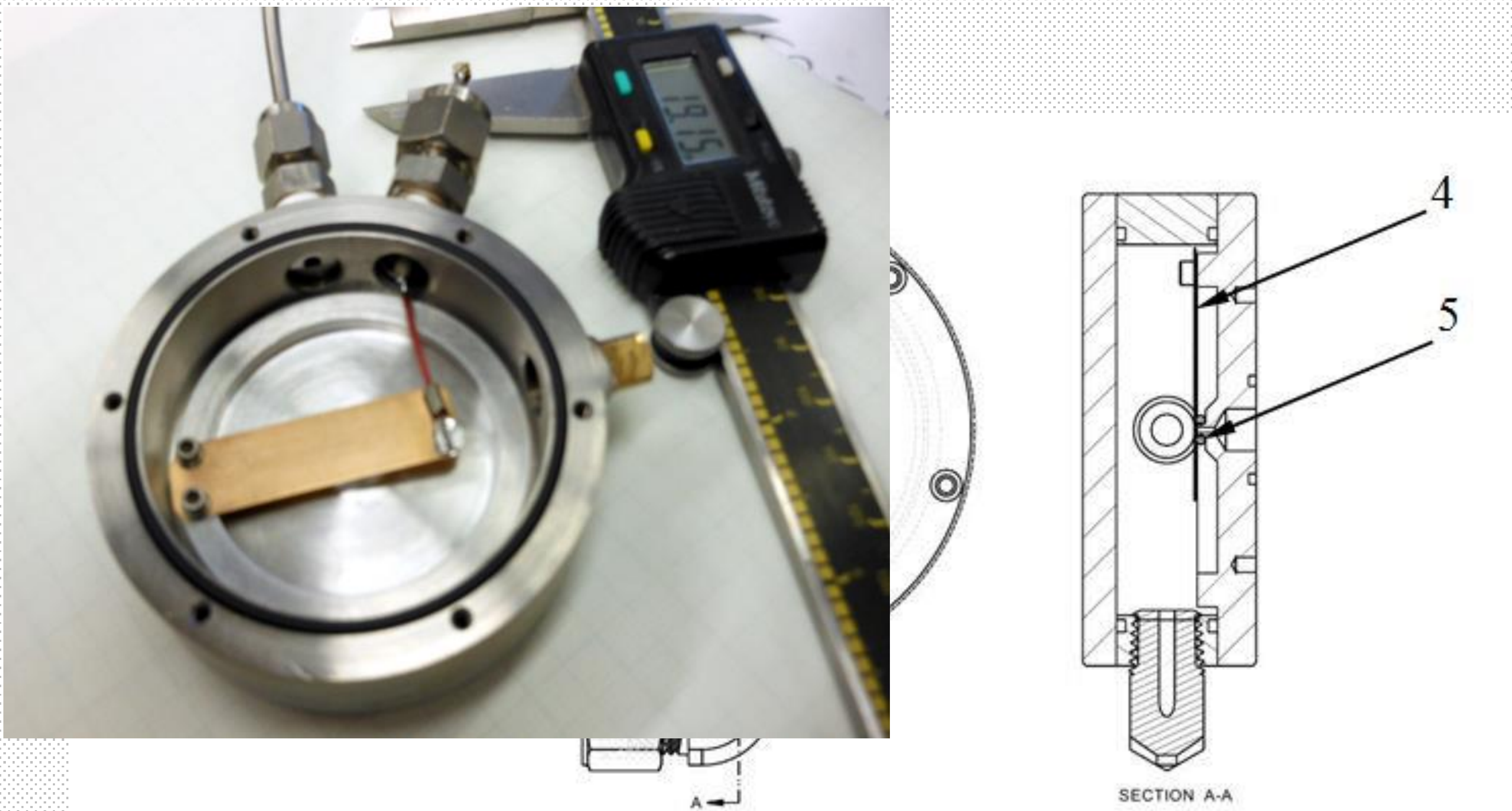
$$d\overrightarrow{F_A} = I[d\vec{l}\ \vec{B}]$$

For I=100 A, L=5 cm, F=15 N).



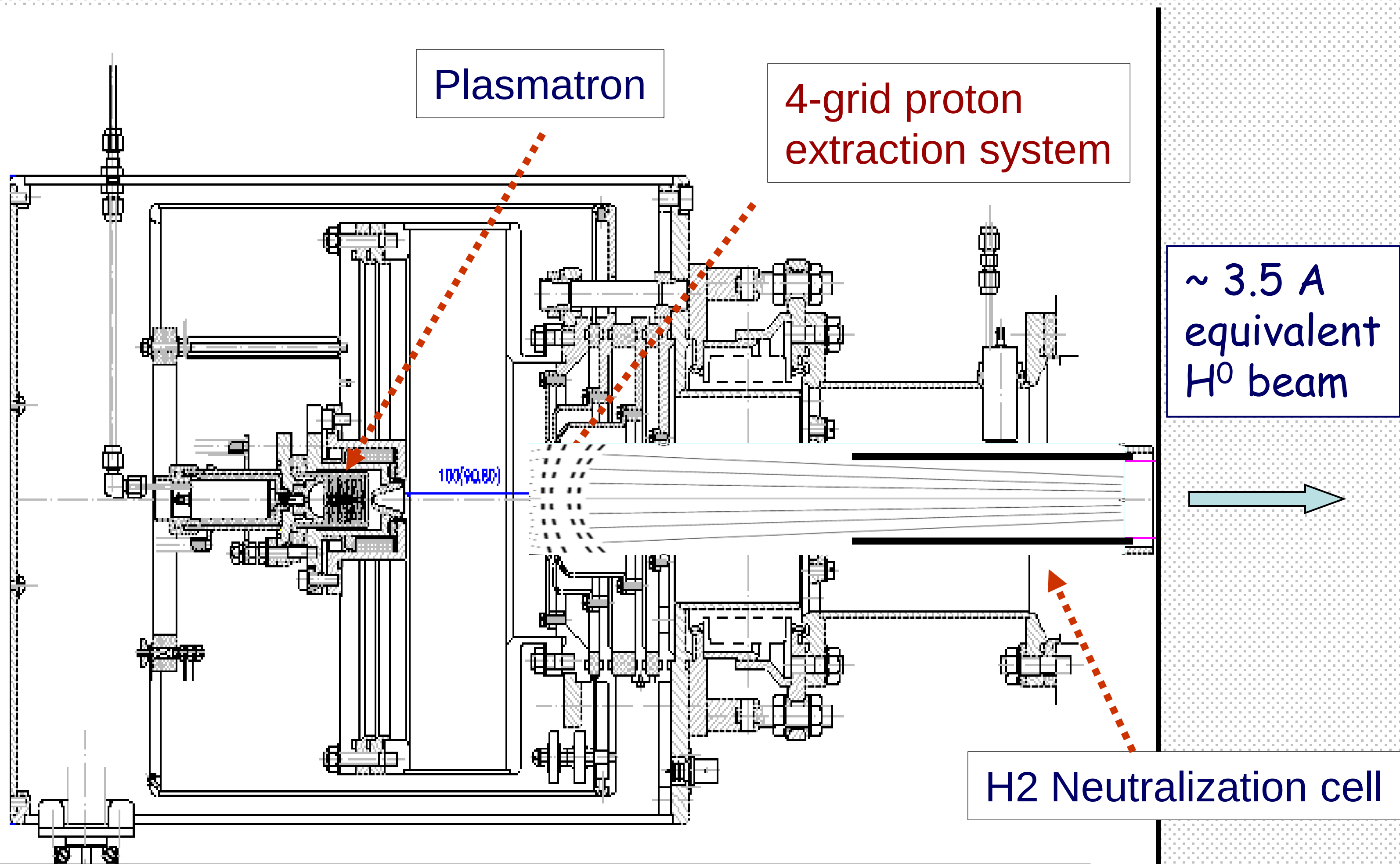
Electro-dynamic valve .

“Electro-magnetic” He-gas valve.



1 – body, 2 – current vacuum feed-through, 3 – gas supply,
4 – flexible springing plate, 5 – “O” -ring.

"Fast Atomic Beam Source", BINP 2011



FABS produces 200-300 mA equivalent H0 beam intensity
Within the Na-jet ionizer acceptance.

FABS 4-grid spherical Ion Optical System (IOS).

1820 holes ,5 cm in diameter

3-5 A of proton beam

Superconducting Solenoid

Magnet designed and built by Cryomagnetics to BNL specification

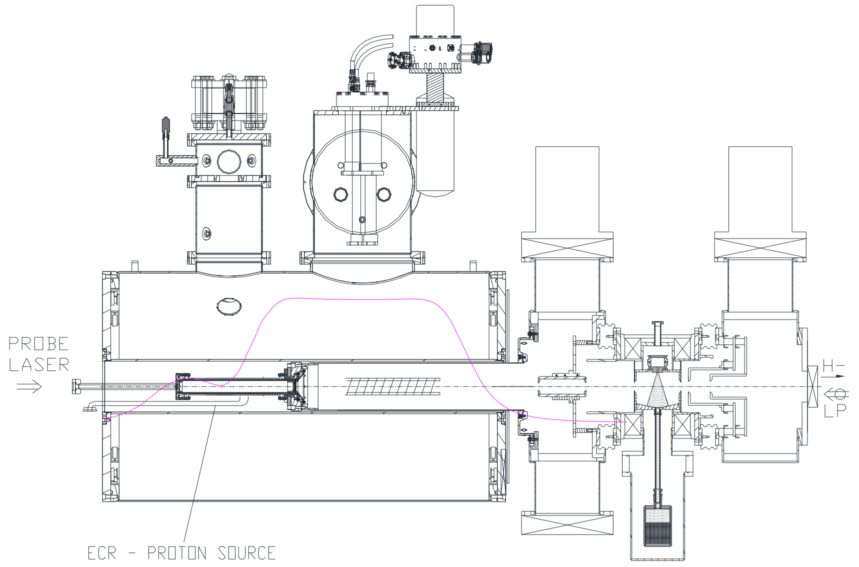
$390k Contract. Delivery- April 2011.

Actual delivery: February-2012. Almost a year delay.

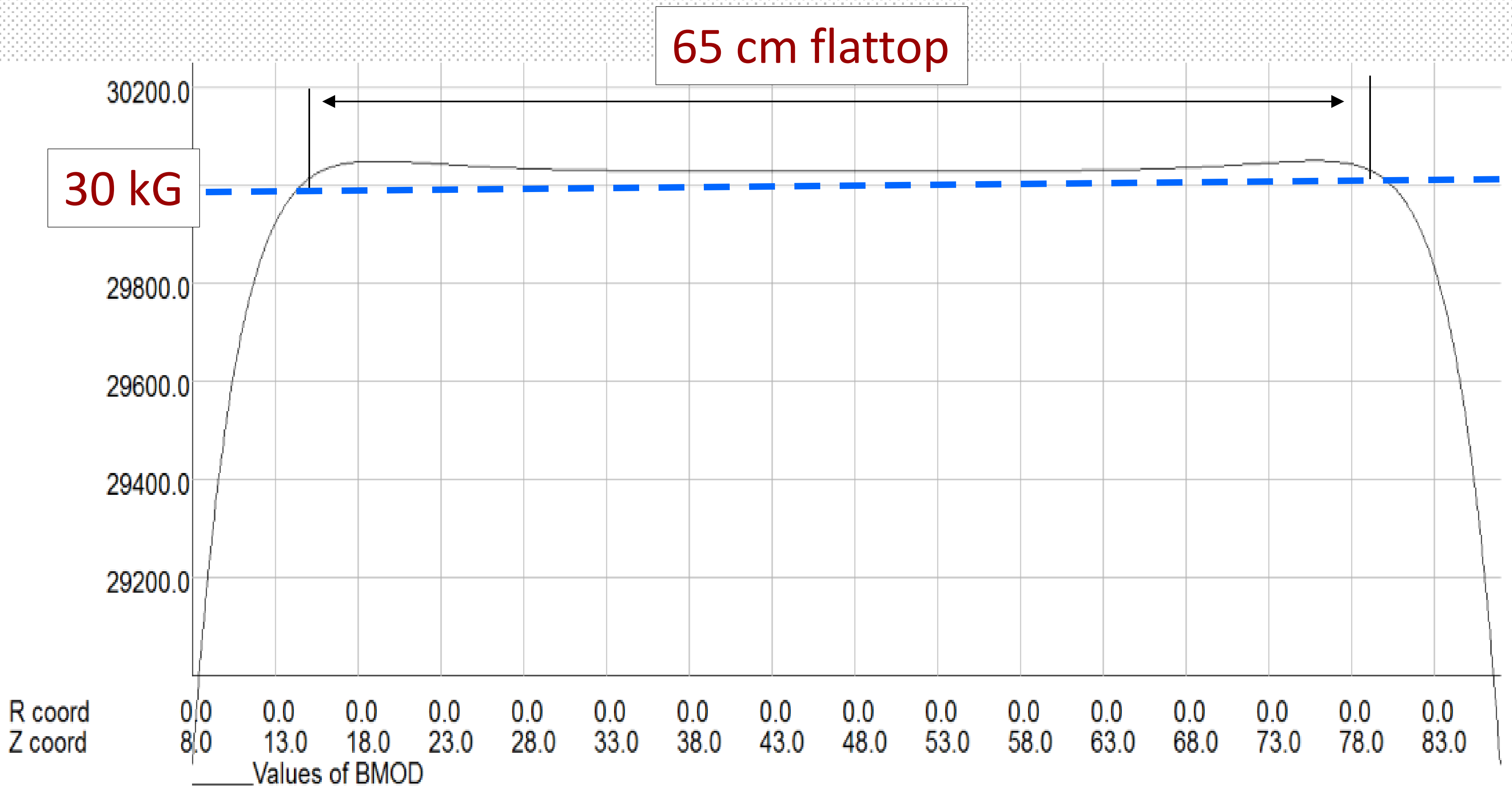
Solenoid can operate with double hump field shape for ECR mode of operation or with a 3T flat field for use with external injector.

Acceptance tests completed in March. Installed at the source bench in May, 2012.

Solenoid is fully re-condensing with no measurable helium losses.

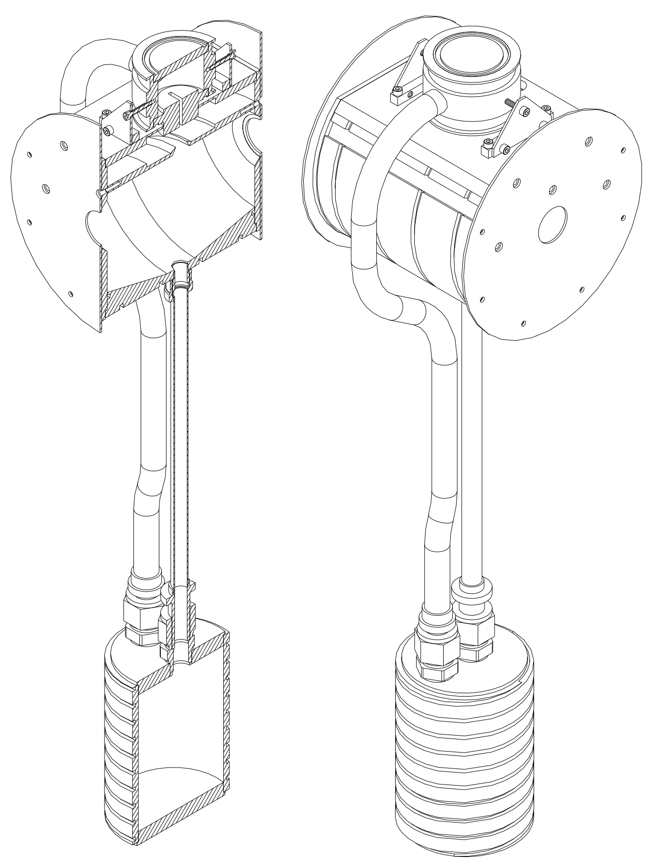


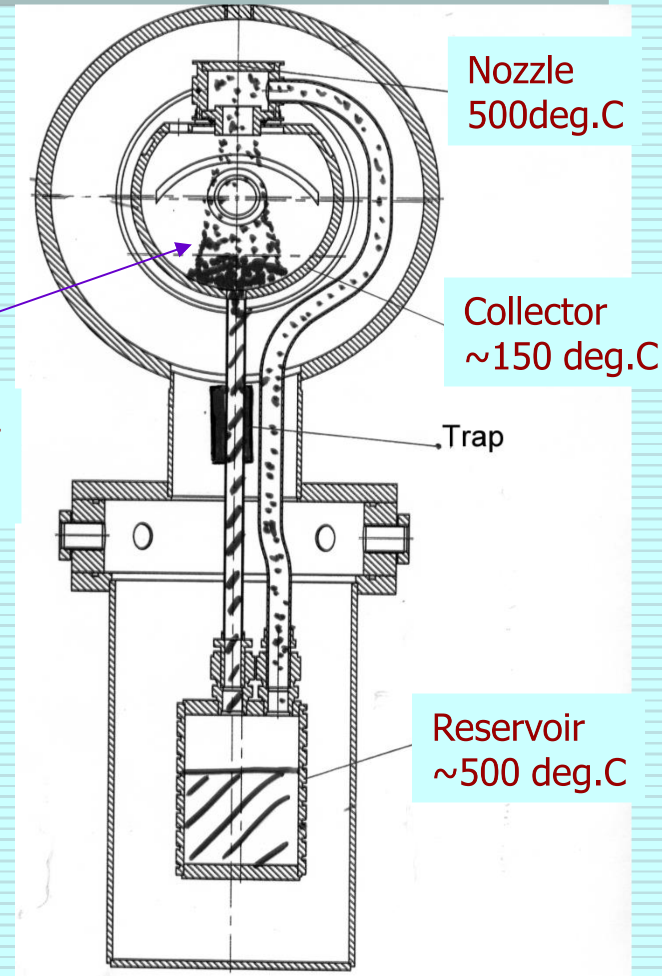
Atomic Beam Mode, flattop.



Sodium-jet ionizer cell.

Transversal vapor flow in the N-jet cell. Reduces sodium vapor losses for 3-4 orders of magnitude, which allow the cell aperture increase up to 3.0 cm .





$NL \sim 2 \cdot 10^{15}$ atoms/cm^2

$L \sim 2\text{-}3$ cm

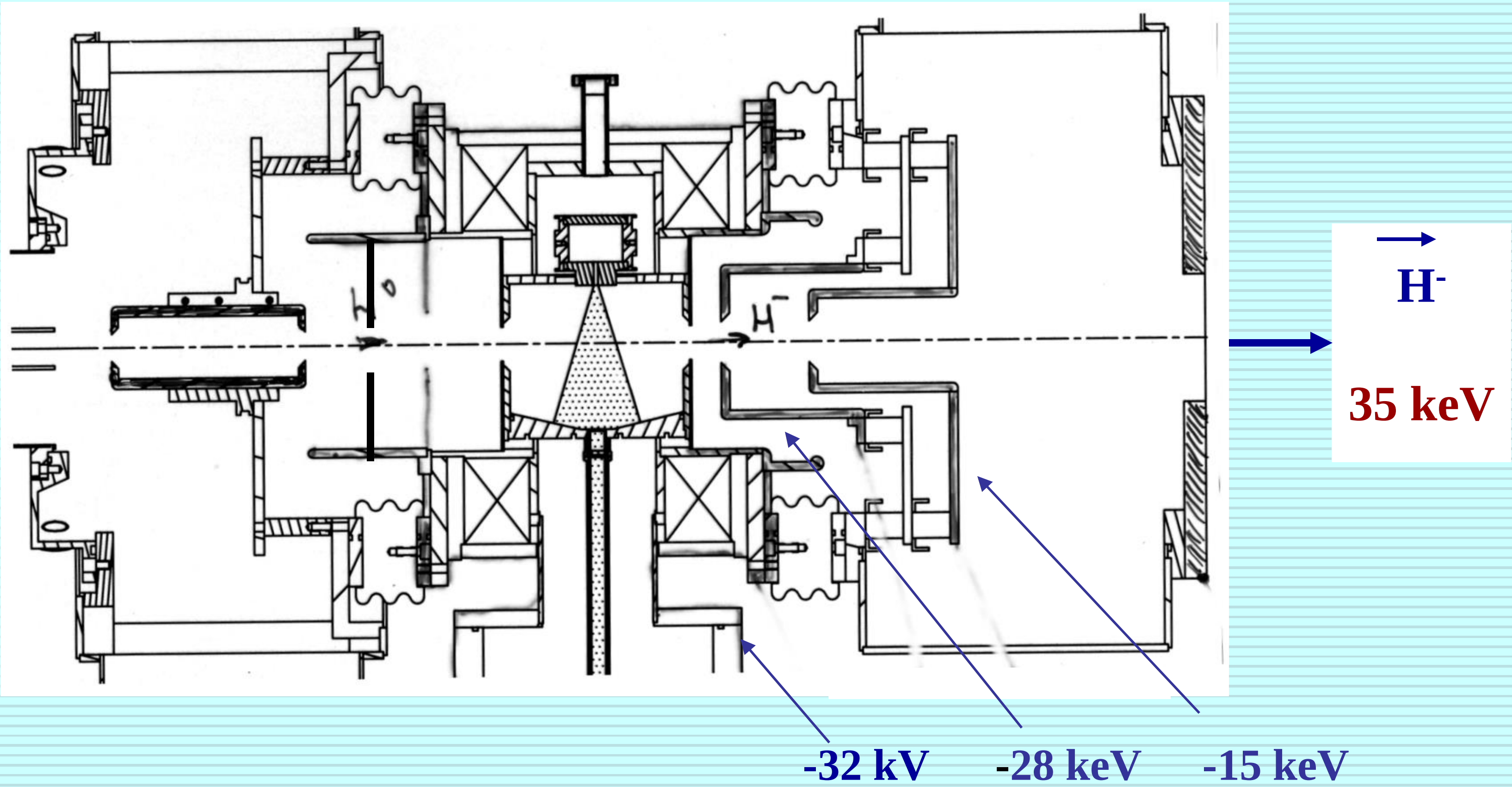
Reservoir– operational temperature. Tres. ~500 °C.

Nozzle – Tn ~500 °C.

Collector- Na-vapor condensation: Tcoll.~120°C

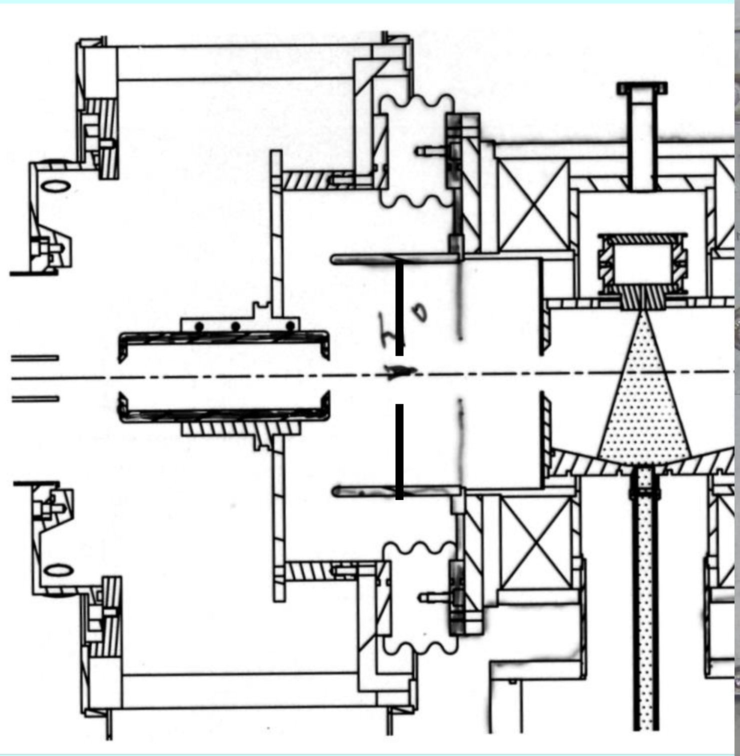
Trap- return line. T ~ 120 – 180 °C.

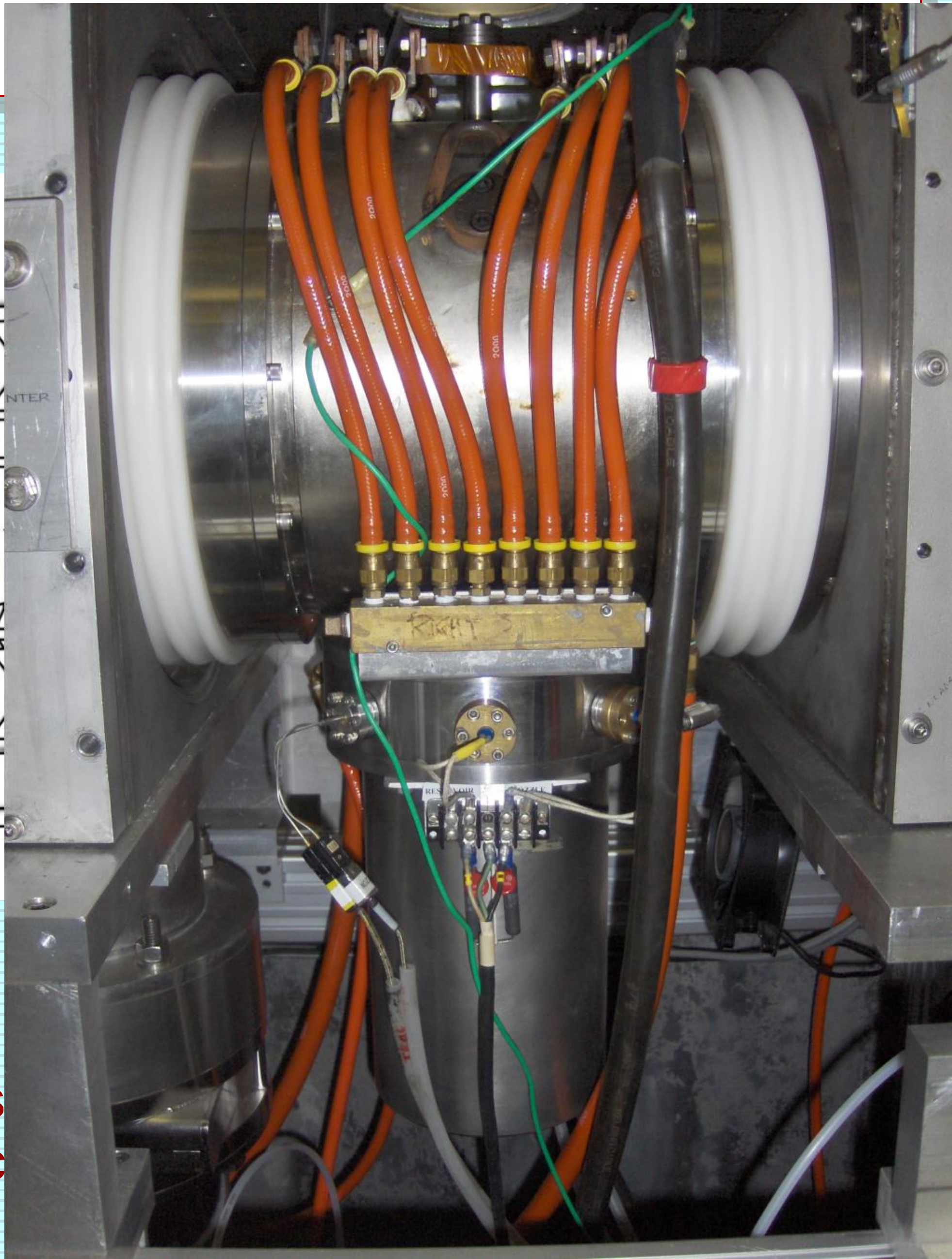
H^- beam acceleration to 35 keV at the exit of Na-jet ionizer cell.



Na-jet cell is isolated and biased to – 32 keV. The H^- beam is accelerated in a two-stage acceleration system.

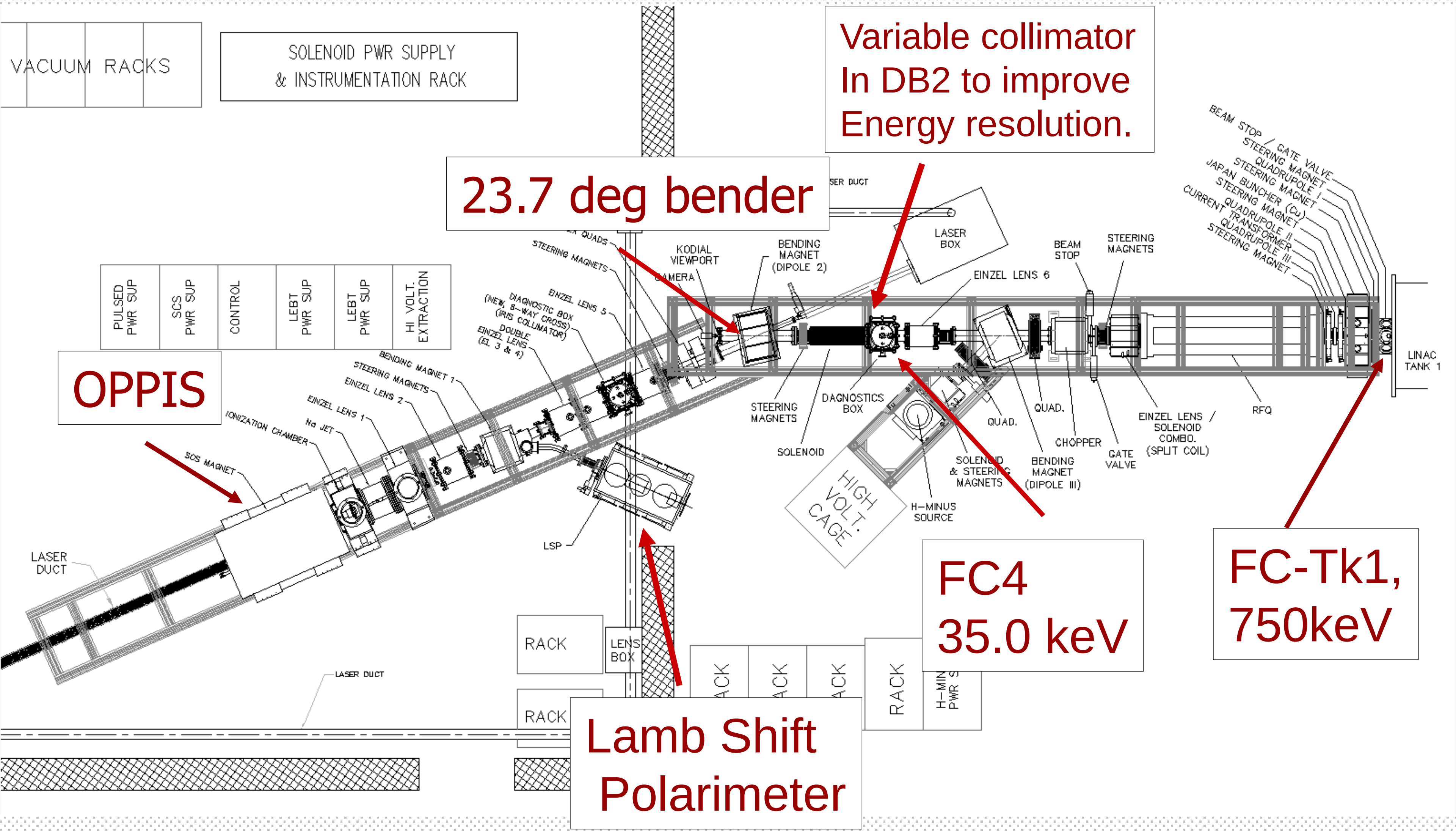
H^- beam acceleration to 35 keV at the exit of Na-jet





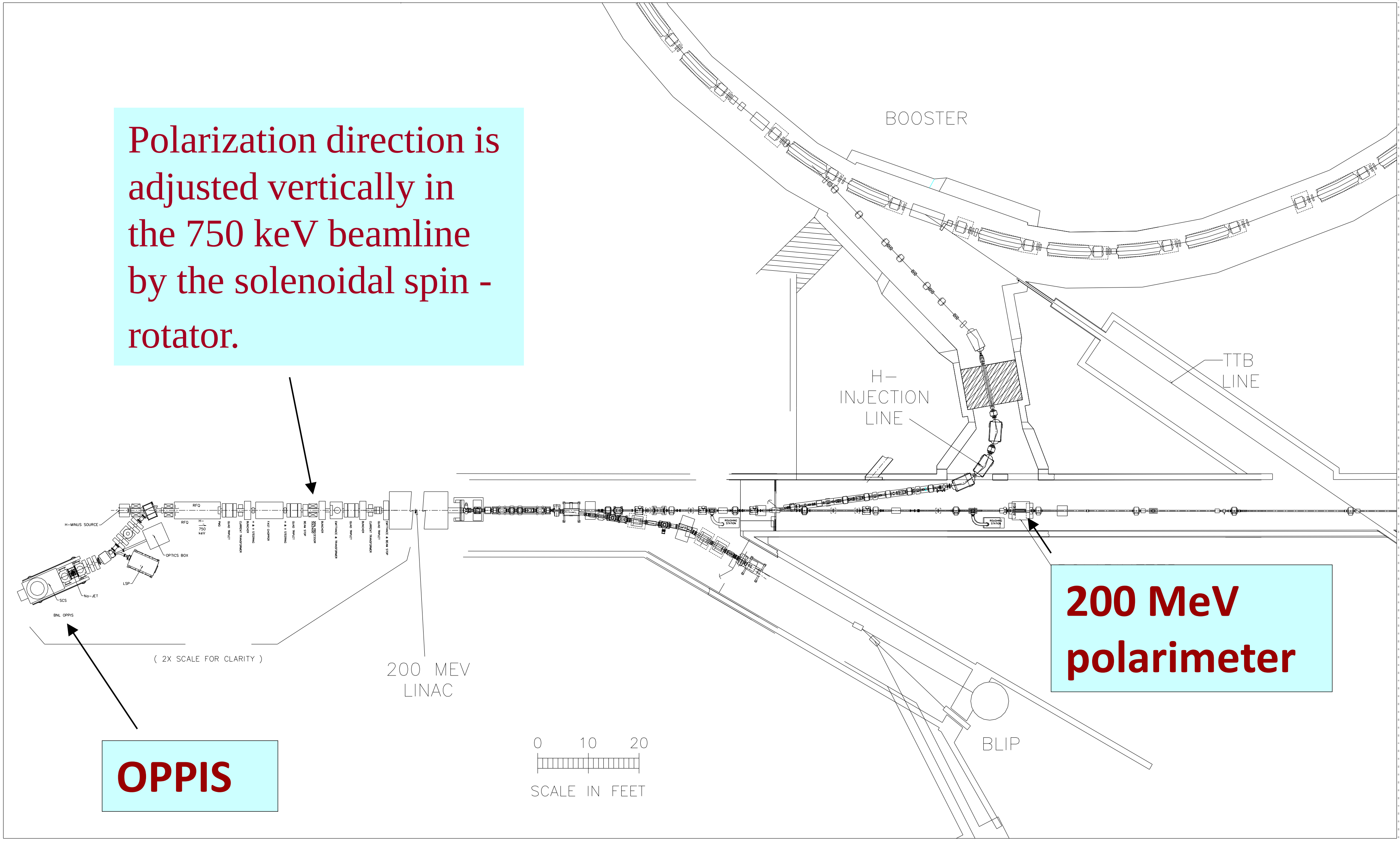
Na-jet cell is isolated and bias
accelerated in a two-stage ac

Low Energy Beam Transport line.



Polarized injector, 200 MeV Linac and HEBT

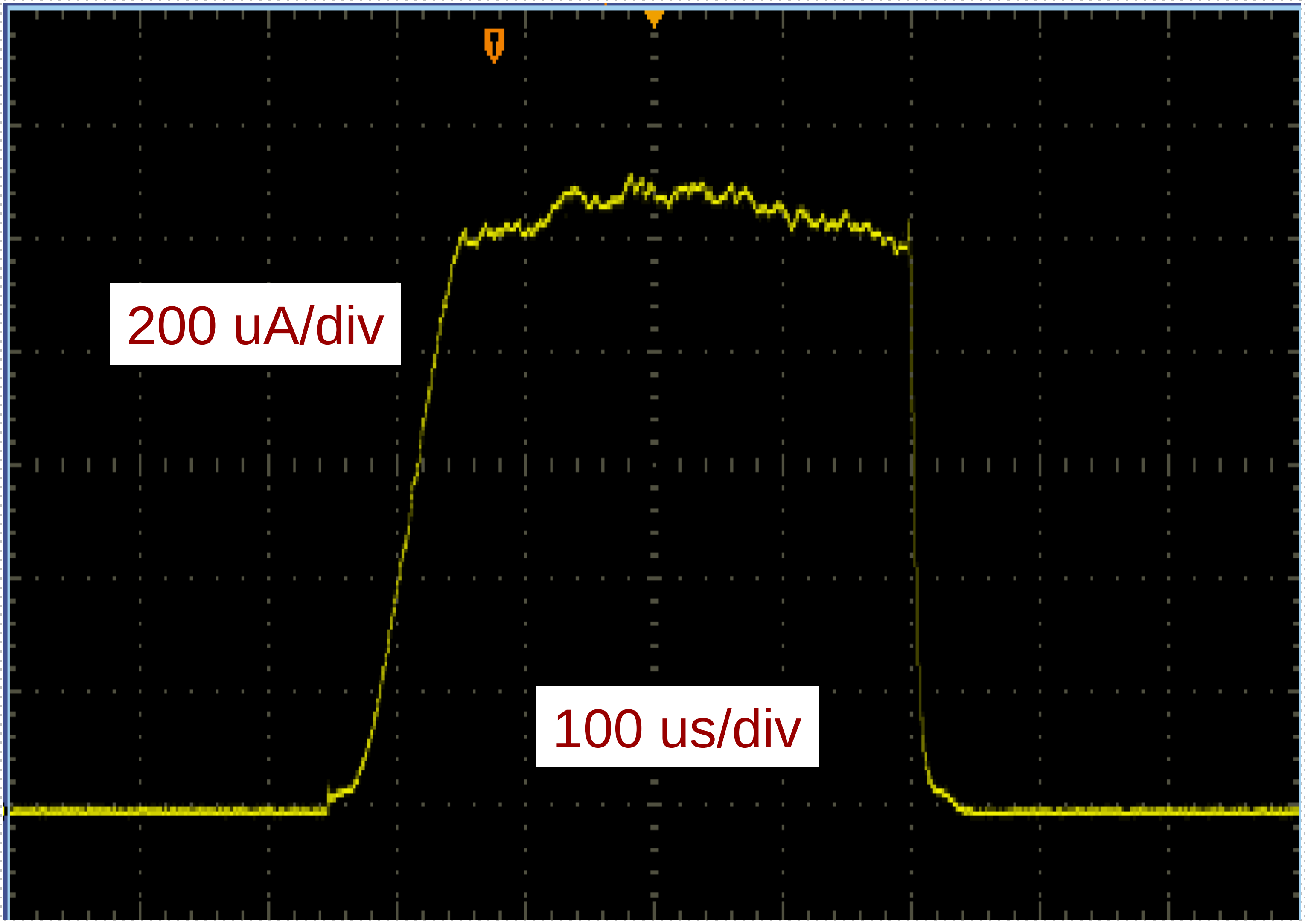
Polarization direction is adjusted vertically in the 750 keV beamline by the solenoidal spin - rotator.



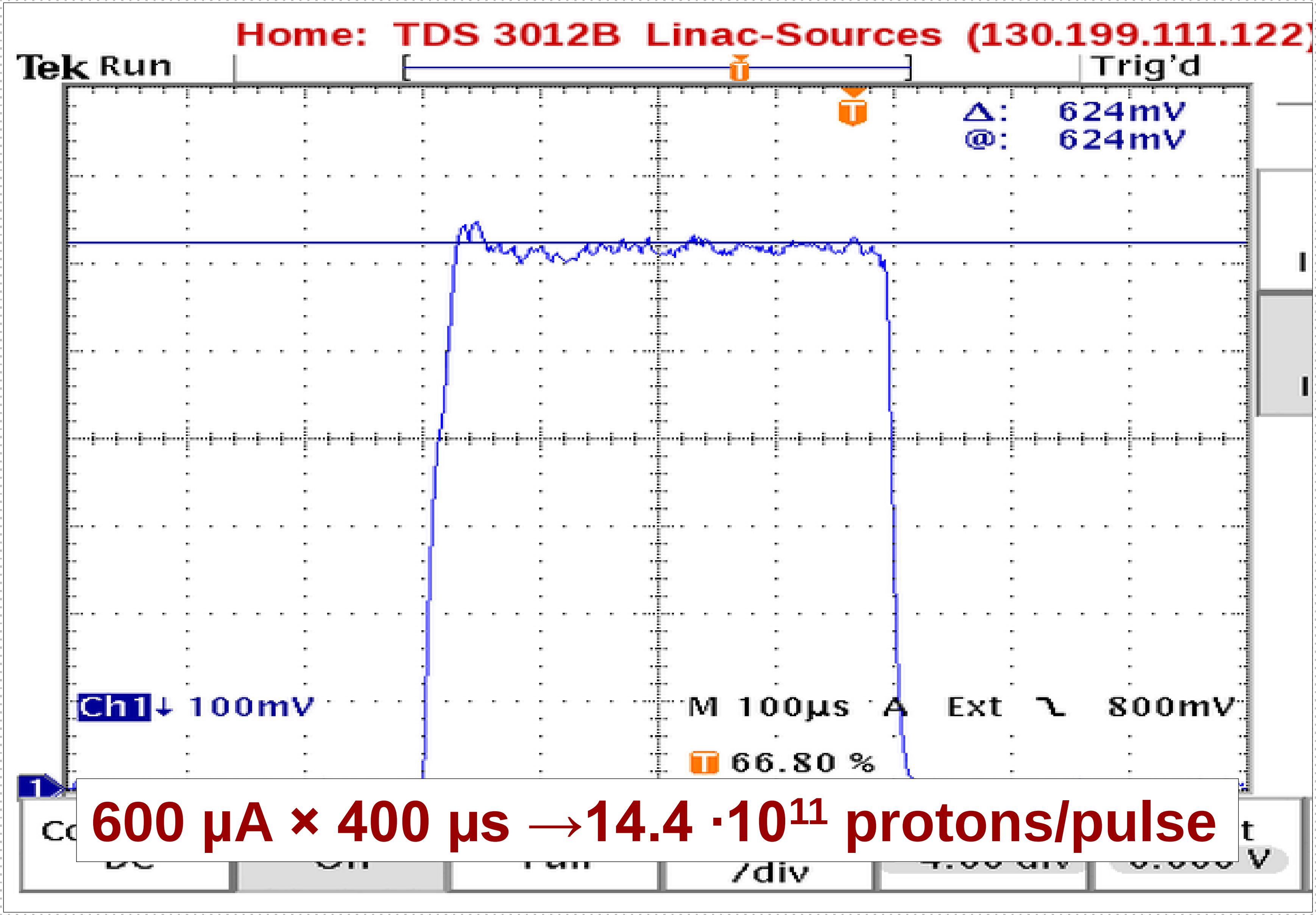
200 MeV polarimeter

OPPIS

Polarized H^- current-1.05 mA, after RFQ 750 keV Rb-98°

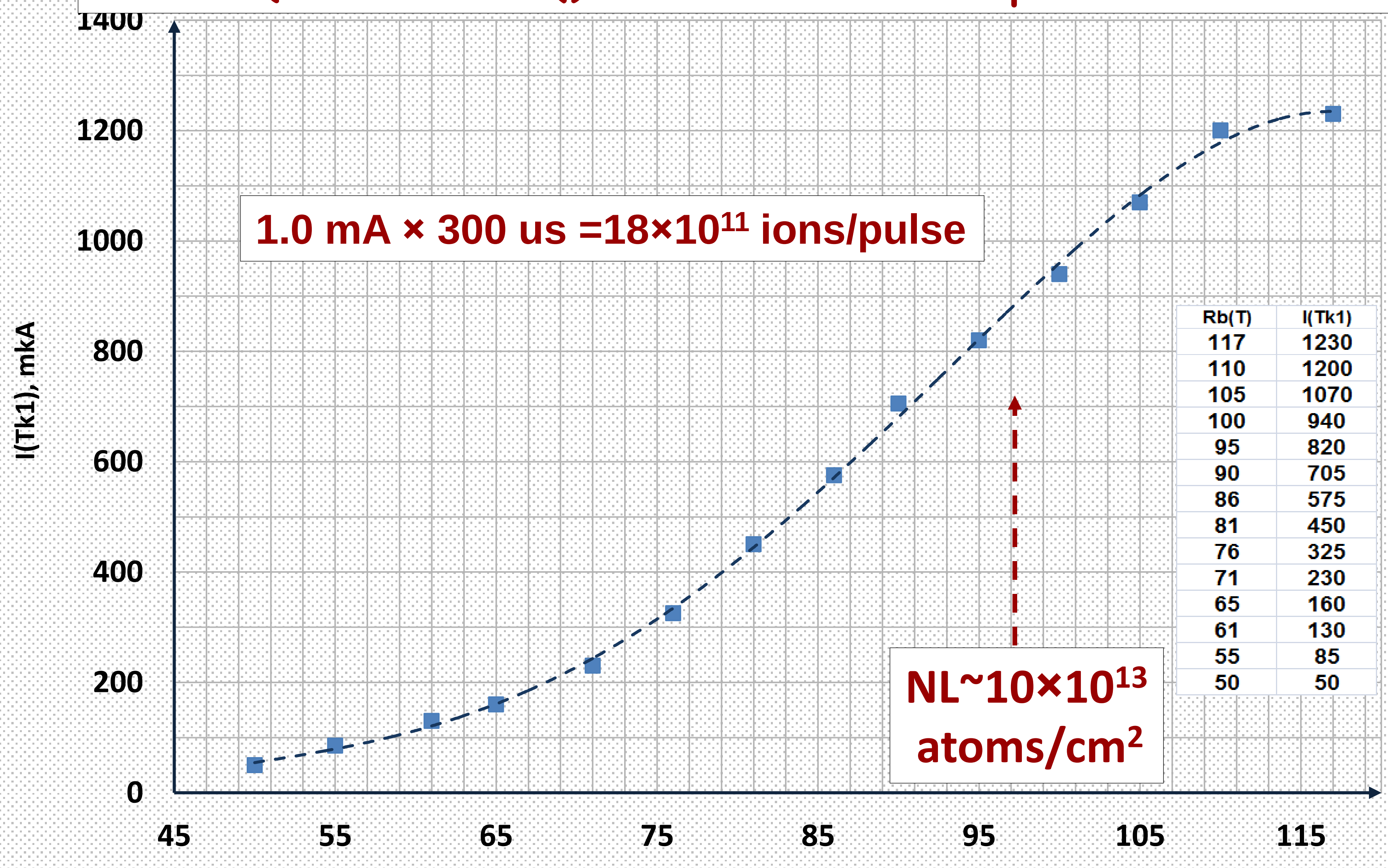


Rb-90, 200 MeV, T9-620uA



600 µA × 400 µs →14.4 ·10^{11} protons/pulse

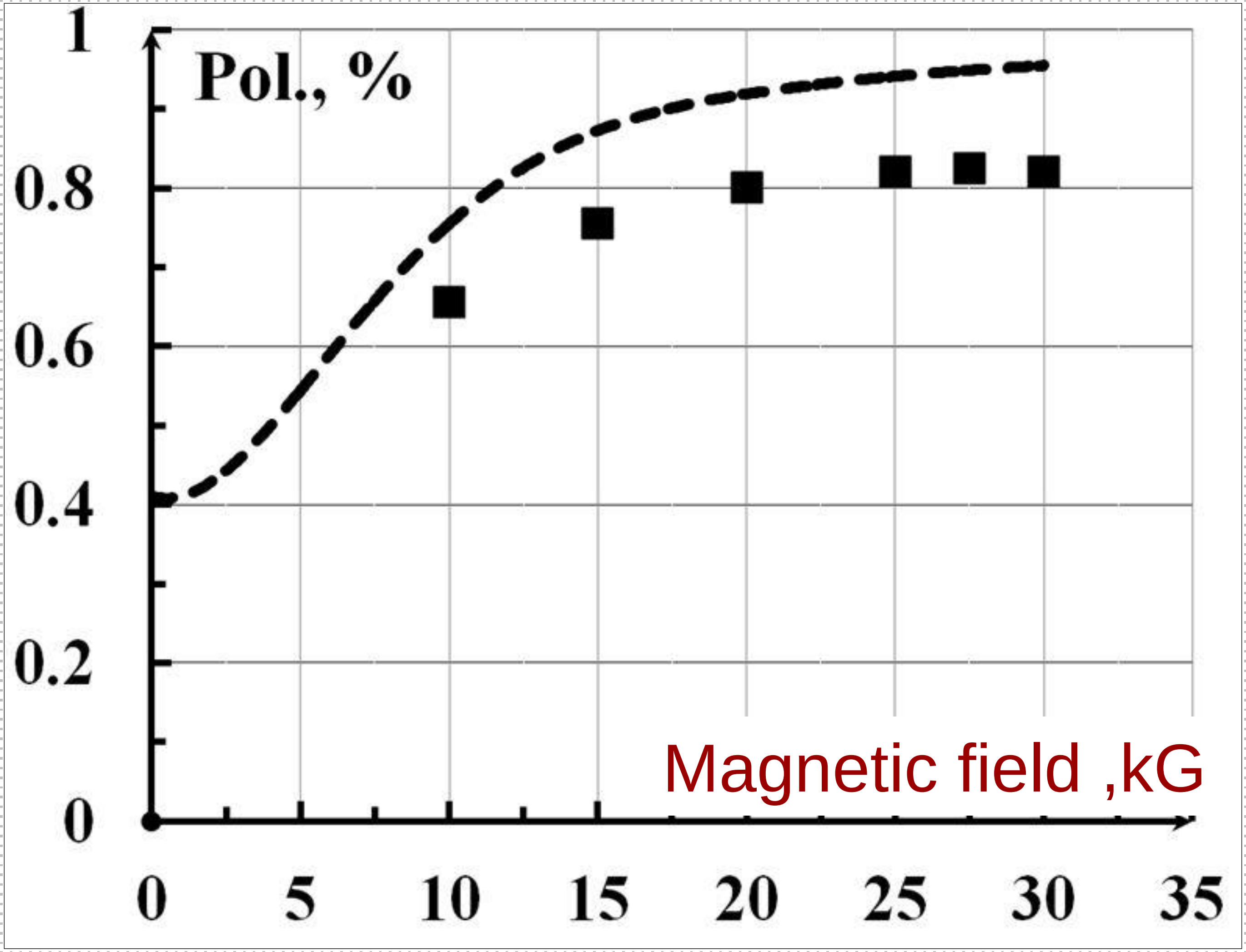
Polarized H⁻current at 750 keV energy (after RFQ) vs. Rb-cell temperature



Rb(T)	I(Tk1)
117	1230
110	1200
105	1070
100	940
95	820
90	705
86	575
81	450
76	325
71	230
65	160
61	130
55	85
50	50

Rb cell temperature, deg. C

Polarization (at 200 MeV) vs. SCS magnetic field in He and Rb-cells



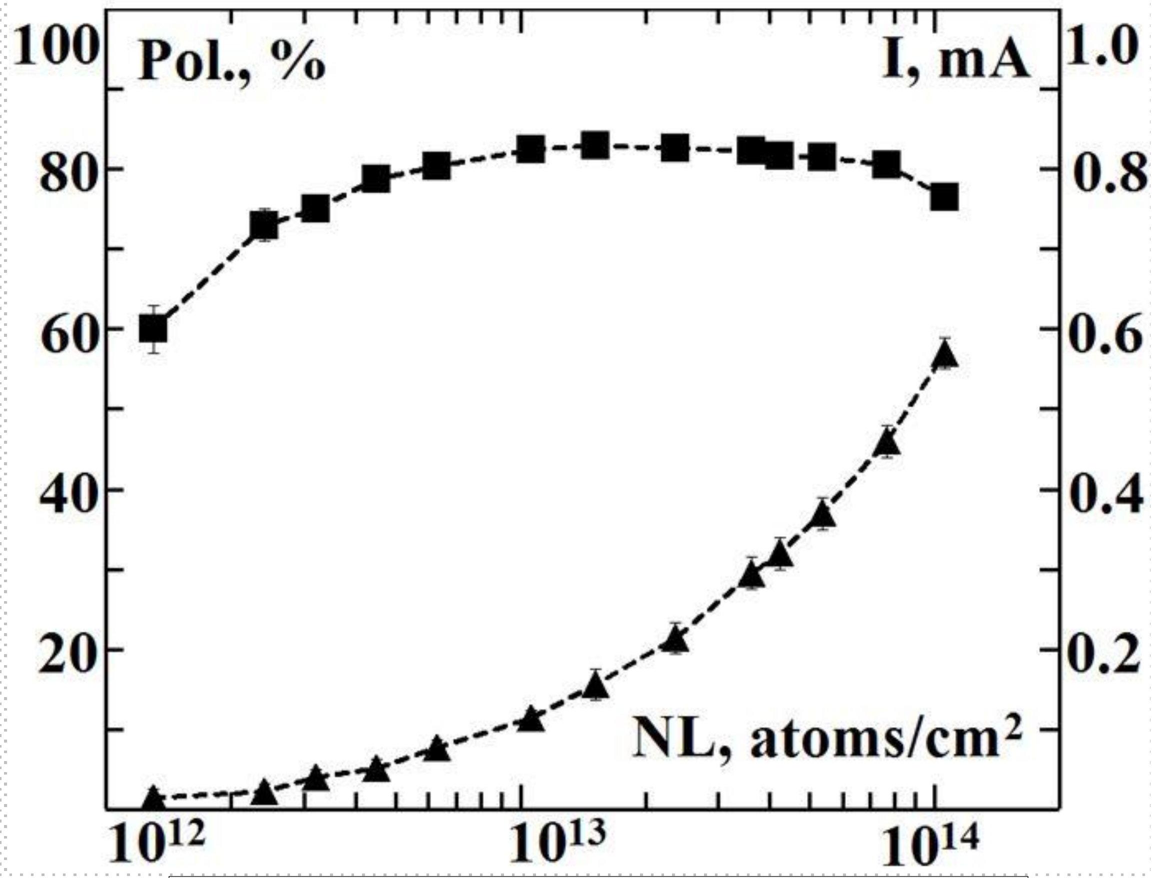
Source intensity and polarization.

- Reliable long-term ·operation of the source was demonstrated.
- Very high suppression of un-polarized beam component was demonstrated.
- Small beam emittance (after collimation for energy separation) and high transmission to 200 MeV.

Rb-cell, Temp., deg. C	81	86	91	96
Linac Current, μA	295	370	430	570
Booster Input $\times 10^{11}$	4.9	6.2	7.3	9.0
Pol. %, at 200 MeV	84	83	80.5	78

H^- beam current and polarization at 200 MeV vs. Rb vapor thickness

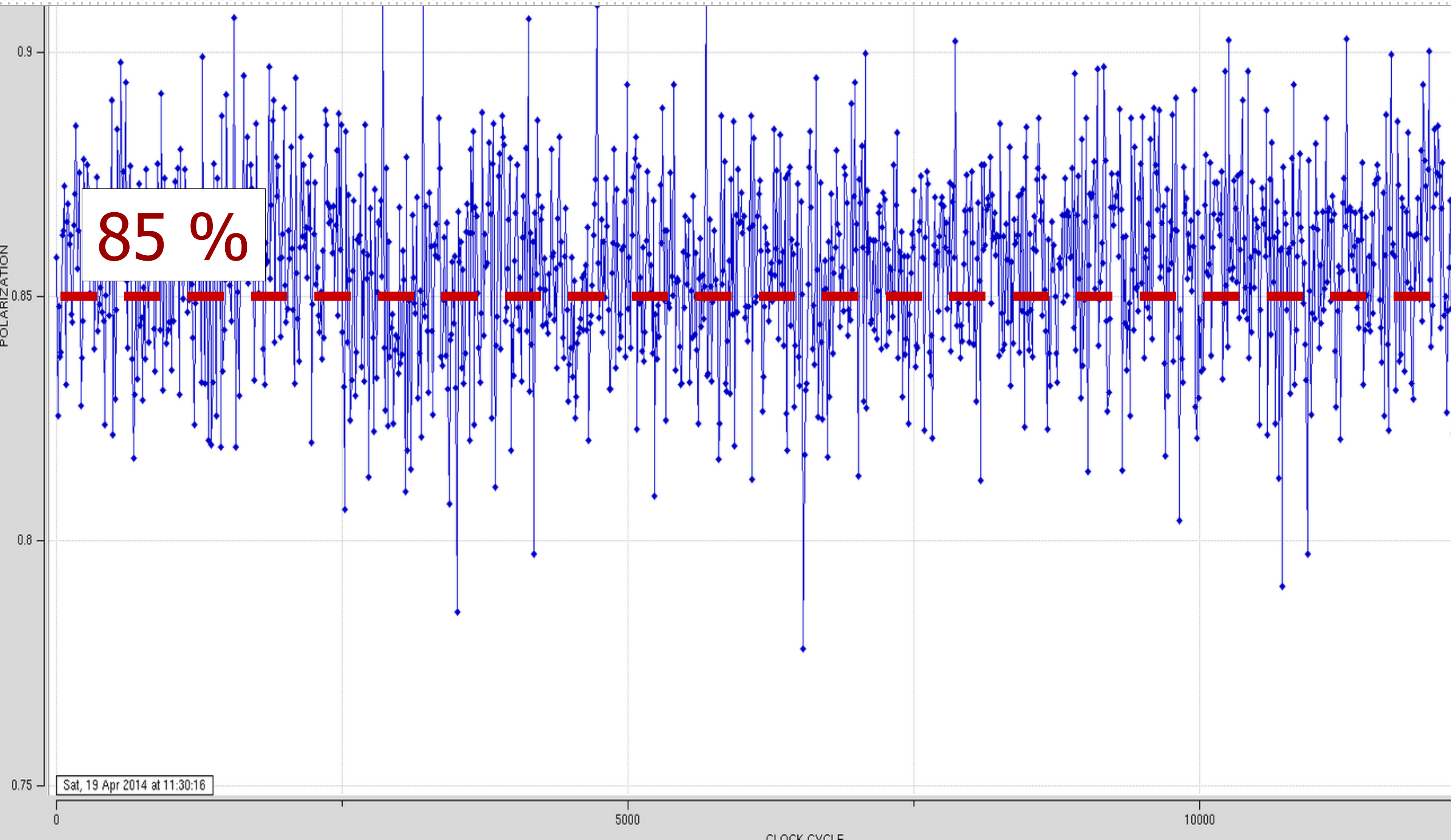
Polarization in 200 MeV polarimeter



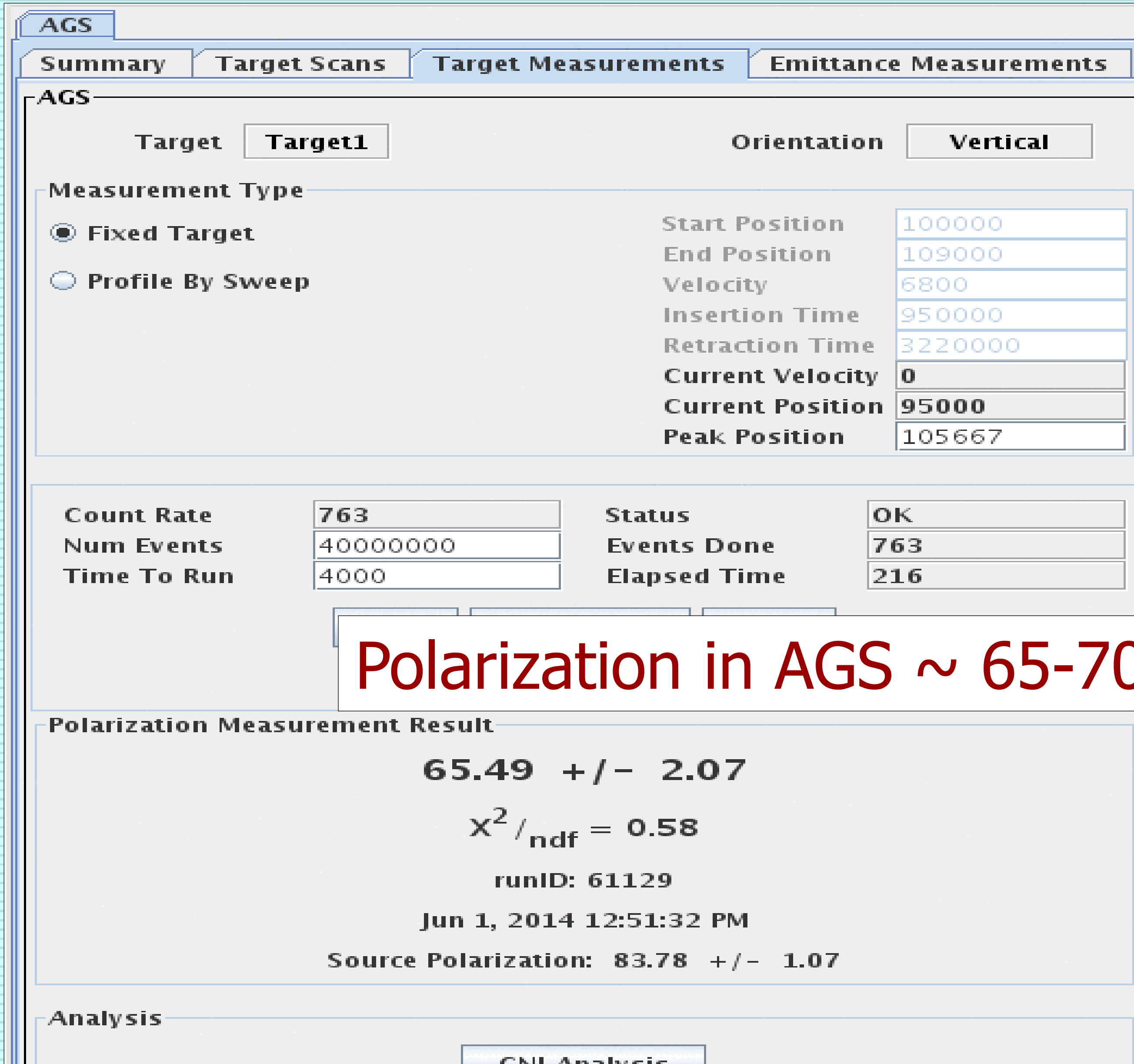
H^- ion beam current (mA)

Rb-vapor thickness –nL

Polarization stability ~12 hrs, April 19

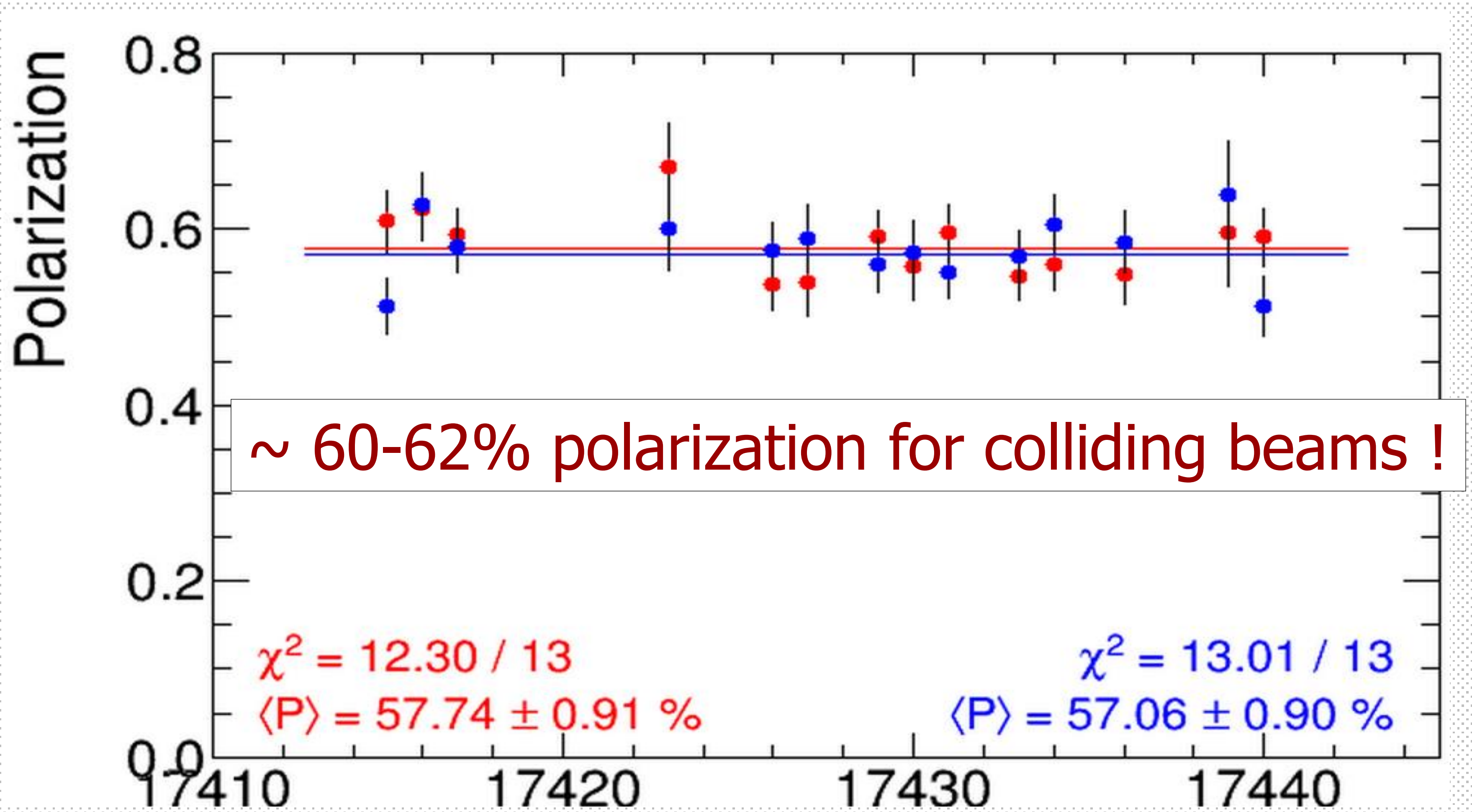


Rb-90deg, Booster input-$9.3 \cdot 10^{11}$, 200 Mev-83.8%



Polarization in AGS ~ 65-70 %

Polarization measurements at 255 GeV in H-jet polarimeter, Run-2013, April-25-30

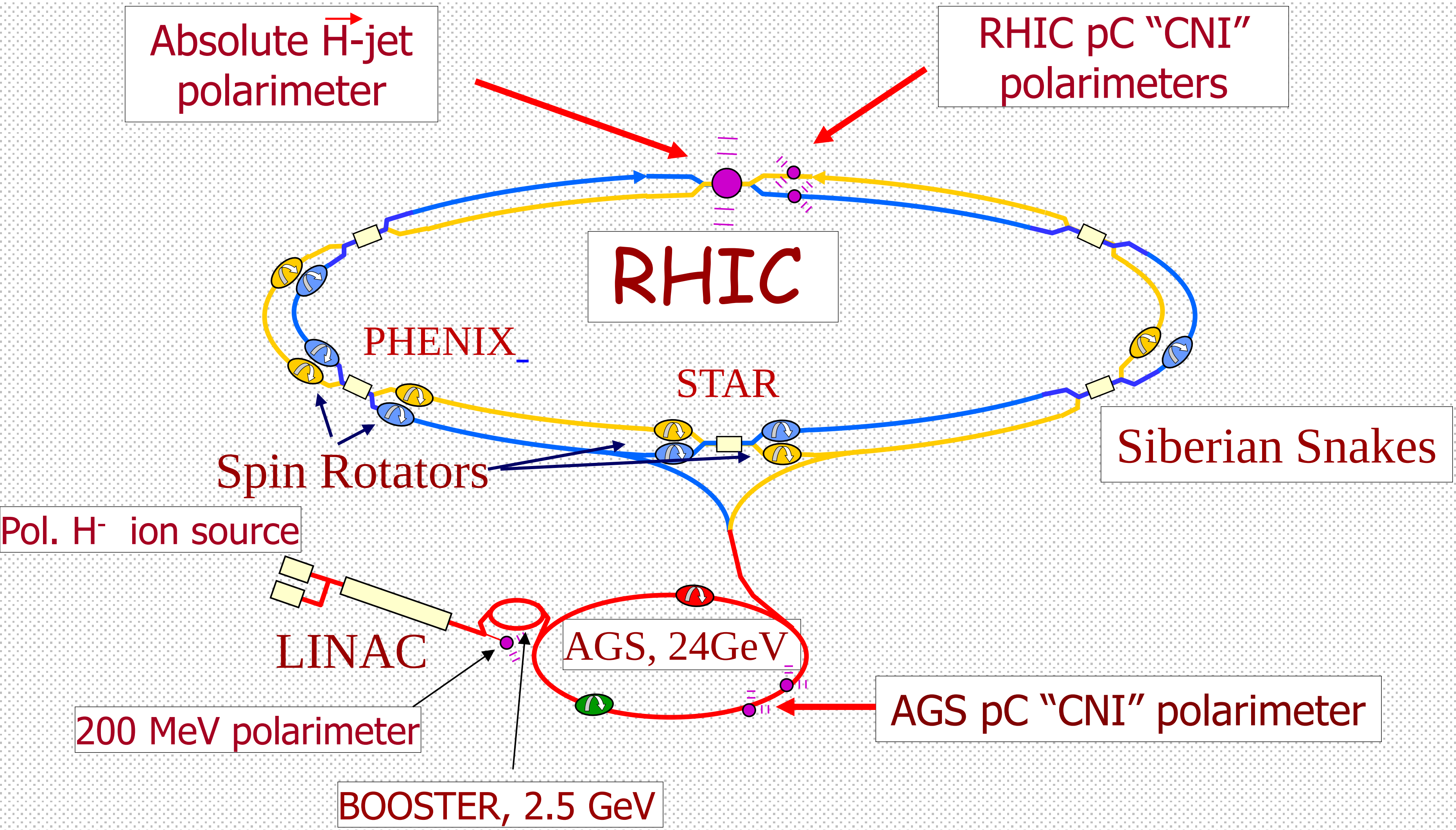


Polarimetry at RHIC

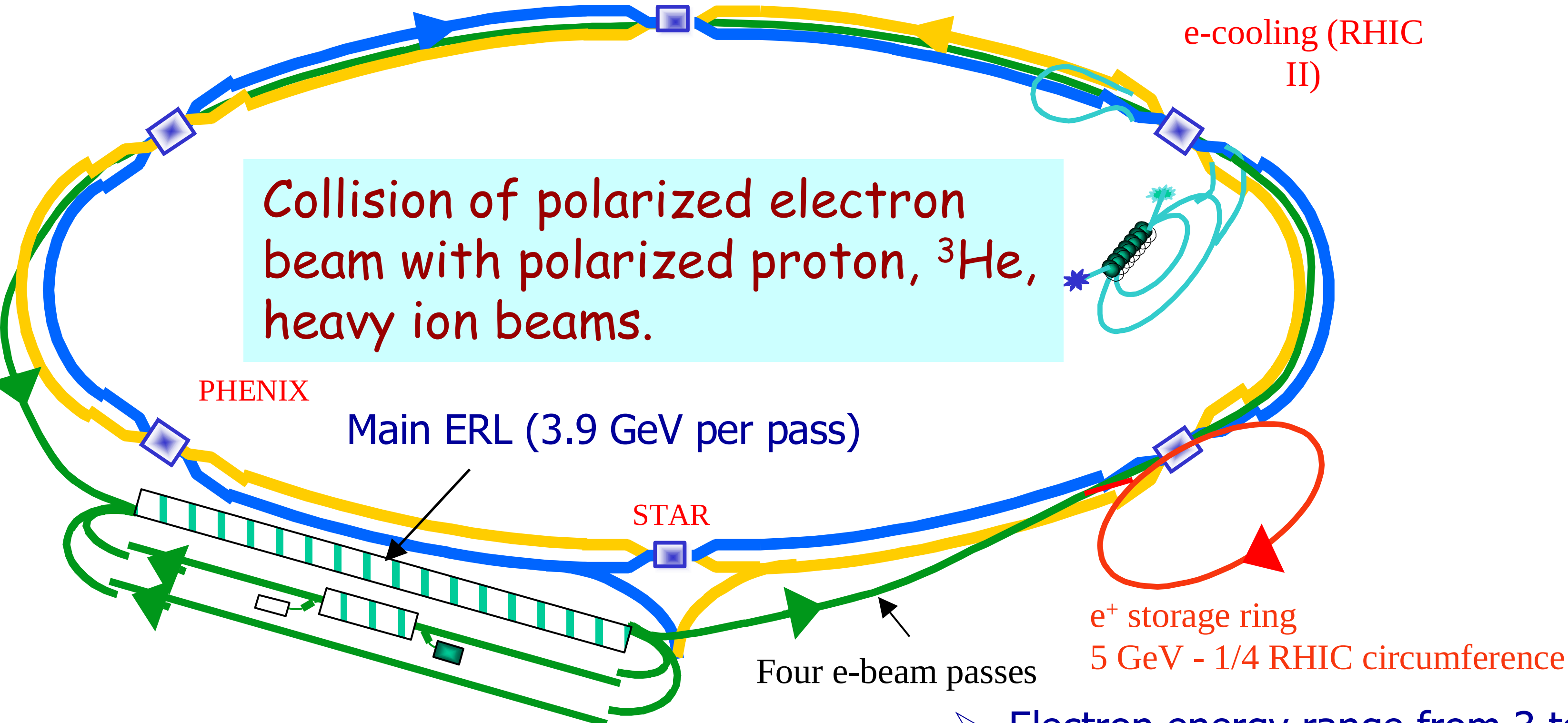
- Lamb-shift polarimeter at the source energy.
- Absolute 200 MeV polarimeter after the Linac.
- P-Carbon CNI polarimeters in AGS and RHIC
- Absolute H-jet polarimeter in RHIC.

Polarization facilities at RHIC

$\mathcal{L}_{max} = 1.6 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 510$ GeV



eRHIC-electron Ion Collider at BNL



- Electron energy range from 3 to 20 GeV
- Peak luminosity of 2.6×10^{33} $cm^{-2}s^{-}$
- high electron beam polarization (~80%)
- full polarization transparency at all energies
- multiple electron-hadron interaction points

The AGS and RHIC "Siberian snakes" should preserve the $^3He^{++}$ beam polarization.

Sources of polarized ^{3}He ions

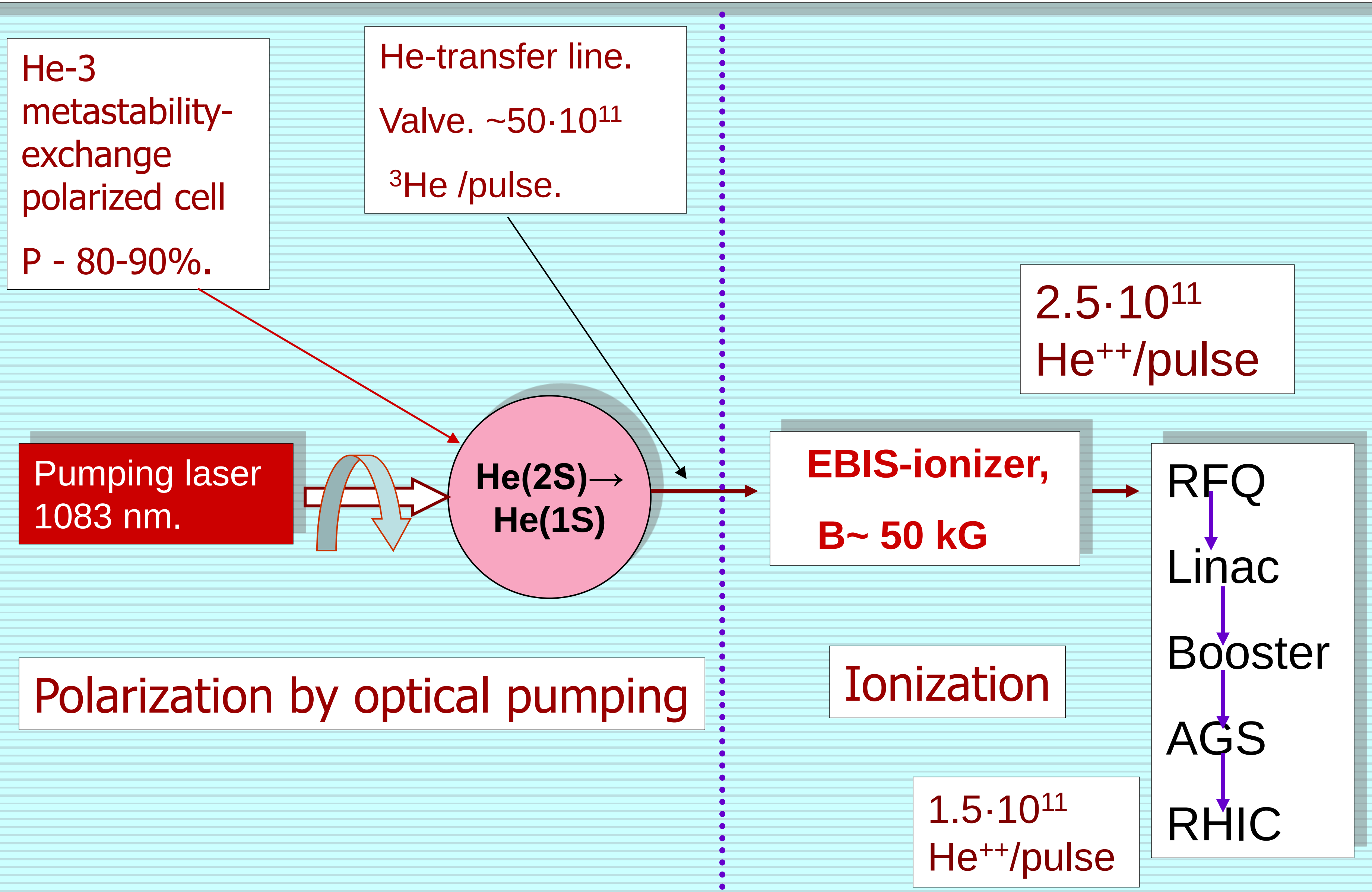
- Rice University, 1969: MEOP for $^3He^+$
  - 16 keV, 8 particle μA at 11% polarization
- Univ. of Birmingham, 1973: Lamb Shift for $^3He^{++}$
  - 29 keV, 50 particle μA at 65% polarization
- Laval University, 1980: Stern-Gerlach for $^3He^+$
  - 12 keV, 100 particle nA at 95% polarization

Our Proposal[1]

- RHIC's **Electron Beam Ion Source** Preinjector
  - Proven in recent RHIC runs, NASA Space Radiation Lab
- Metastability Exchange Optical Pumping
- Doubly ionize $^3He^{++}$ for injection

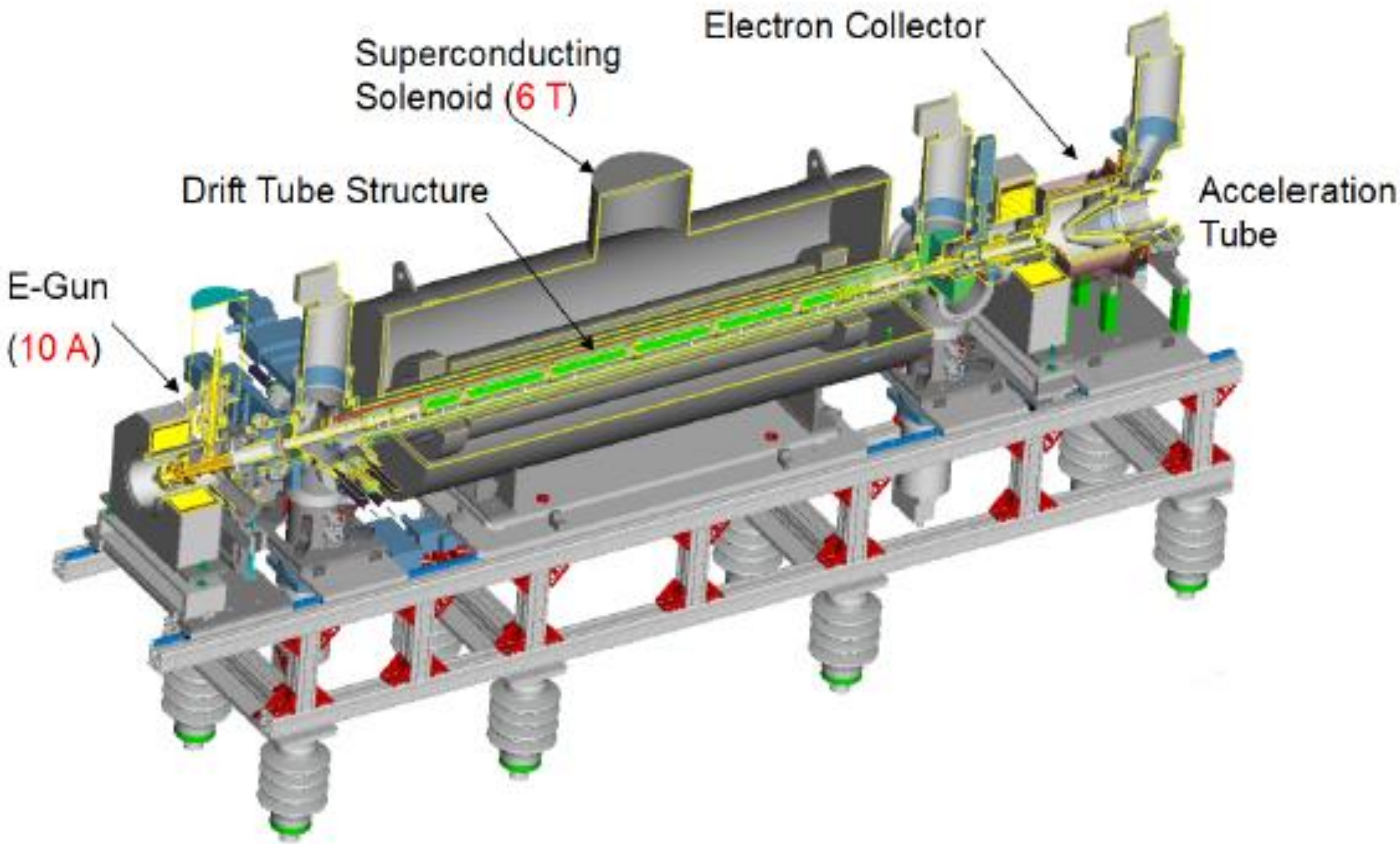
[1] A. Zelenski, J. Alessi, ICFA Newsletter (2003).

^{3}He++ ion source development at BNL in collaboration with MIT. (J. Maxwell talk in this session.)



RHIC's Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm^2 Current Density
- **Any** species, switch between species in 1 sec



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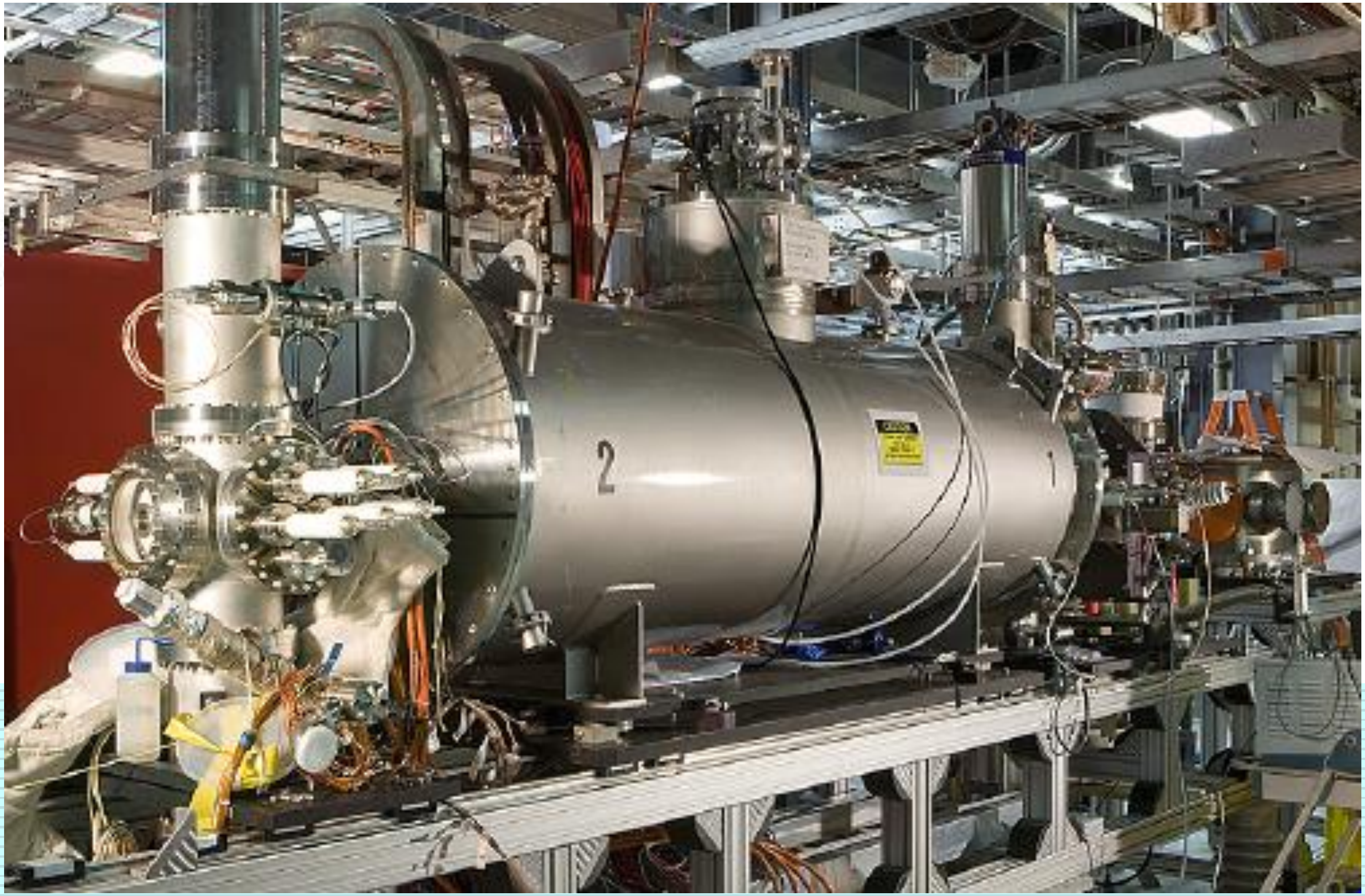
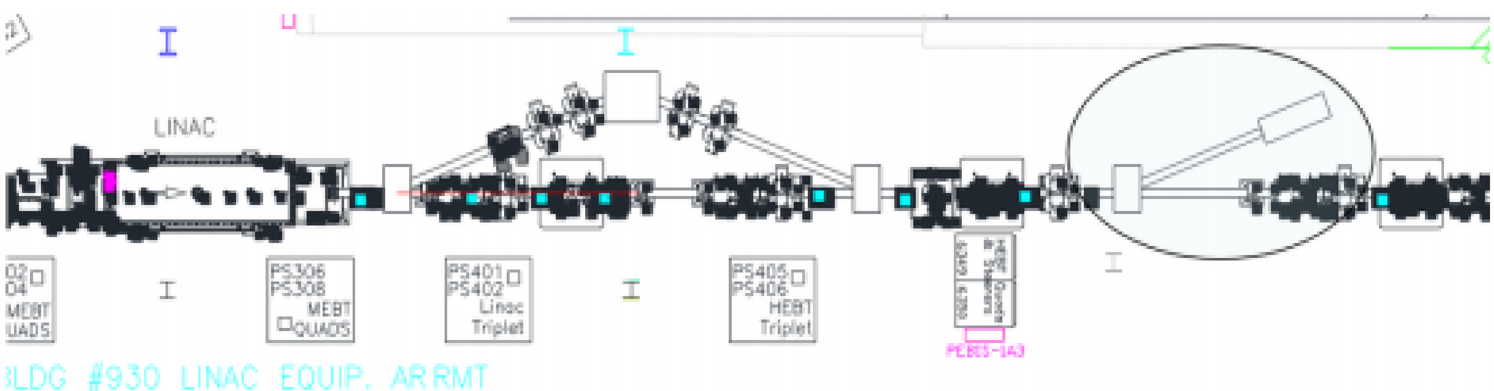


5.3 MeV Helium3–Helium4 Polarimeter

- Transverse polarized ^{3}He beam on unpolarized ^{4}He at 5 torr[10], early design by C. Epstein
- At 5.3 MeV, asymmetry due to polarization goes to 1 at 91° center of mass $\rightarrow$ ^{3}He at 53.6°and 2.66 MeV
- Recoil ^{4}He as a background at 1.83 MeV, so use 500 μm partially depleted silicon detector for energy resolution
- At 50% polarization, expect 3.7% accuracy in 1 minute



[10]G.R. Plattner, A.D. Bacher. Physics Letters B 36.3 (1971)

Summary

- The present high intensity OPPIS and ABS sources provide required beam intensity for present and future pp, and ep Colliders.

- In the future RHIC, eRHIC will require high-intensity $^{3}He^{++}$ ion beams.

- The high intensity $^{3}He^{++}$ ion source on the basis of new EBIS injector is under development at RHIC.