OPTICALLY-PUMPED POLARIZED H^- AND $3He^{++}$ ION SOURCES DEVELOPMENT AT RHIC

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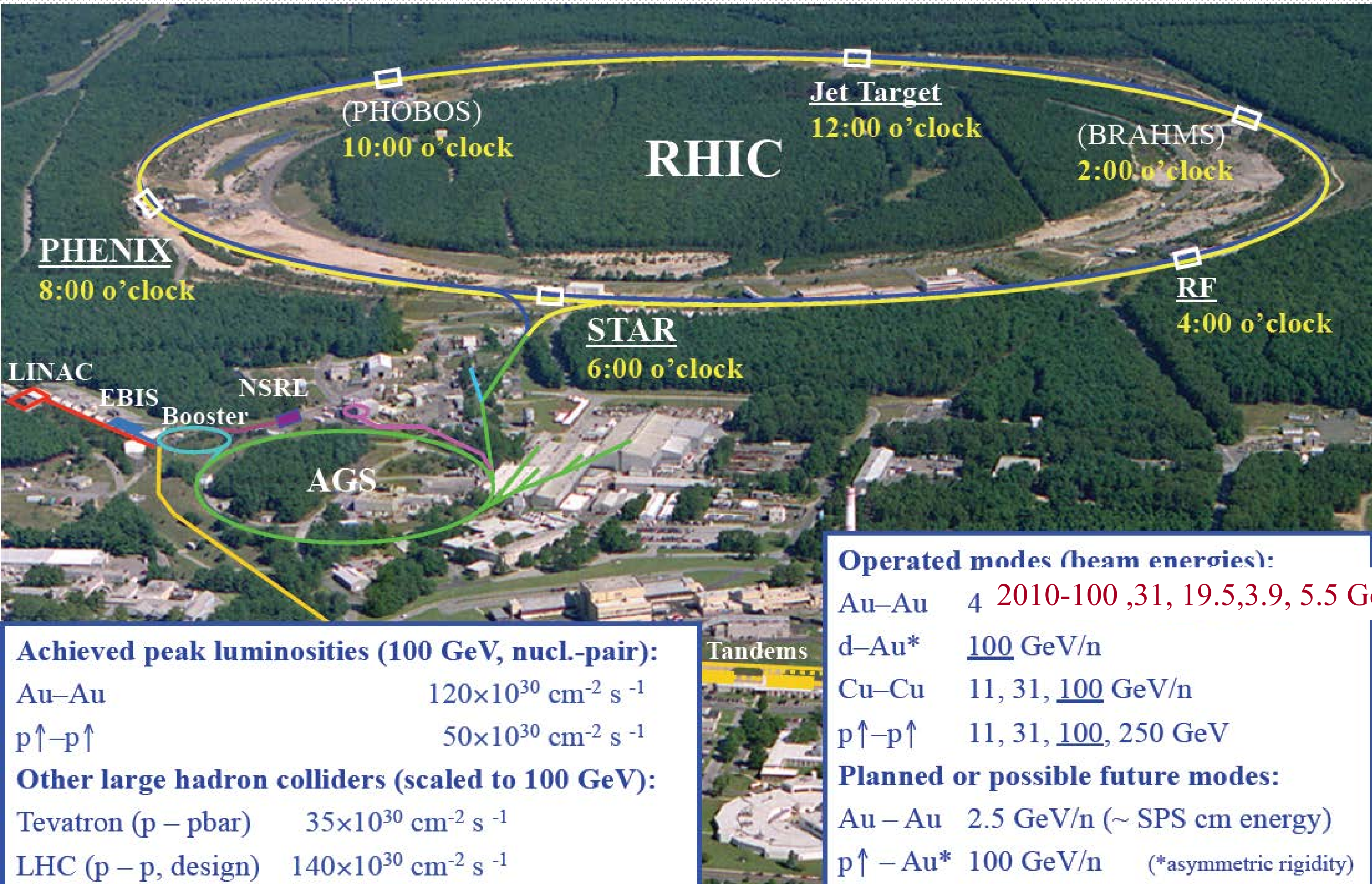
- Optical pumping polarization technique
- High-intensity polarized H^- ion source at RHIC
- Polarized $3He^{++}$ source development at RHIC

IPAC 2018, May 1

RHIC High-Luminosity Relativistic Heavy Ion (Polarized protons) Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	50×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	35×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

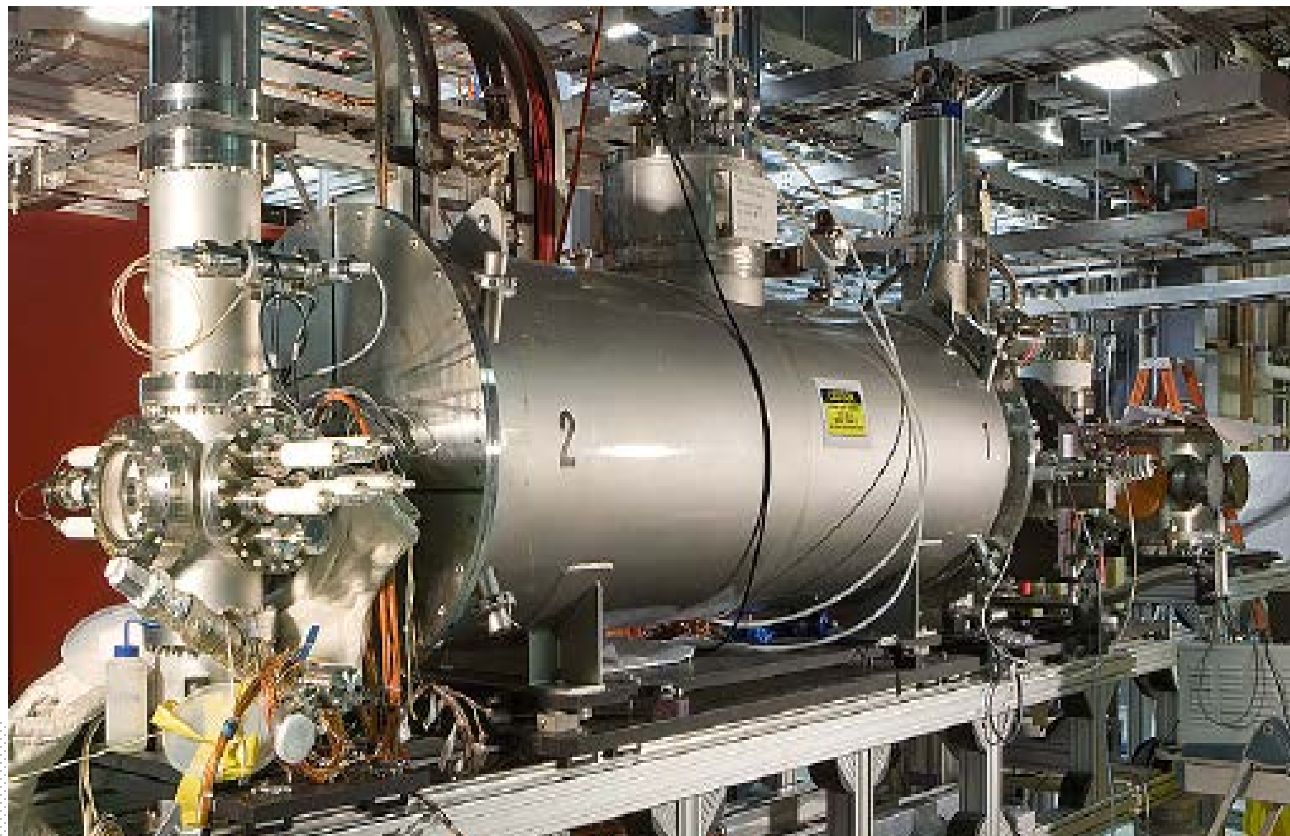
Au–Au	4 2010-100 ,31, 19.5,3.9, 5.5 GeV
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u>, 250 GeV

Planned or possible future modes:

Au – Au	2.5 GeV/n (~ SPS cm energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

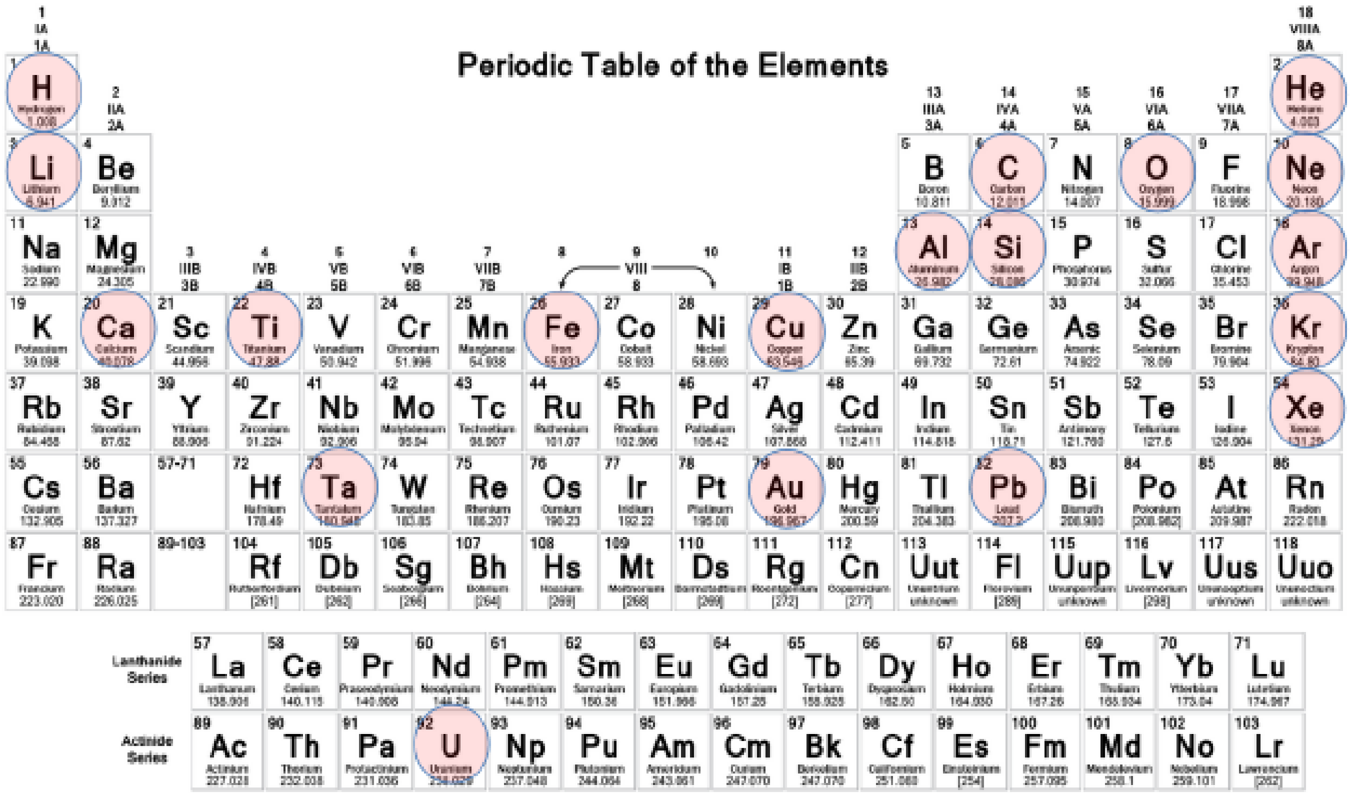
Electron Beam Ion Source (EBIS) of multiple charged Heavy ions at RHIC

- 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



leration

EBIS Beams Run to Date



D, $^3He^{2+}$, $^4He1^{+,2+}$, Li^{3+}, C^{5+}, O^{7+}, Ne^{5+}, Al^{5+}, Si^{11+}, Ar^{11+}, Ca^{14+}, Ti^{18+}, Fe^{20+}, Cu^{1+}, Kr^{18+}, Xe^{27+}, Ta^{38+}, Au^{32+}, Pb^{34+}, U^{39+}. Capable of $^3He \Rightarrow {}^3He^{++}$ at nearly 100%

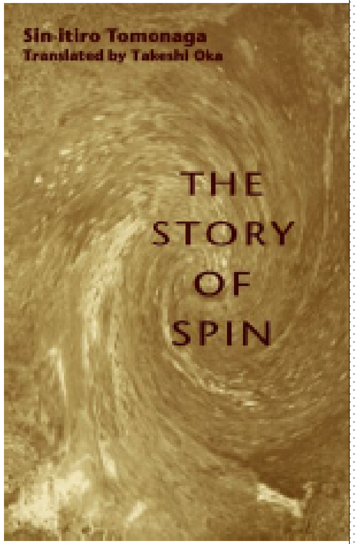
Zr, Ru

The RHIC OPPIS upgrade with atomic hydrogen injector, Run-2013-17

BNL - BINP, Novosibisk, INR, Moscow- collaboration

The Story of Spin

Shin'ichiro Tomonaga



It is a **mysterious beast**, and yet its practical effect prevail the whole of science. The existence of spin, and statistics associated with it, is the most subtle and **ingenious design of Nature** - without it the whole universe would collape. (from the preface)

exploring spin is of fundamental importance

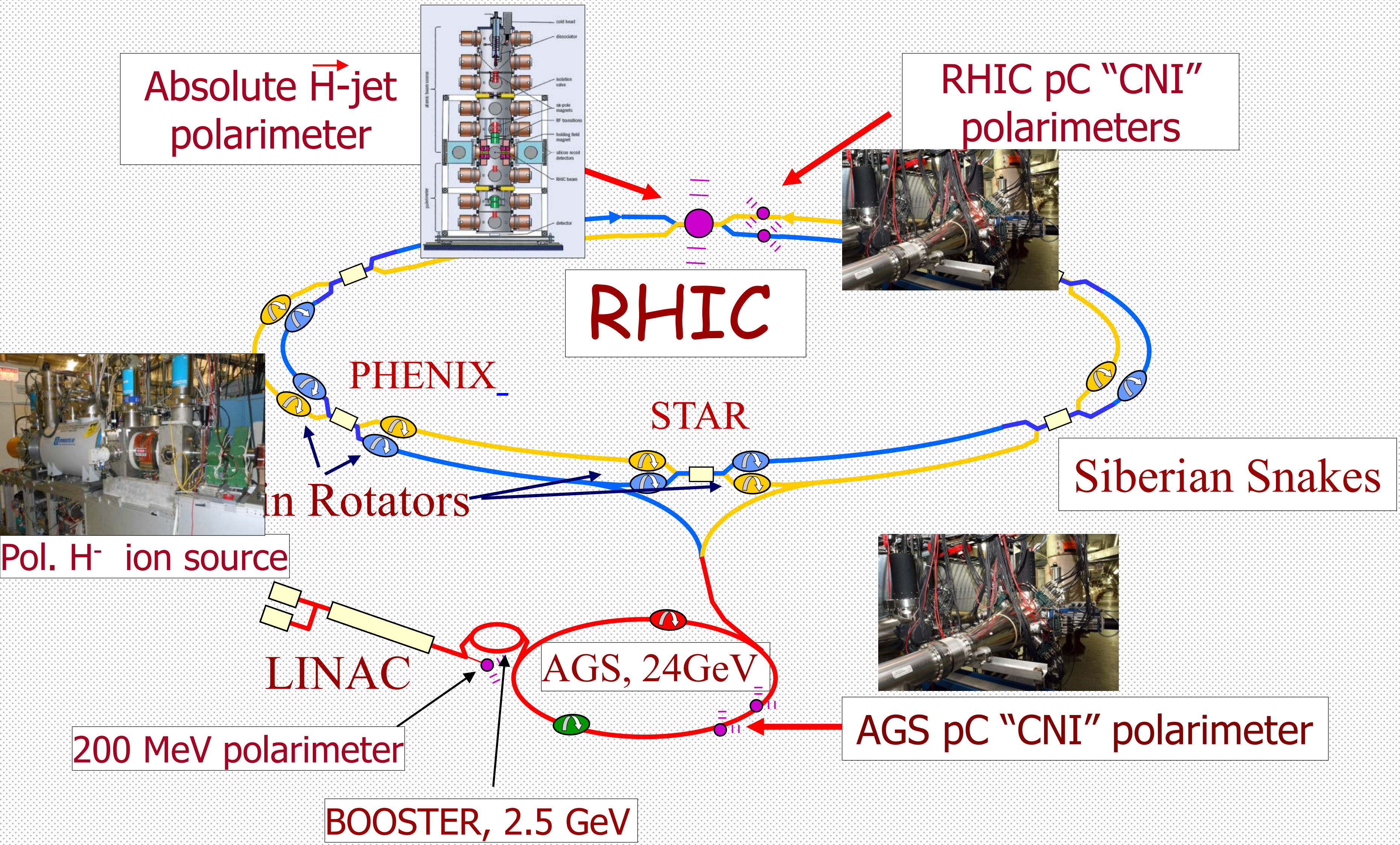
High intensity polarized proton source and "Siberian Snakes" made possible high luminosity RHIC operation with colliding polarized protons beams to study:

- proton spin structure,
- fundamental tests of QCD and electro-weak interaction.

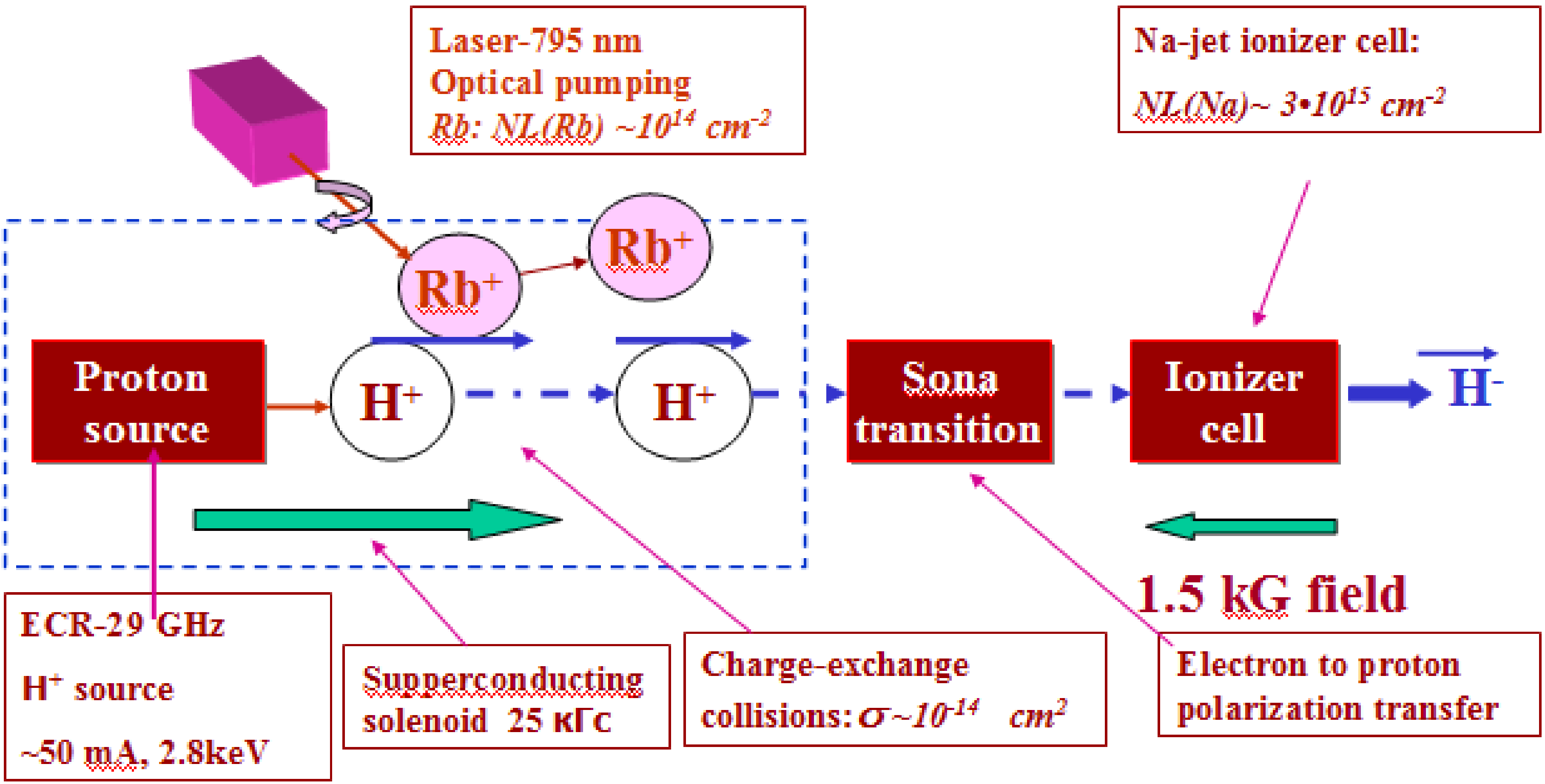
Polarized proton accelerations was discussed for HERA, FNAL, LHC and even SSC colliders

Polarization facilities at RHIC

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



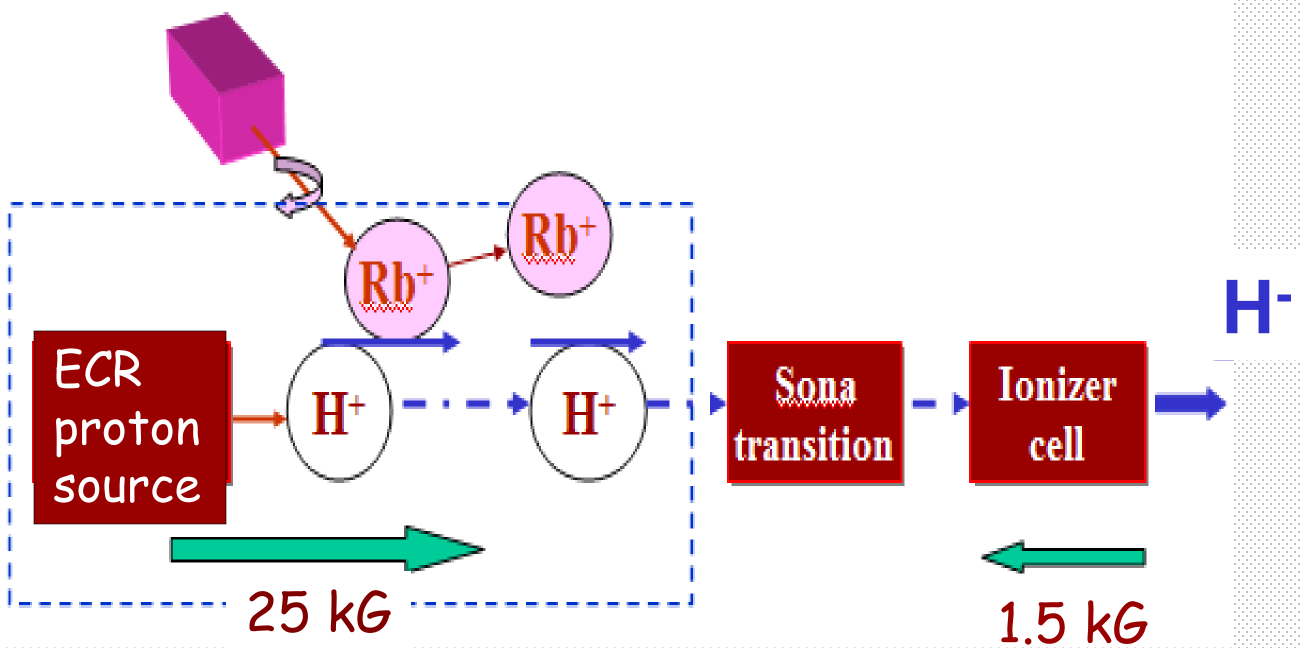
SPIN -TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS



Laser beam is a primary source of angular momentum:

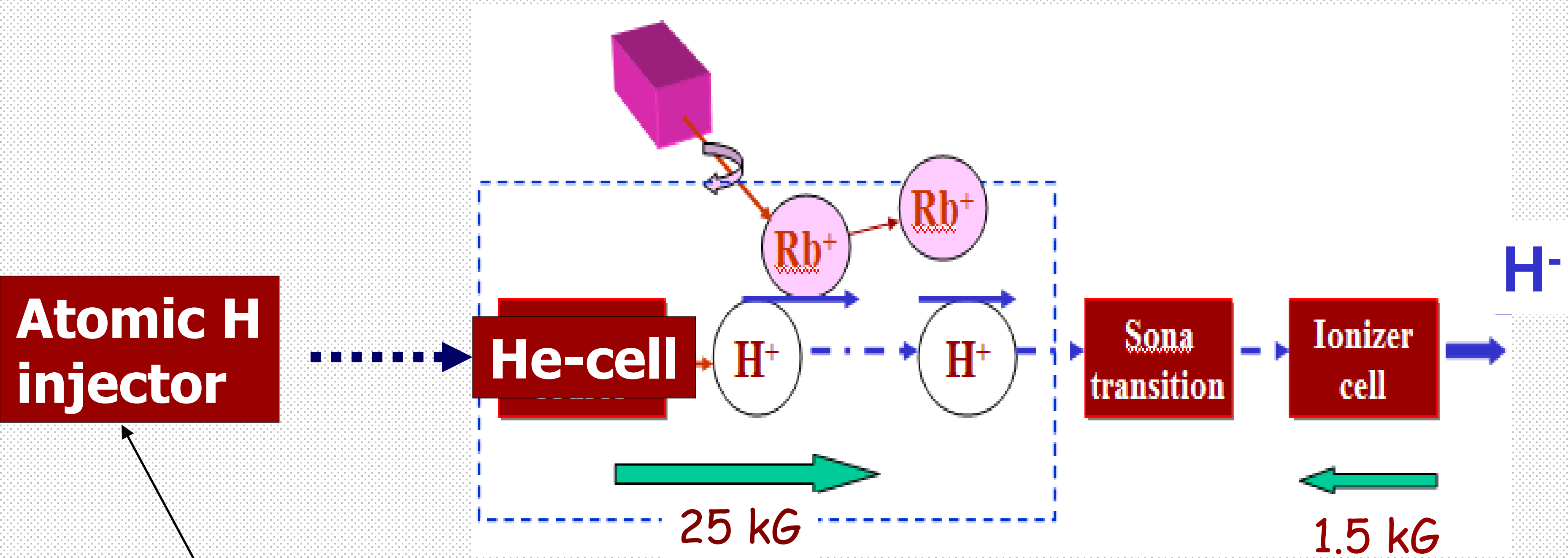
10 W (795 nm) ⇨ $4 \cdot 10^{19}$ hν/sec ⇨ 2 A, H^0 equivalent intensity.

ECR primary proton source, 2000-2012
BNL. KEK, TRUMF and INR, Moscow



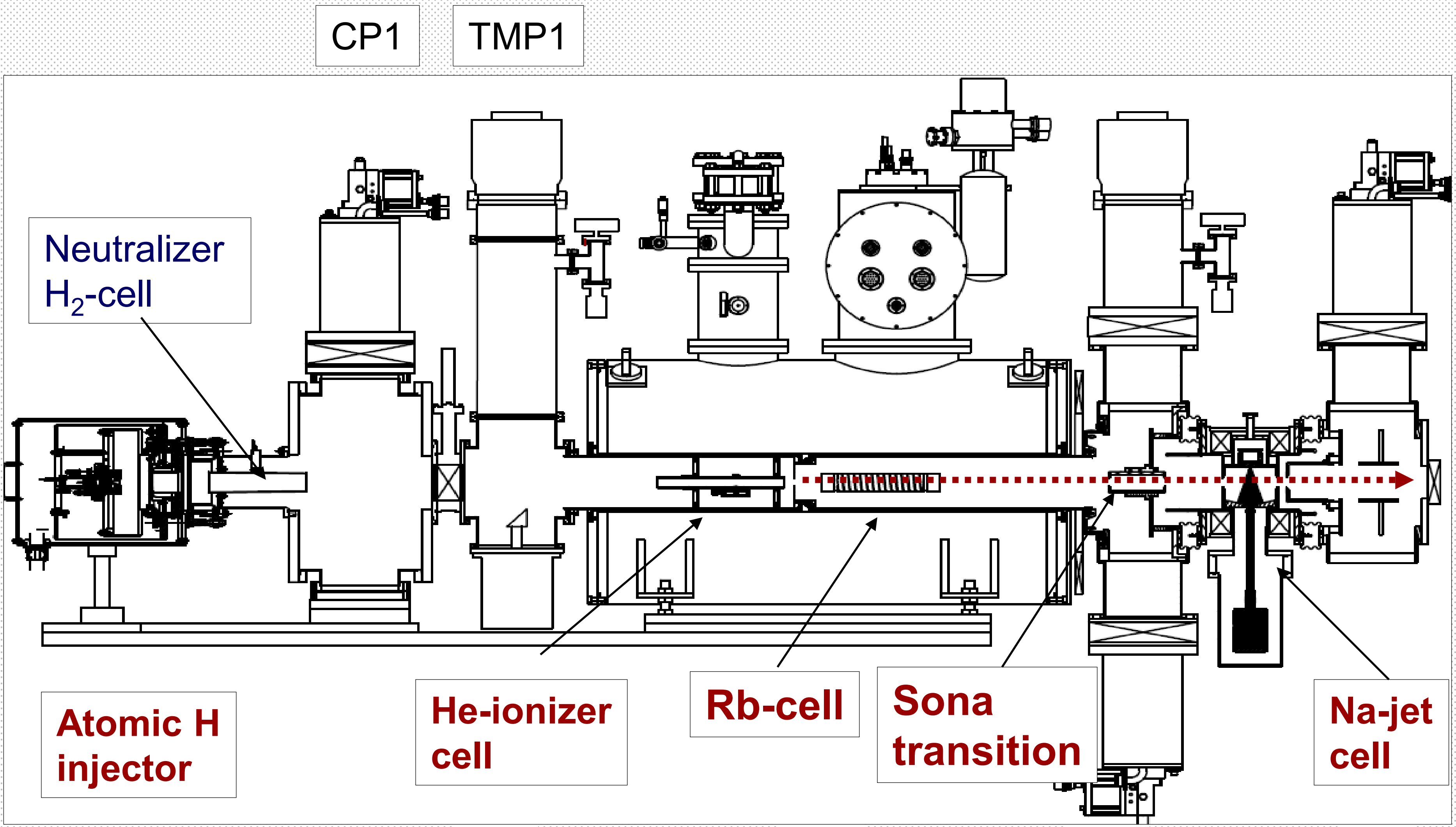
New generation OPPIS with atomic H^0 injector, 2013-17

High-brightness proton beam inside strong 2.5 T solenoid field produced by atomic H beam ionization in the He-gas ionizer cell



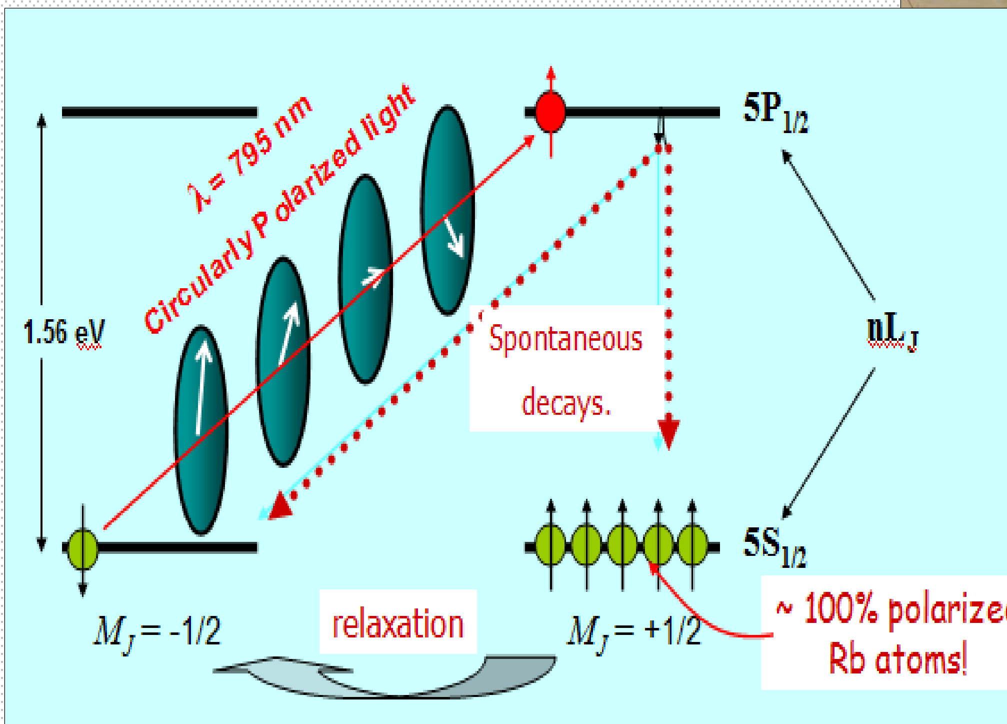
The primary proton beam and
Equivalent atomic H intensity
current is 2.5 A at 6.5 keV beam energy !

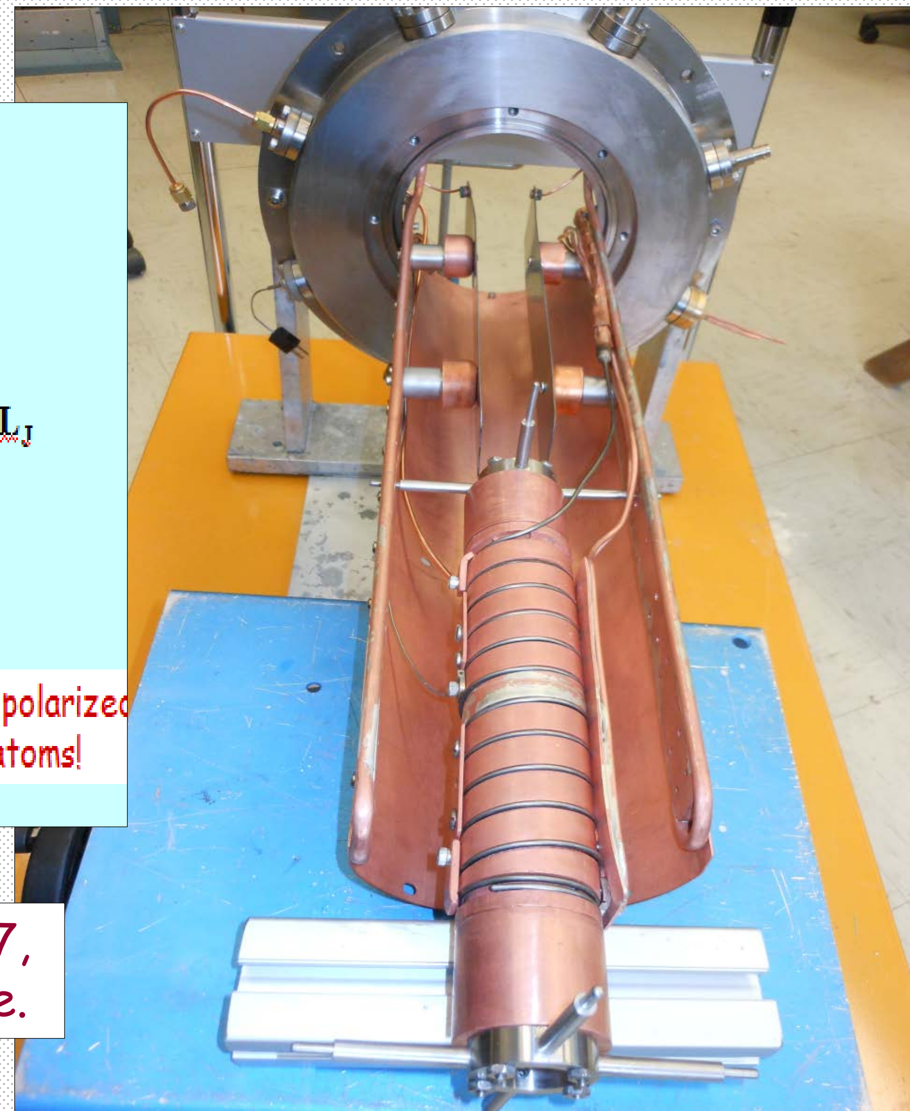
OPPIS with atomic H^0 injector layout, 2013-17



$H^+ \longrightarrow H2 \xrightarrow{H^0} He \xrightarrow{H^+} Rb \xrightarrow{H^0} Na \xrightarrow{H^-}$

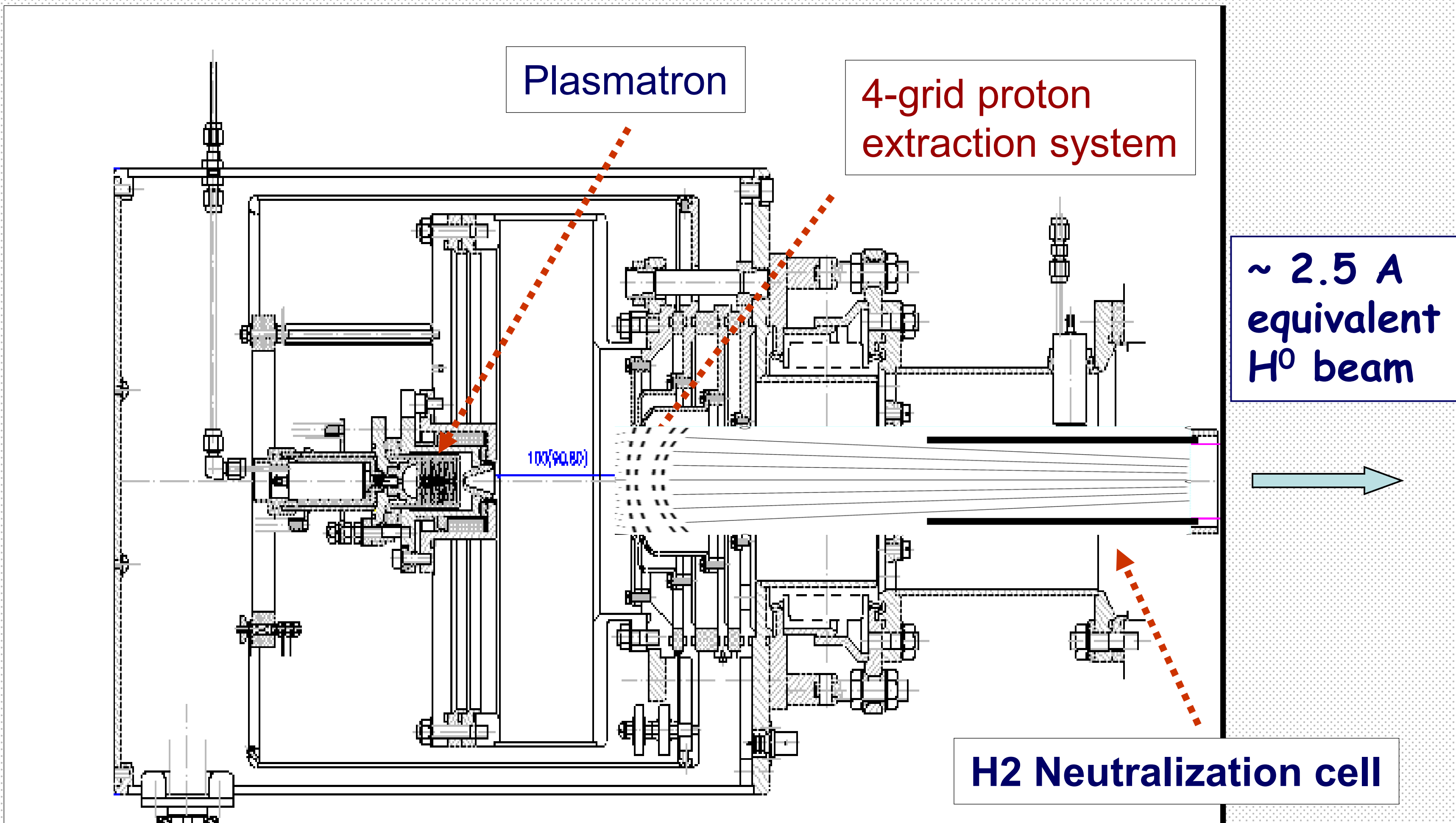
Optically-pumped Rb-vapor cell





Rb –cell preparation for the Run-2017, higher 6.0 kV deflecting plate voltage.

“Fast Atomic Beam Source”, FABS, BINP, Novosibirsk



FABS produces 100-150 mA equivalent H0 beam intensity Within the Na-jet ionizer acceptance.

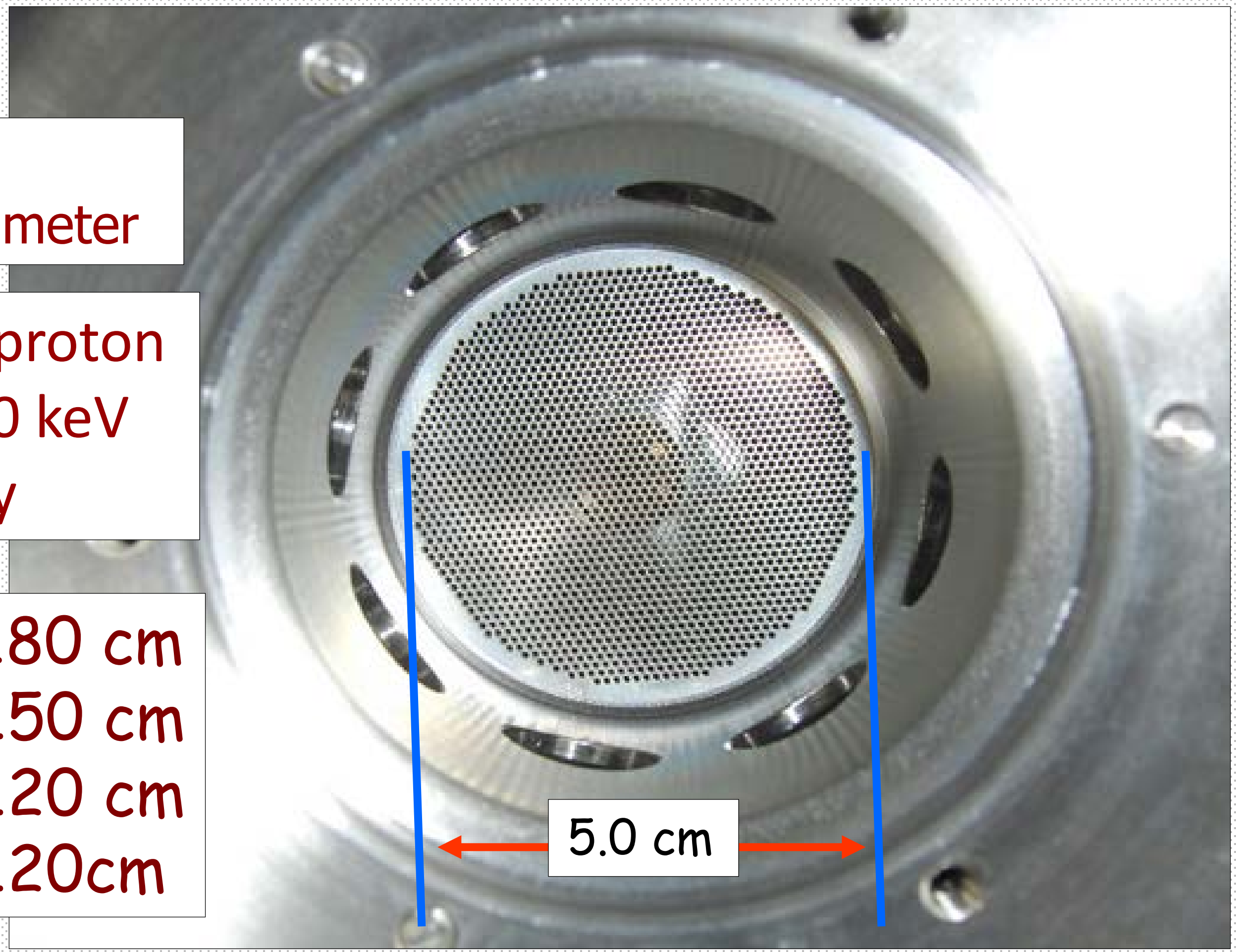
4-grid spherical Ion Optical System

F ~200 cm, δα -10 mrad

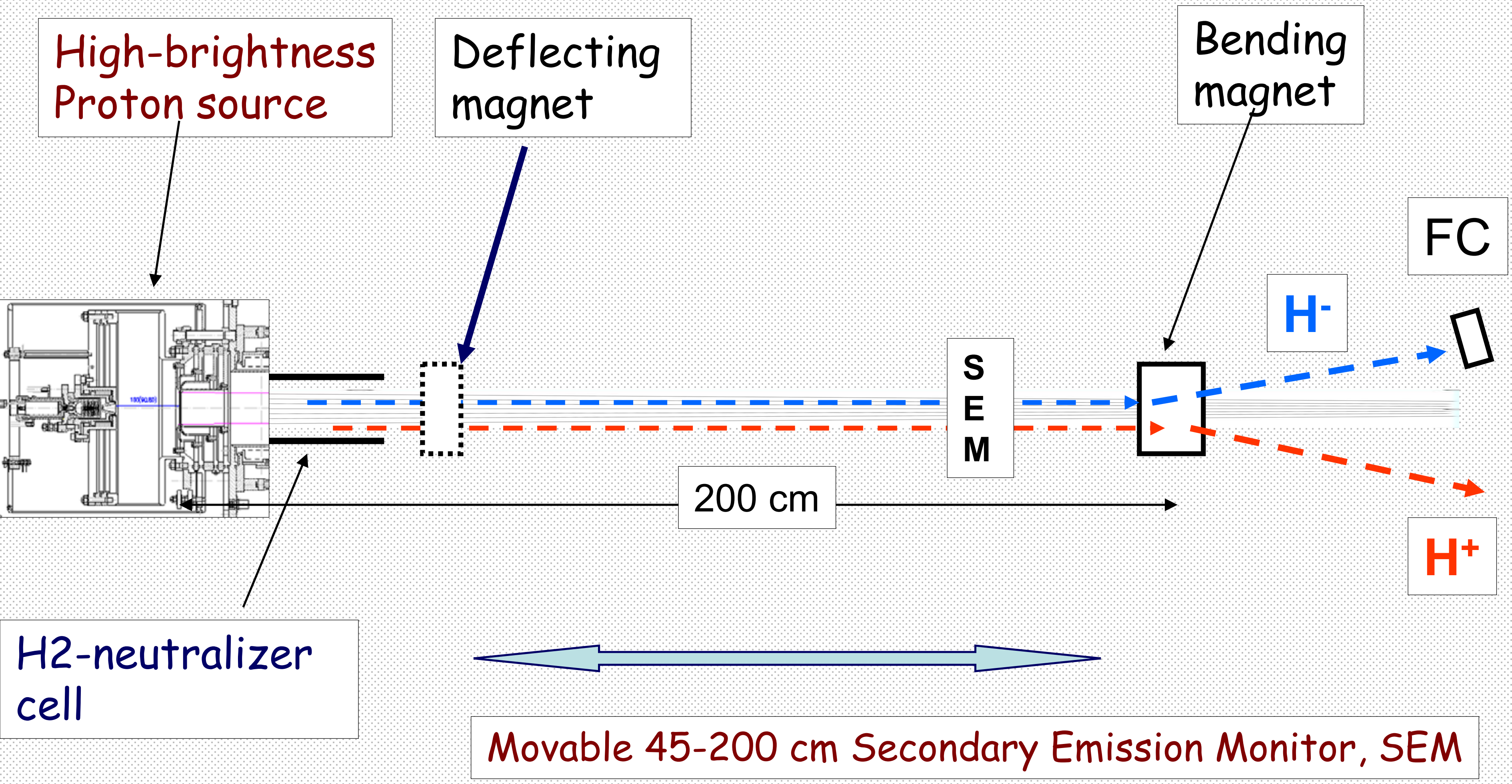
1820 holes ,
1.0 mm in diameter

2.5-5.0 A of proton beam at 6-10 keV Beam energy

R1, grid1-180 cm
R2, grid2-150 cm
R3, grid3-120 cm
R4, grid4-120cm

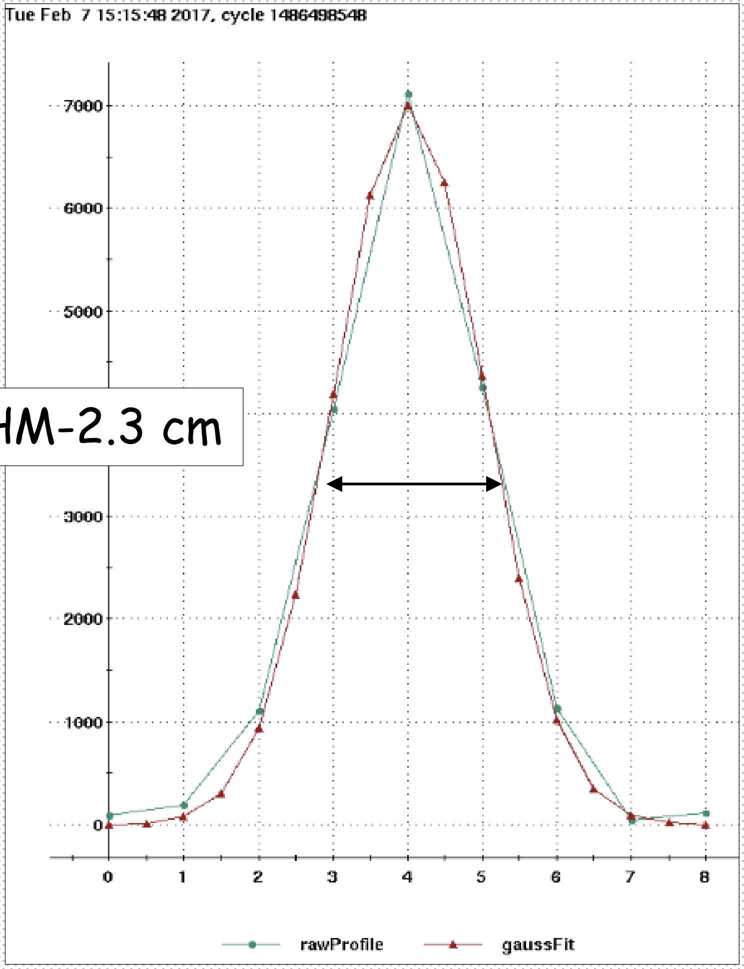


Atomic beam profile measurements



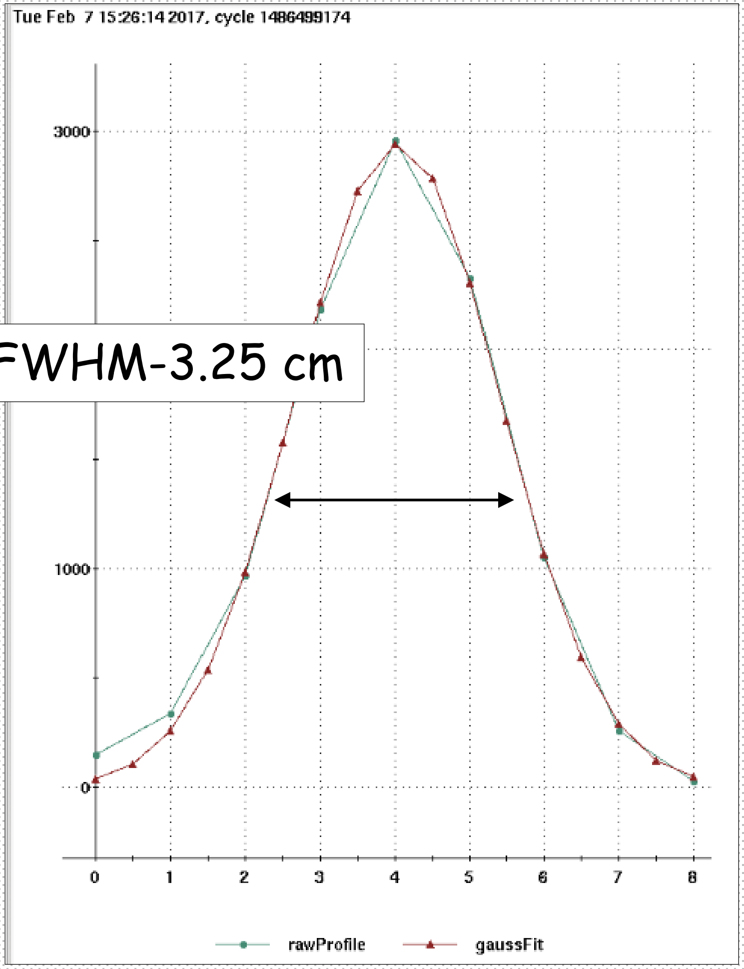
Atomic beam intensity profile vs. distance from the source.

Re-1.40 cm at the distance: L=100 cm-from the source



FWHM-2.3 cm

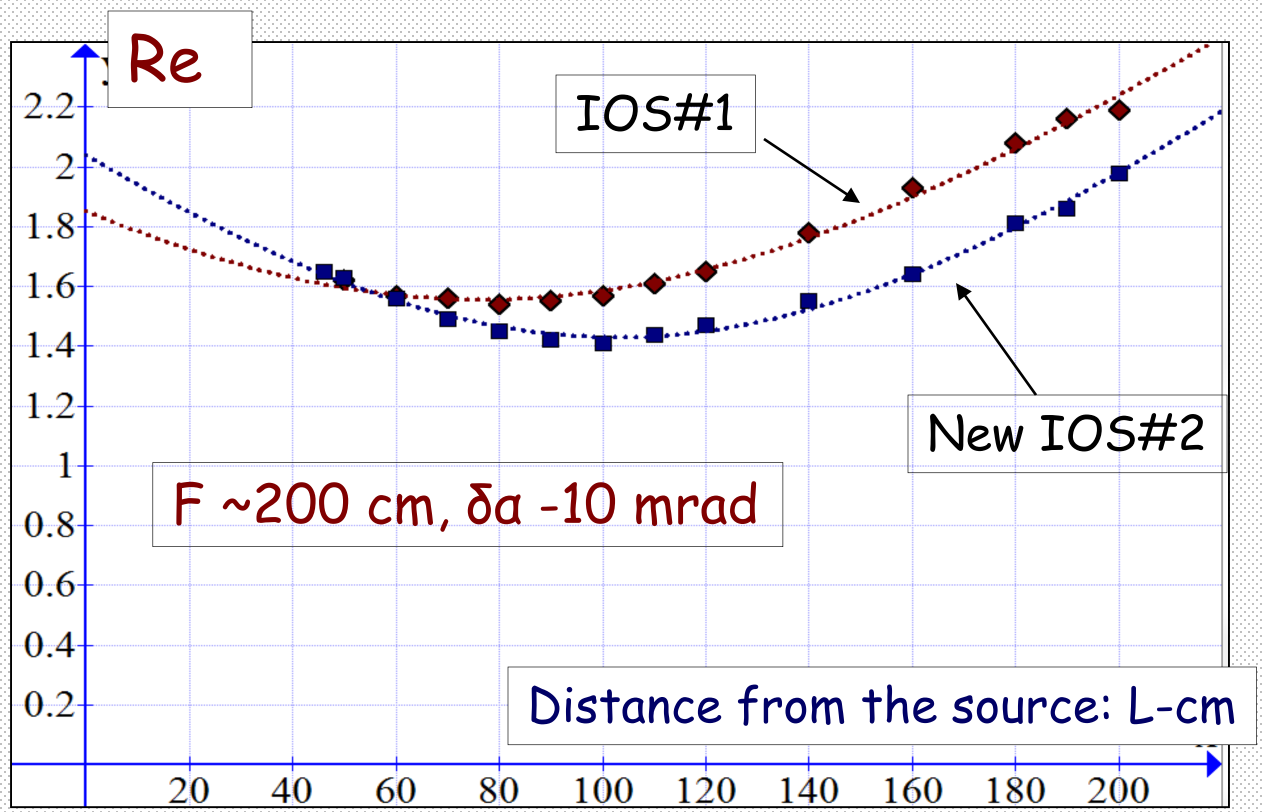
Re-1.98 cm at the distance: L=200 cm-from the source



FWHM-3.25 cm

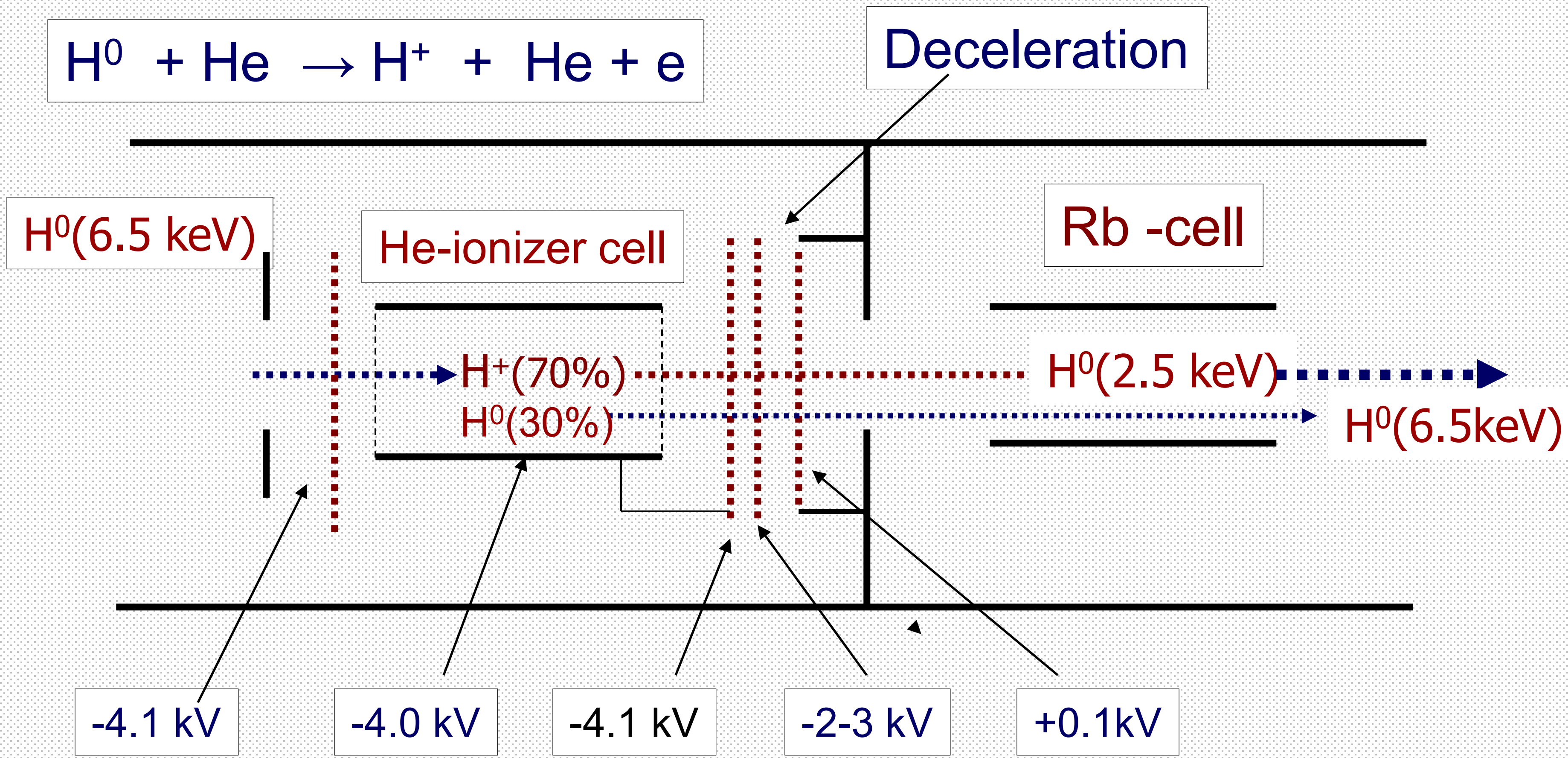
Atomic beam intensity profile vs. distance from the source measured with the movable secondary emission monitor.

Total equivalent H beam intensity 2.5A

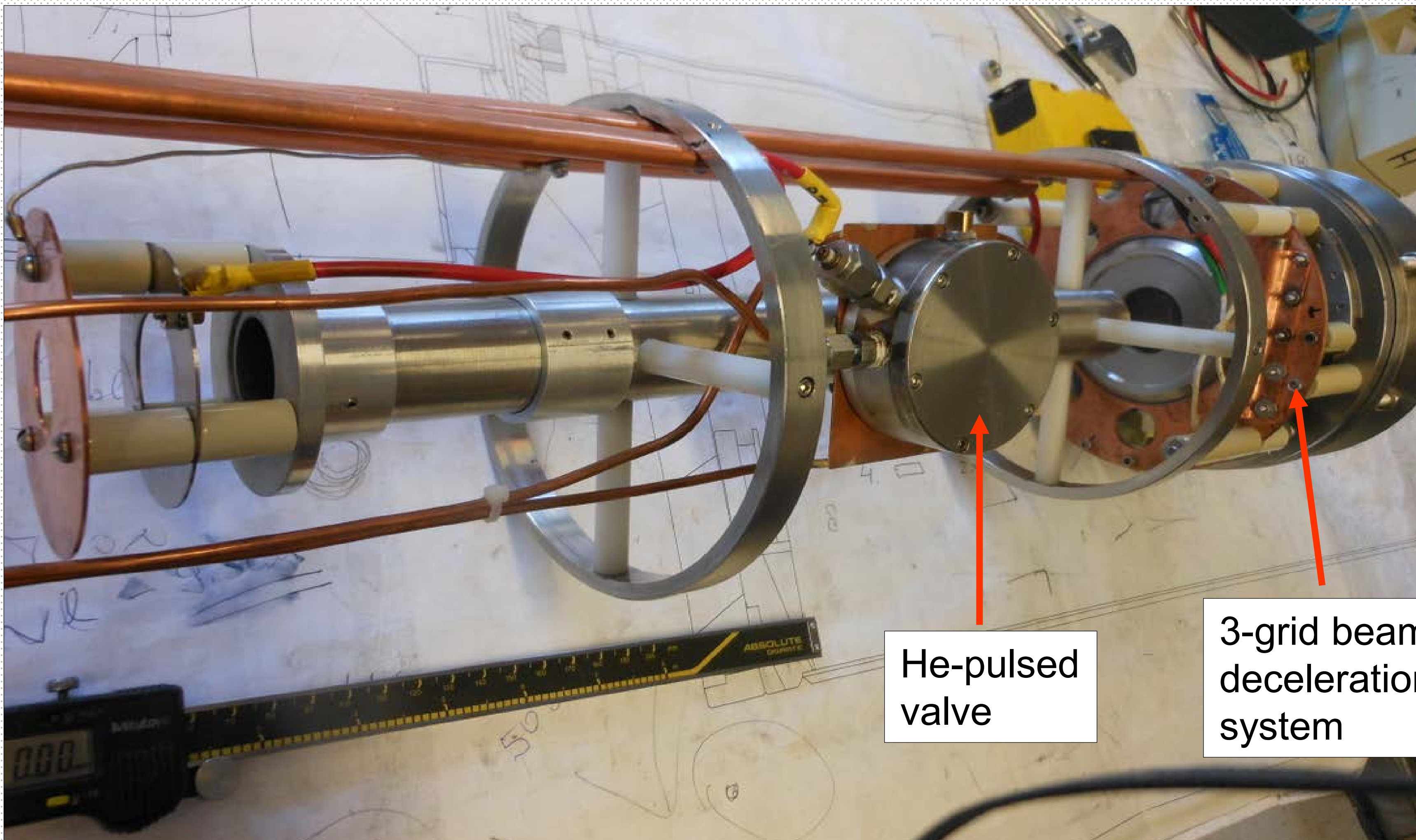


Re- half-width of beam intensity profile at -1/e level.
Beam profile FWHM = 1.67 Re

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



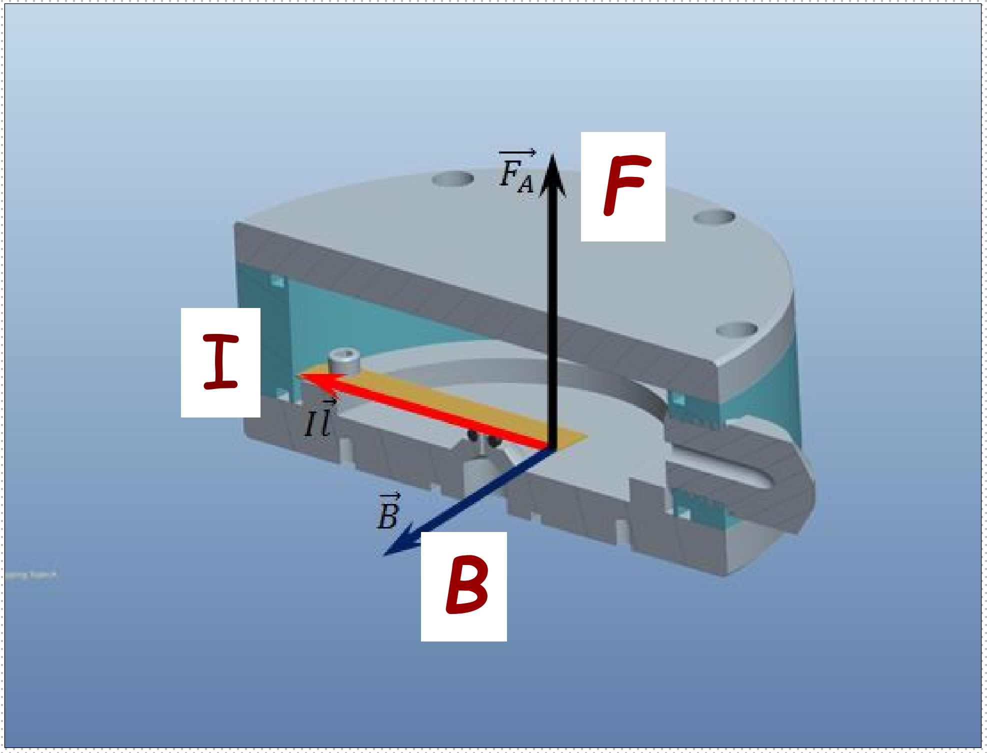
He-ionizer cell and 3-grid energy separation system.

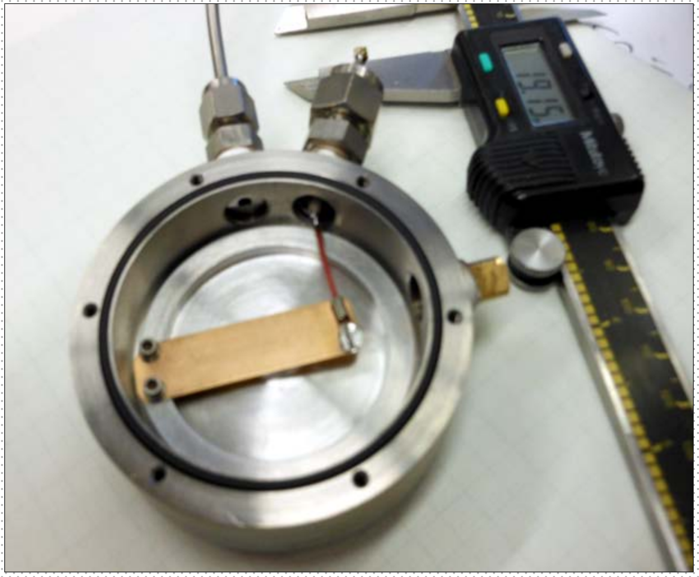


“Electro-dynamic” valve operation principle.

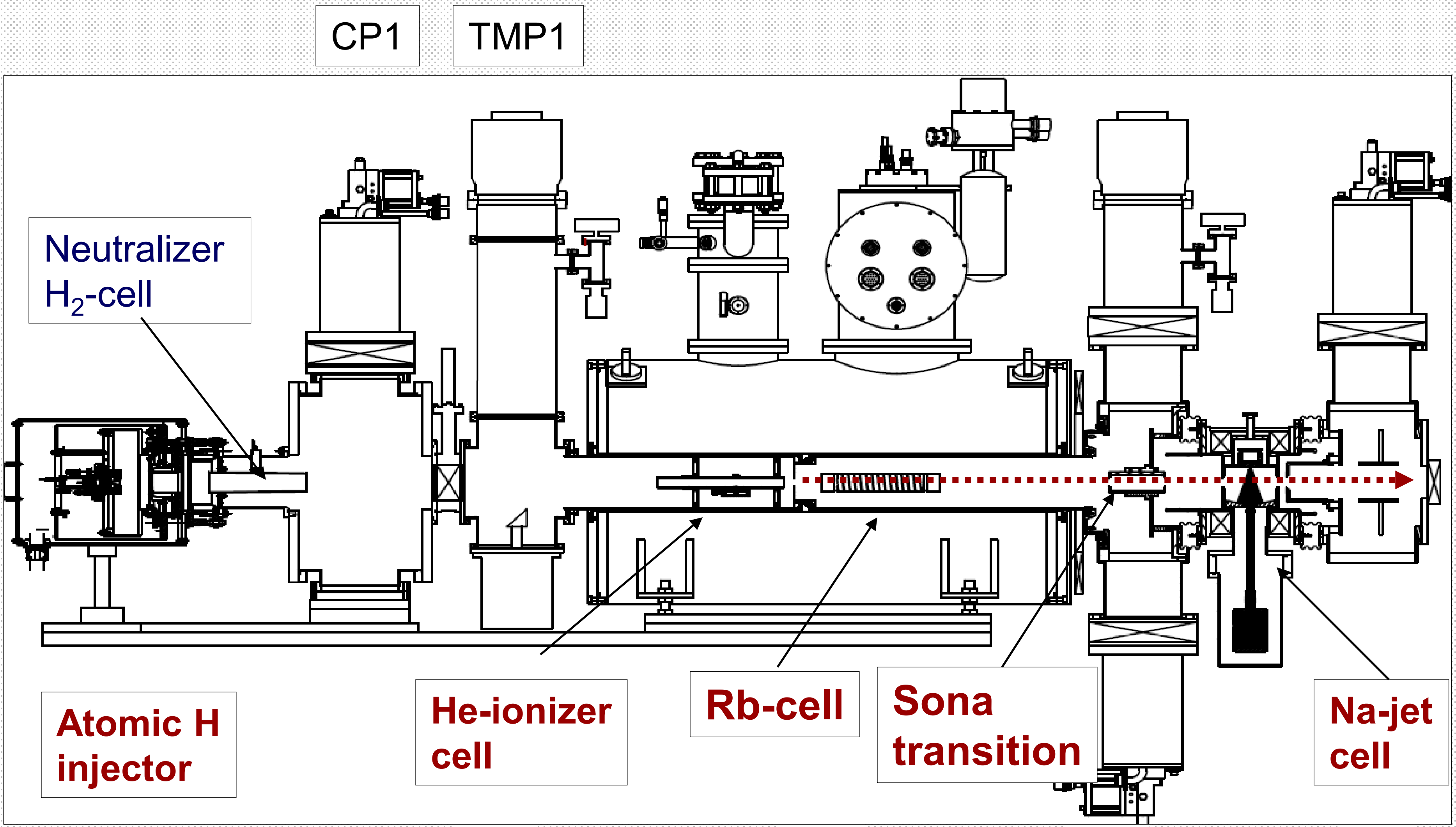
Lorentz force to the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=100 A, L=5 cm, F=15 N. Current pulse duration ~100 us

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





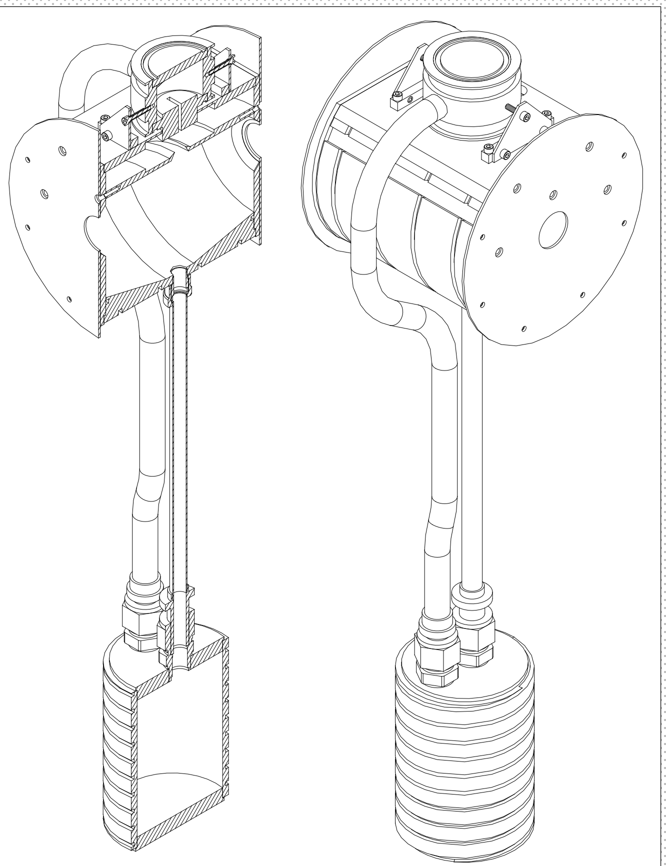
New OPPIS with atomic H^0 injector layout, 2013-17



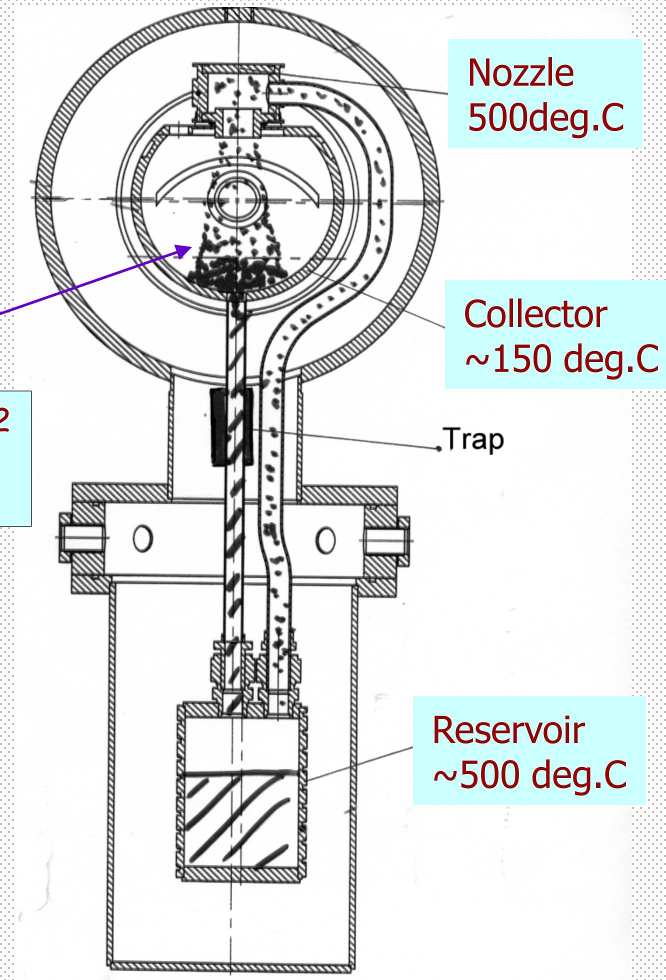
$H^+ \longrightarrow$ **H2** $\xrightarrow{H^0}$ **He** $\xrightarrow{H^+}$ Rb $\xrightarrow{H^0}$ **Na** $\xrightarrow{H^-}$

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 .

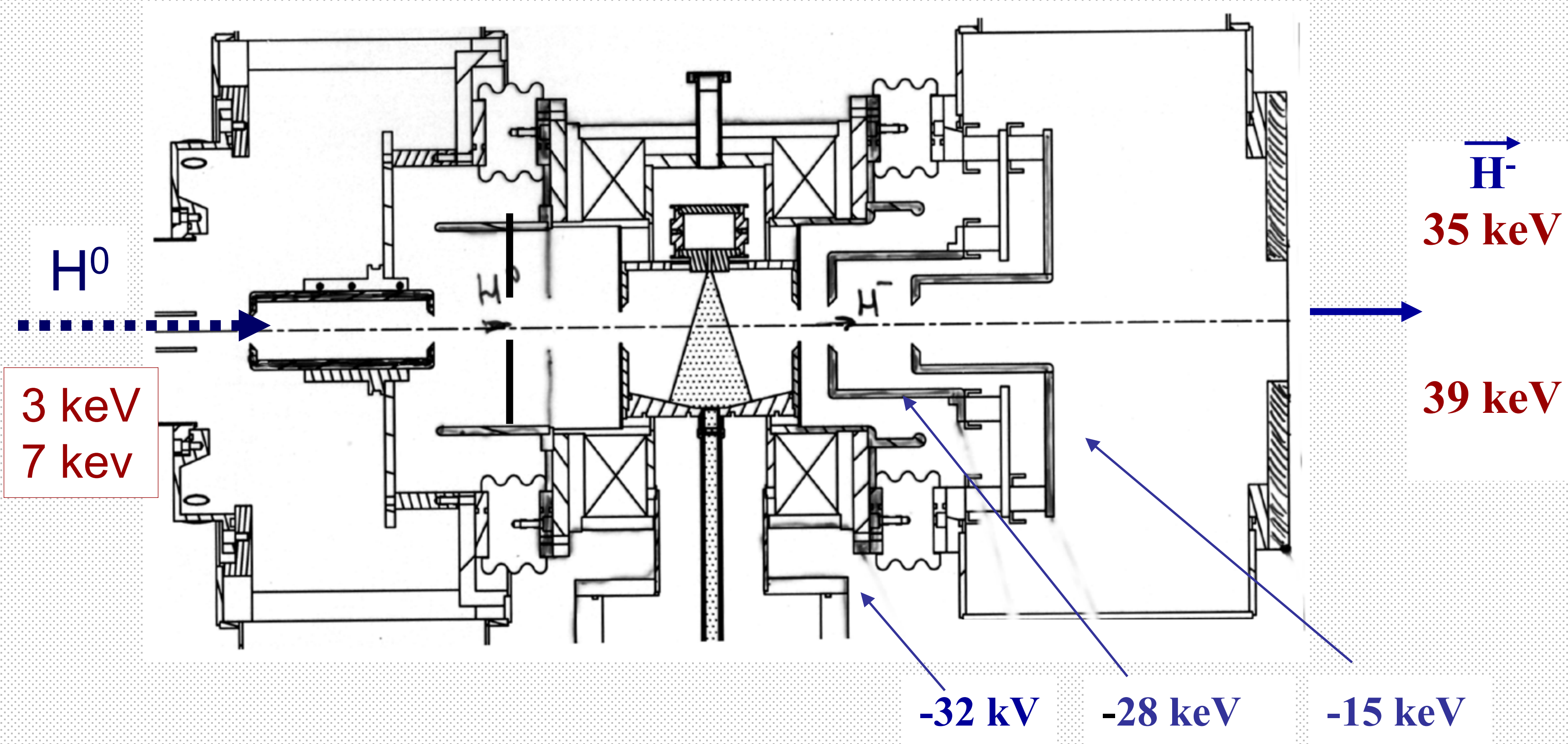


$NL \sim 2\cdot 10^{15}$ atoms/cm^2
L ~ 2-3 cm



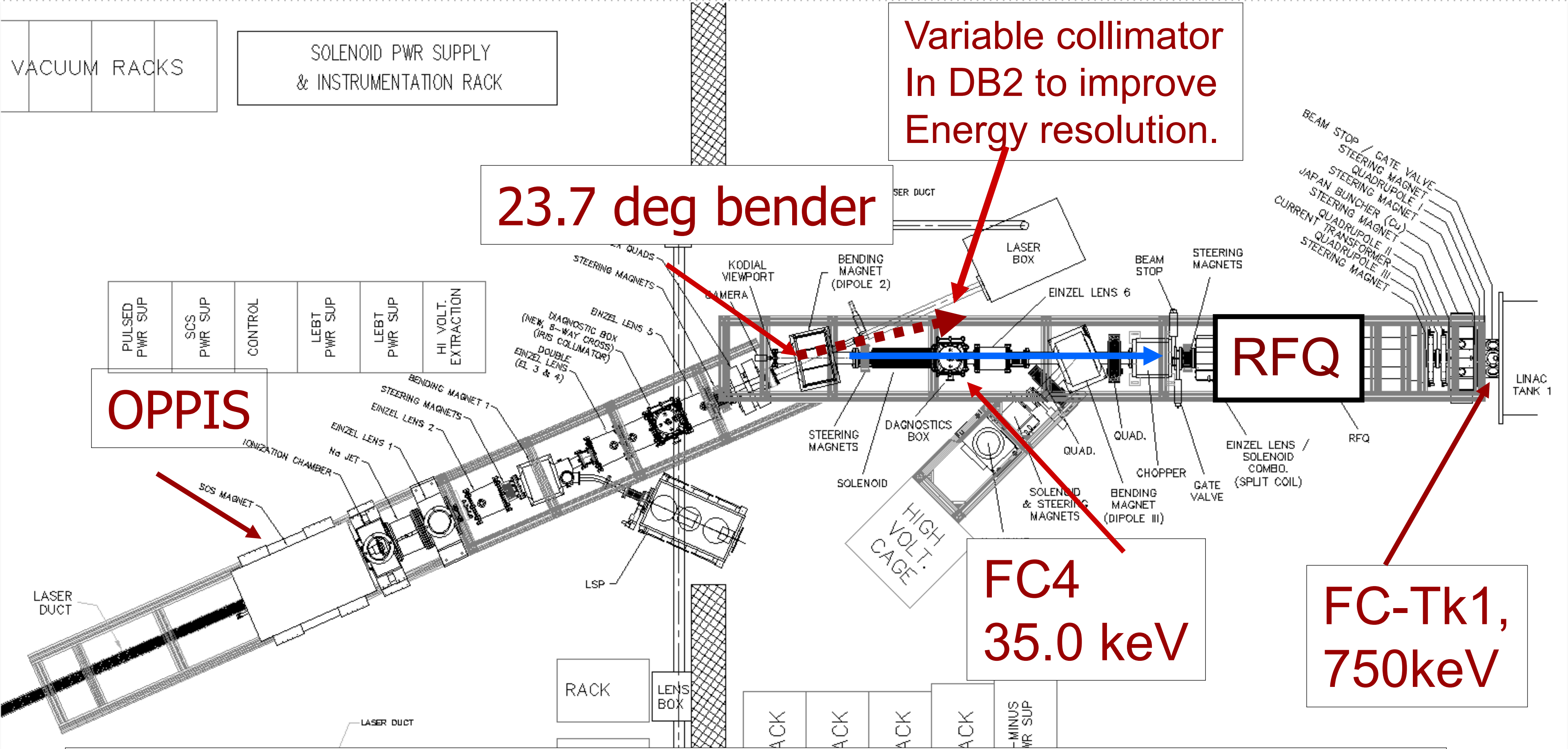
Reservoir– operational temperature. Tres. ~500 °C.
Nozzle – Tn ~500 °C.
Collector- Na-vapor condensation: Tcoll.~120°C
Trap- return line. T ~ 120 – 180 °C.

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.

Low Energy Beam Transport line.



Polarized beam energy is 35 keV
Unpolarized beam of a 39 keV energy is well separated and removed after the bending magnet

H^- current at 200 MeV-1.050 mA, June12, 2017

Beam intensity and polarization at 200 MeV

- 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 thickness-NL	4.5	5.5	7.5	10.4
Linac Current, μA	440	520	740	950
Booster Input $\times 10^{11}$	10.0	12.0	14.0	17.1
Pol. %, at 200 MeV	86	86	84.5	83

Rb-cell thickness ,NL $\times 10^{13}$ atoms/cm^2

RHIC Polarized beam in Run 2013-17

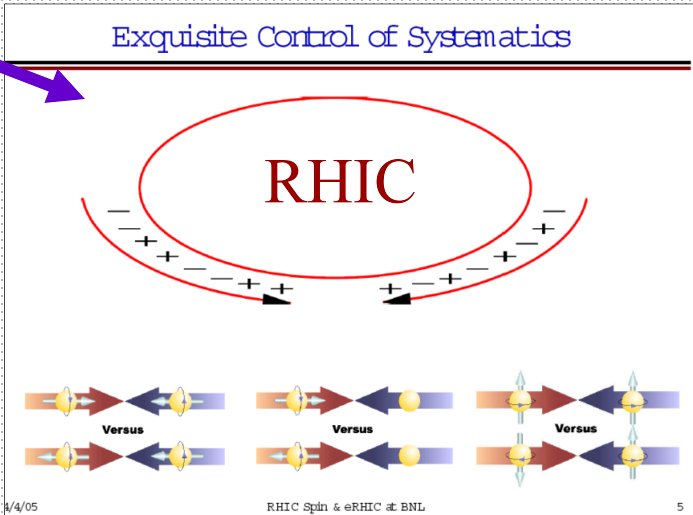
OPPIS → 1.0 mA x 300us→18·10^{11} polarized H^- /pulse.

LINAC → 9.0 ·10^{11} polarized H^- /pulse at 200 MeV routinely in Run-17, Polarization-85%

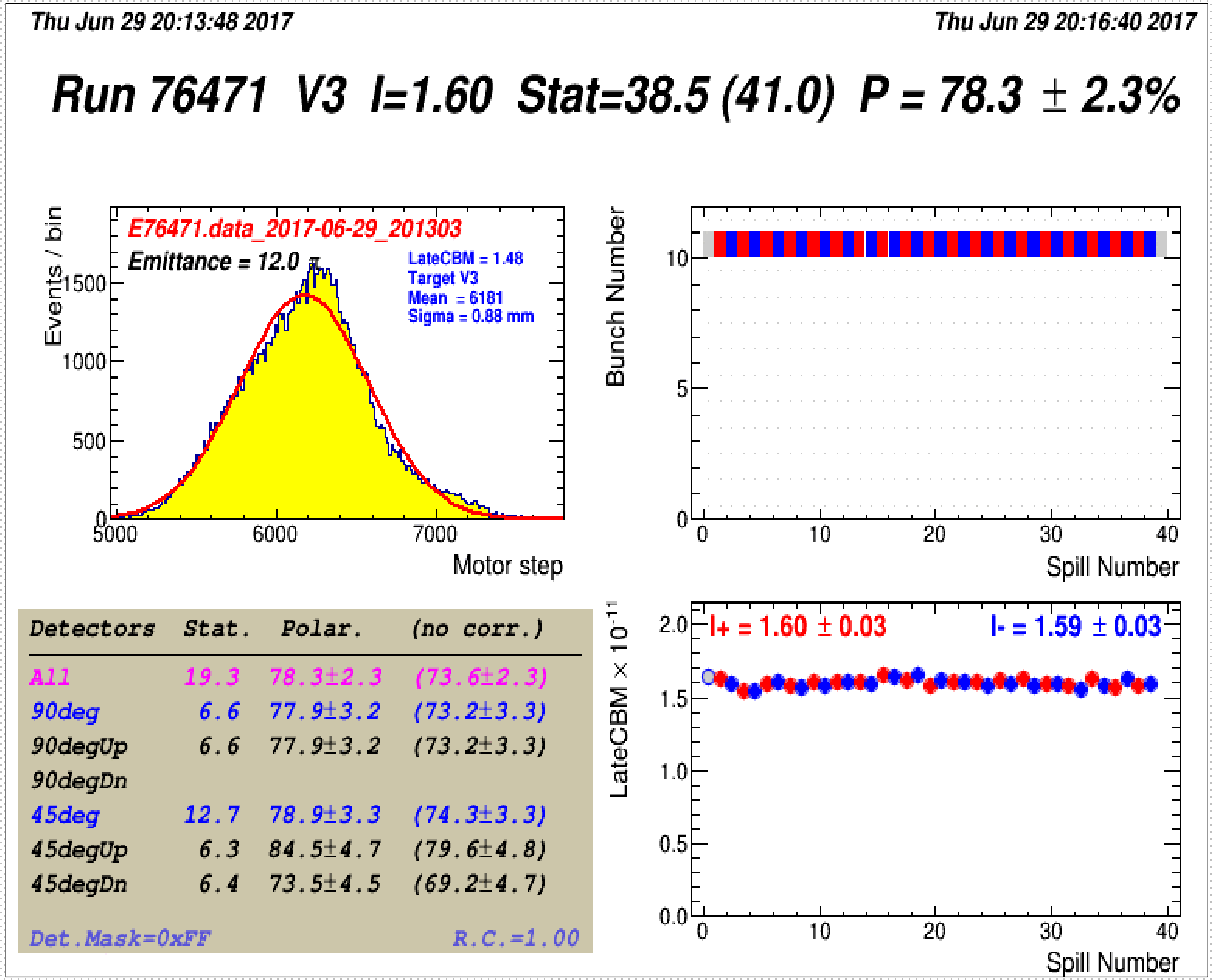
Booster: (2.5-3.0) ·10^{11} protons /pulse at 2.3 GeV

AGS: (2.0-2.5) ·10^{11} p/bunch, P-70%

~1.8·10^{11} p/bunch, P~65-75% at 100 GeV
P ~ 60-65% at 255 GeV



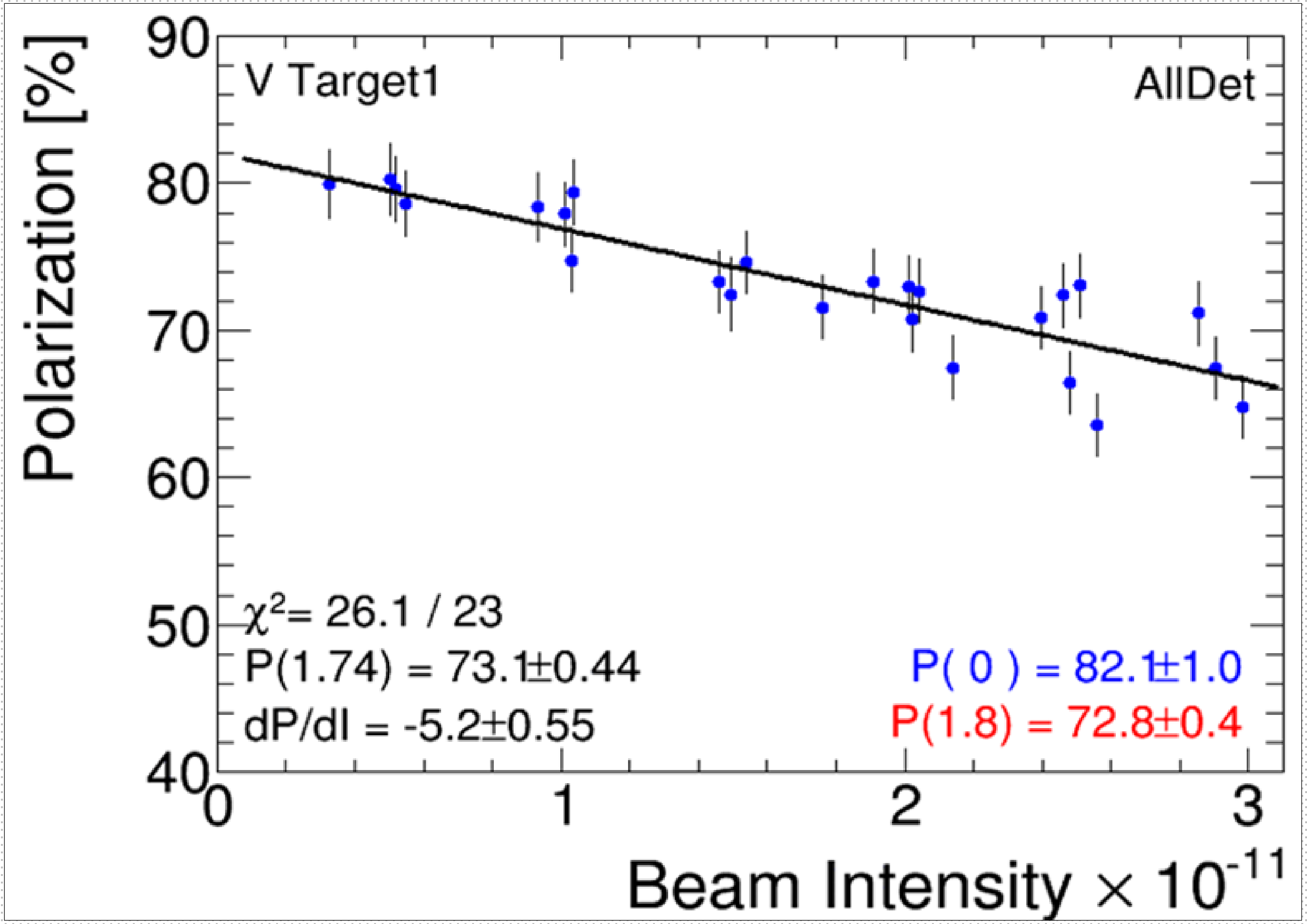
Polarization in AGS, 23 GeV, Run-2017



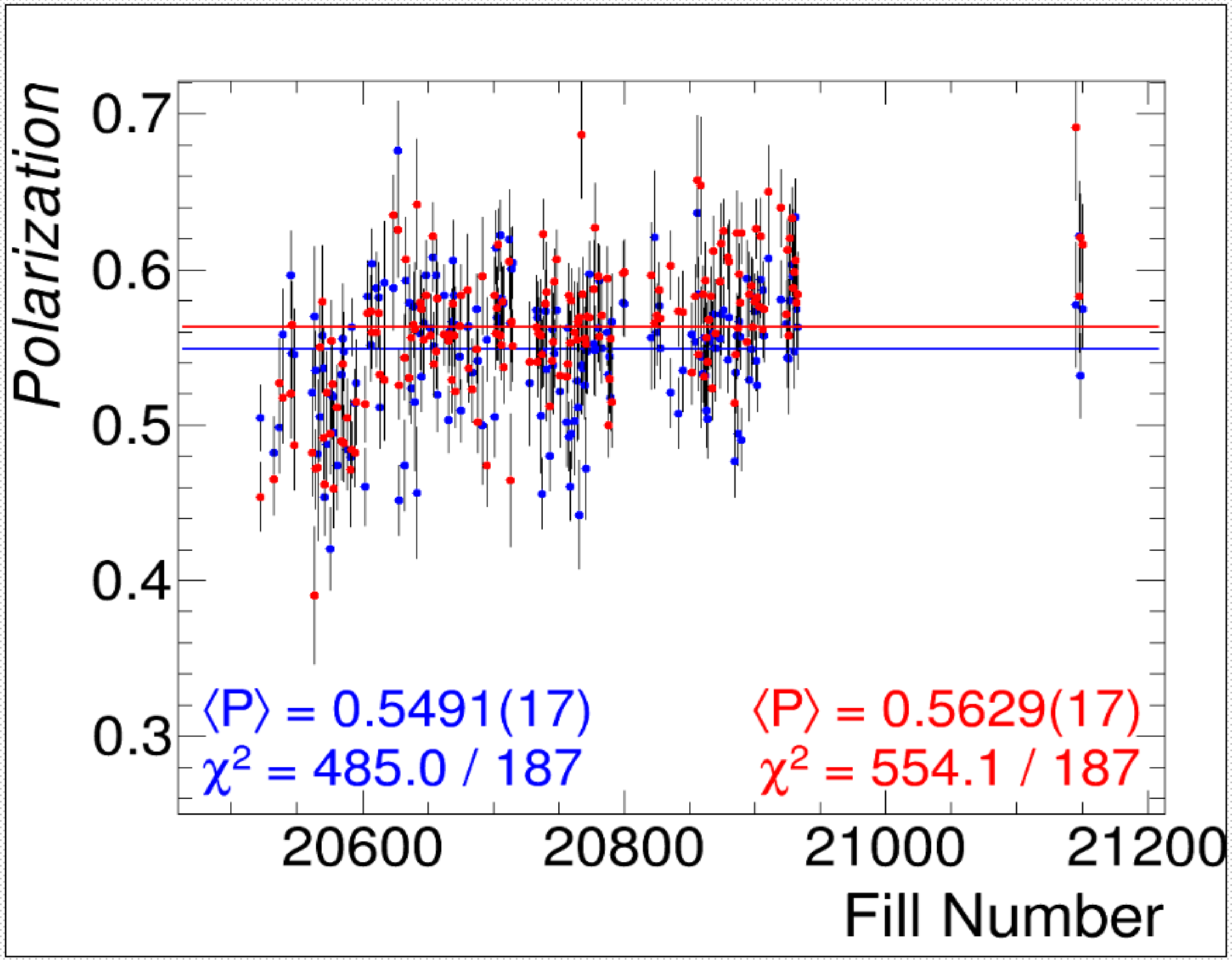
Detectors	Stat.	Polar.	(no corr.)
All	19.3	78.3±2.3	(73.6±2.3)
90deg	6.6	77.9±3.2	(73.2±3.3)
90degUp	6.6	77.9±3.2	(73.2±3.3)
90degDn			
45deg	12.7	78.9±3.3	(74.3±3.3)
45degUp	6.3	84.5±4.7	(79.6±4.8)
45degDn	6.4	73.5±4.5	(69.2±4.7)

Det.Mask=0xFF R.C.=1.00

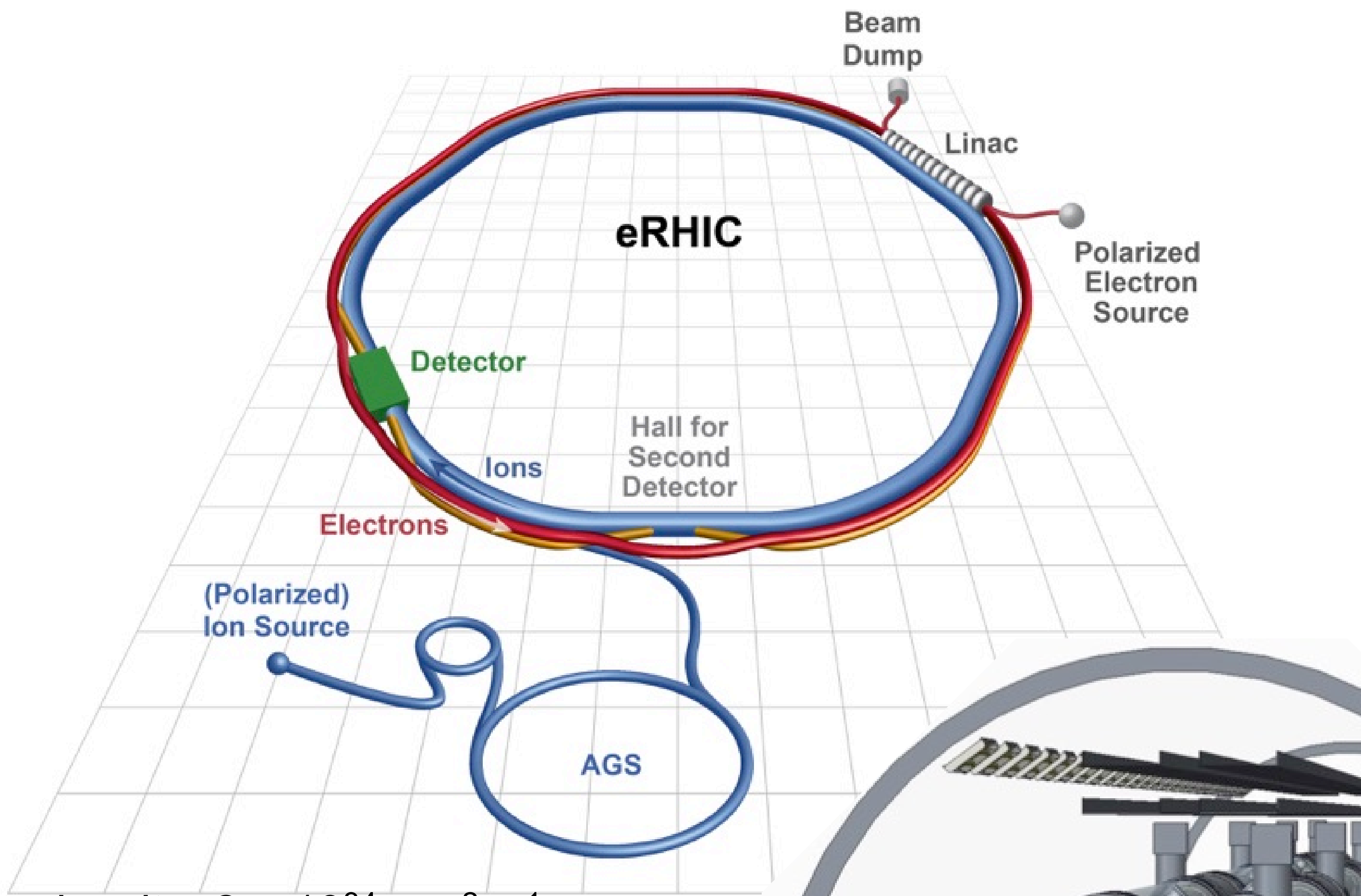
Polarization at 23 GeV in AGS

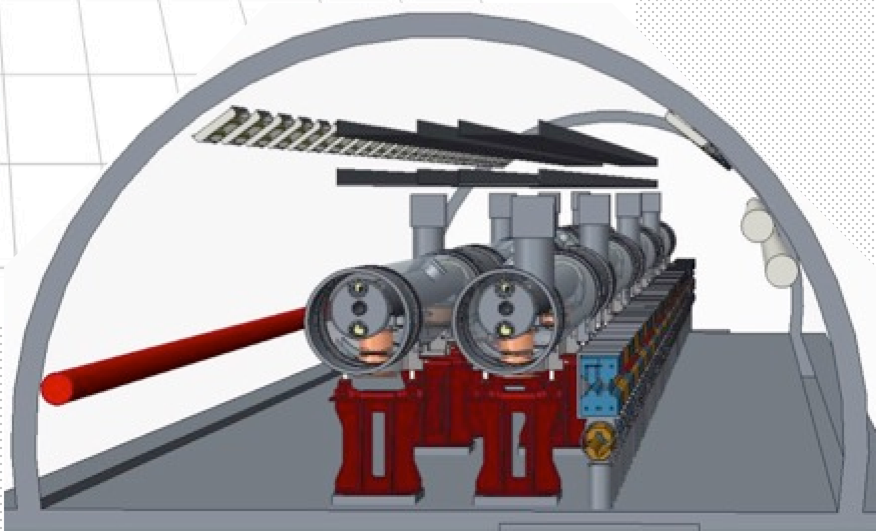


255 GeV beams Polarization measured with the H-jet polarimeter in Run-2017



Ultimate eRHIC design
Advanced Electron-Ion Collider



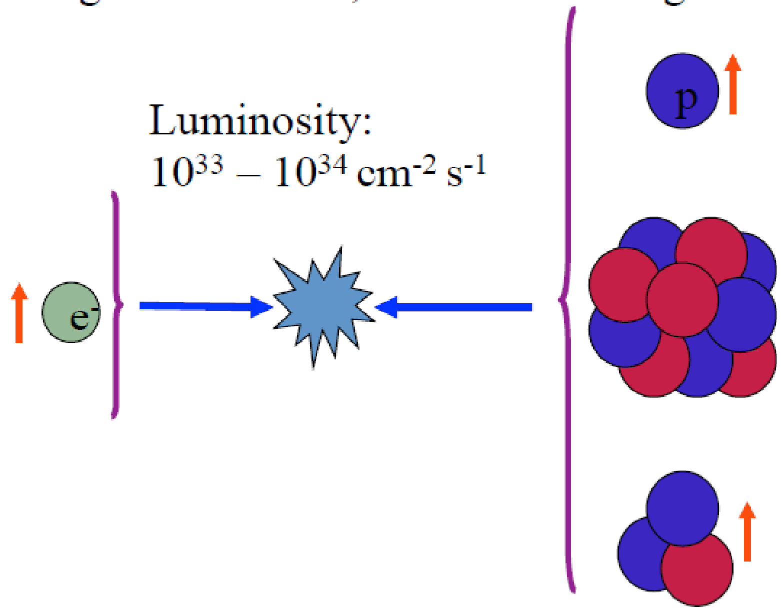


- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL and permanent magnet arcs greatly reduce electric power consumption to about 15 MW!

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

80% polarized electrons:
2.6 – 21.2 GeV



70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

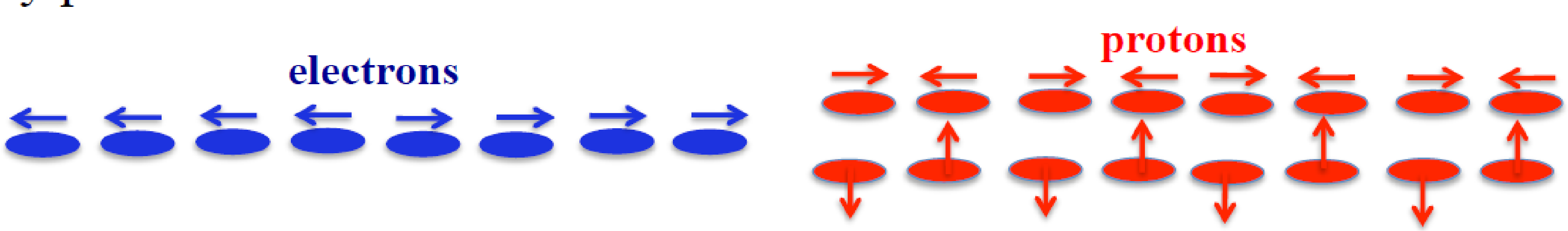
Pol. light ions (He-3)
17 - 167 (184*) GeV/u

Center-of-mass energy range: 20 – 145 GeV

Full electron polarization at all energies

Full proton and He-3 polarization with six Siberian snakes

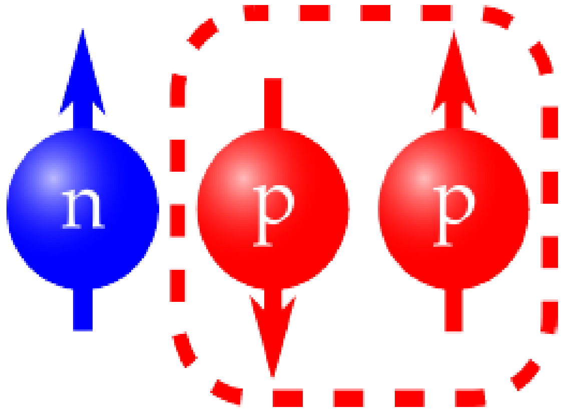
Any polarization direction in electron-hadron collisions:



* It is possible to increase RHIC ring energy by 10%

Why polarized 3He^{++} ion source and beams?

- Polarized DIS crucial for study of neutron spin structure
    - PPDFs; tests of QCD, Bjorken sum rule; higher energies



State	Probability
S	88.6%
S'	1.5%
D	8.4%

- S-state ^{3}He: nuclear spin carried by the neutron
- ^{3}He's magnetic moment close to n, compatible with RHIC spin manipulation
- Polarized ^{3}He ions offer a "polarized neutron beam" for RHIC and a future eRHIC

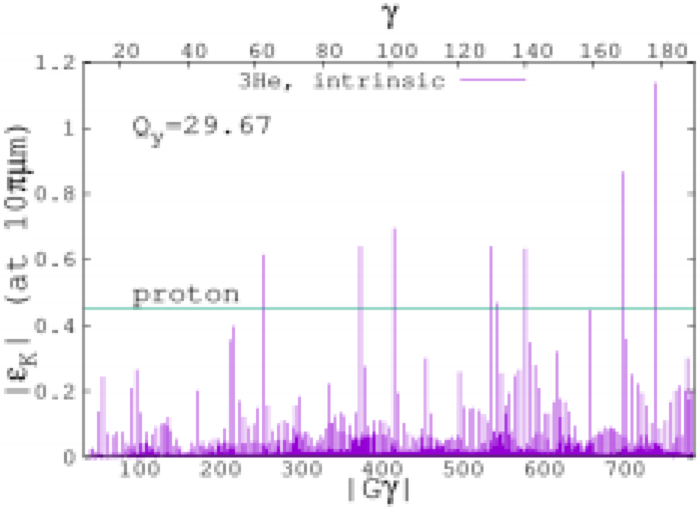
eRHIC plans: Helion

F.Meot

- Transverse ^{3}He bunch emittance is comparable to proton's ($\lesssim$2.5 μm)
- Resonances are $\sqrt{|G_{^3He^{2+}}|/G_p} = \sqrt{4.18/1.79} \approx 1.5$ stronger, snakes are $|G_{^3He^{2+}}|/G_p \approx 2.3$ as strong.

- On the other hand:

- resonance spectrum is denser
- imperfection and intrinsic resonances overlap, this affects polarization (excites snake resonances)



- Simulations show that

  - 2 snakes do not maintain polarization upon crossing $G\gamma = -411 + Q_y$ ($\gamma \approx 91$) or $G\gamma = -393 - Q_y$ ($\gamma \approx 101$).

  - a 6-snake configuration preserves polarization up to beyond the strong resonance at $G\gamma = 717 + Q_y$ ($\gamma \approx 180$).

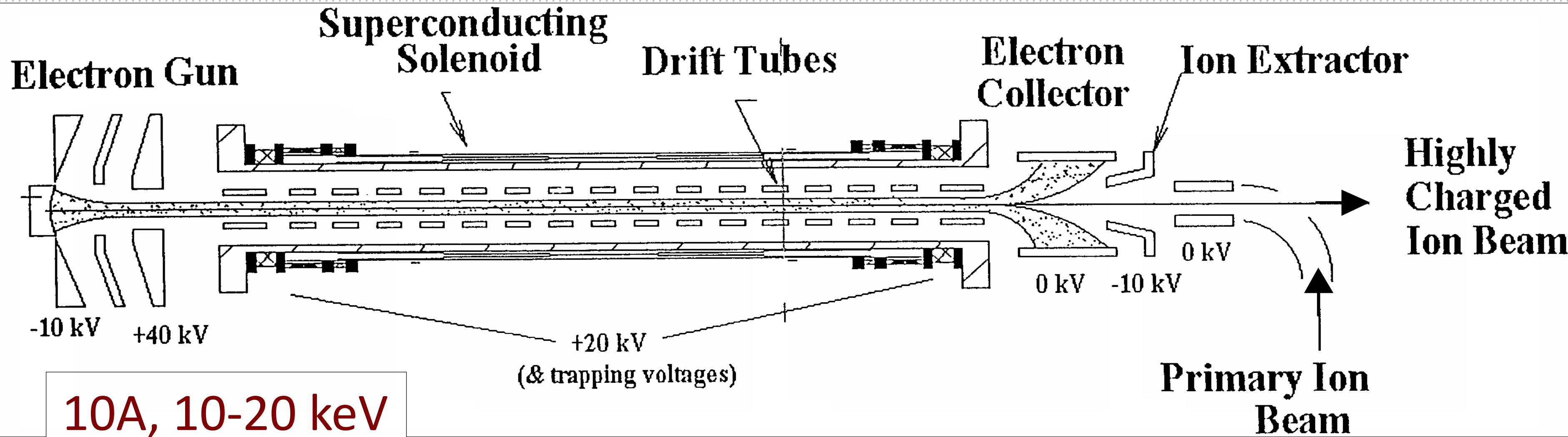
Production of polarized $^{3}He^{++}$ beam in EBIS.

A.Zelenski, J.Alessi, ICFA Beam Dynamics Edition Newsletter **30**, p.39, (2003)

- ^{3}He polarization by optical pumping and metastability-exchange technique inside the EBIS in high (5.0T) magnetic field. No polarization losses in $3He^{+}$ state.

- EBIS is used for efficient ionization and accumulation of polarized $3He^{++}$ ions to the full capacity of about $2{\cdot}10^{11}$, $3He^{++}$ ions.

Principle of EBIS Operation



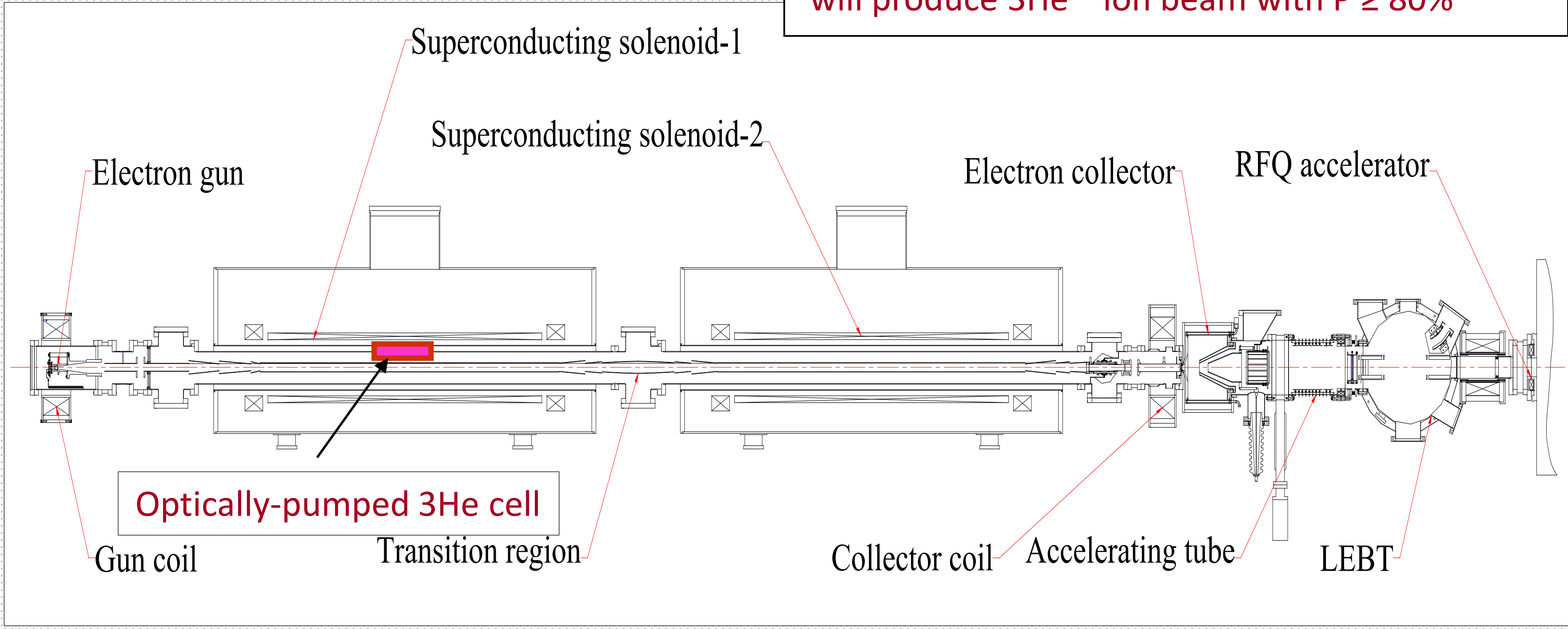
10A, 10-20 keV

Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.

- The total charge of ions extracted per pulse is ~ (0.5 – 0.8) x (# electrons in the trap)
- Ion output per pulse is proportional to the trap length and electron current.
- Ion charge state increases with increasing confinement time.
- Output current pulse is independent of species or charge state!

"Extended" EBIS upgrade with new "injector" solenoid for polarized 3He^{++} ion production.

Polarization and ionization in high magnetic field will produce 3He^{++} ion beam with P ≥ 80%

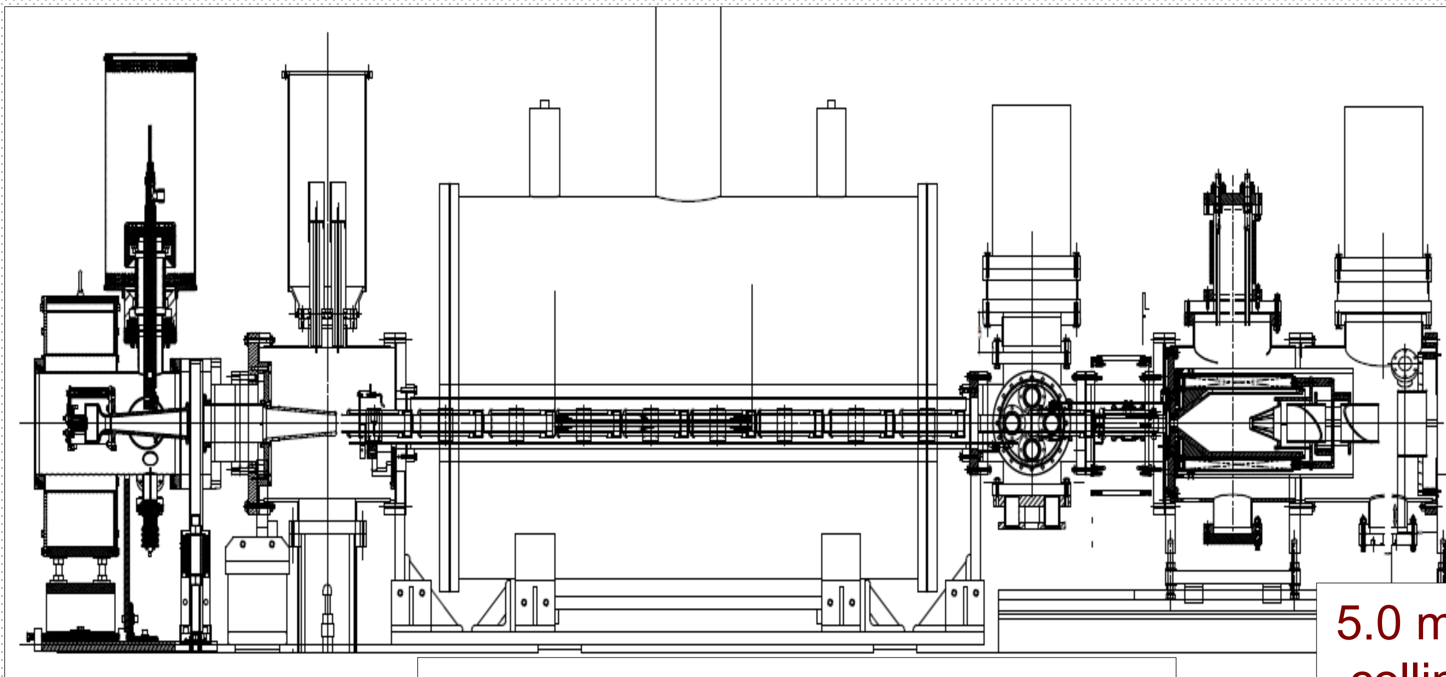


3He^{+} → Ionization to 3He^{++} → Up to 2×10^{11} 3He^{++} ions/pulse

Extended EBIS superconducting solenoids, April 2018

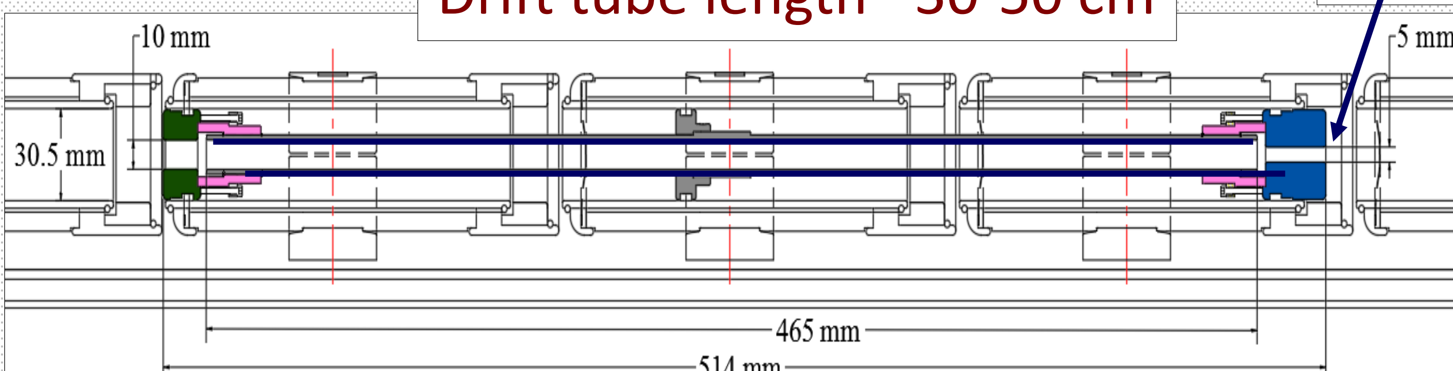
5.0 T field, about 1.0 T field at minimal solenoid separation-30 cm

Feasibility study of the small 10 mm diameter drift tube in EBIS with pulsed gas injection in the center

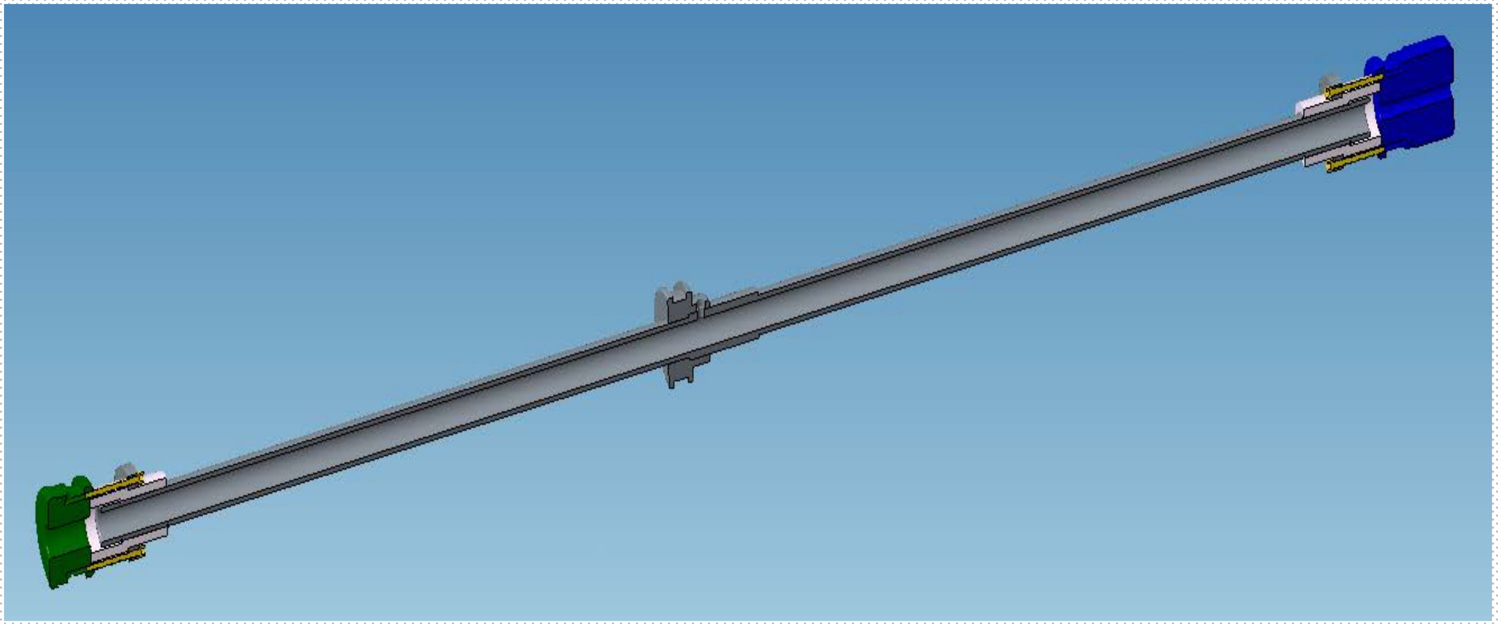


Drift tube length ~30-50 cm

5.0 mm collimators

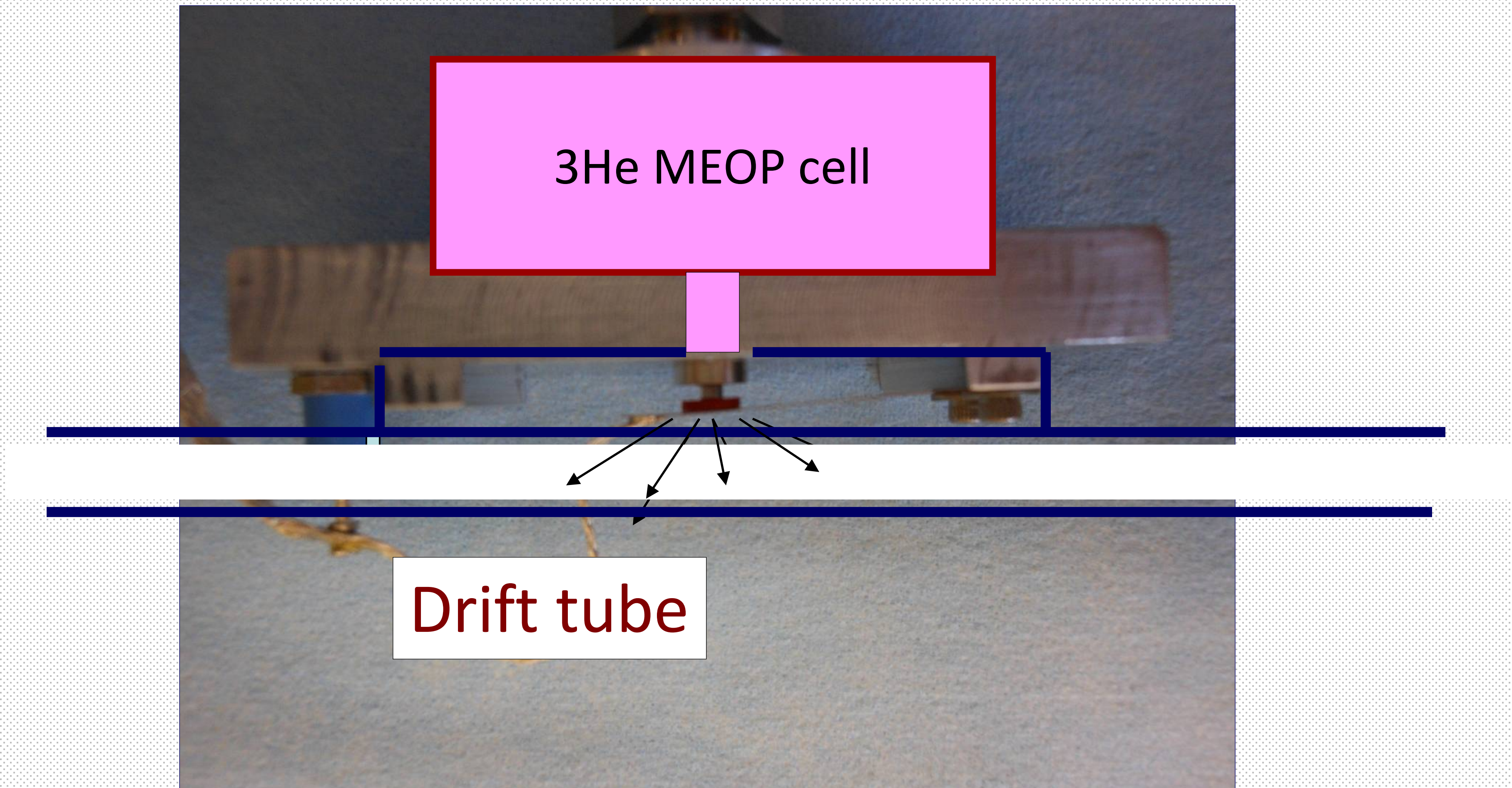


Gas Injection Cell with end caps for Electron Beam transmission at the BNL Test EBIS . E.Beebe

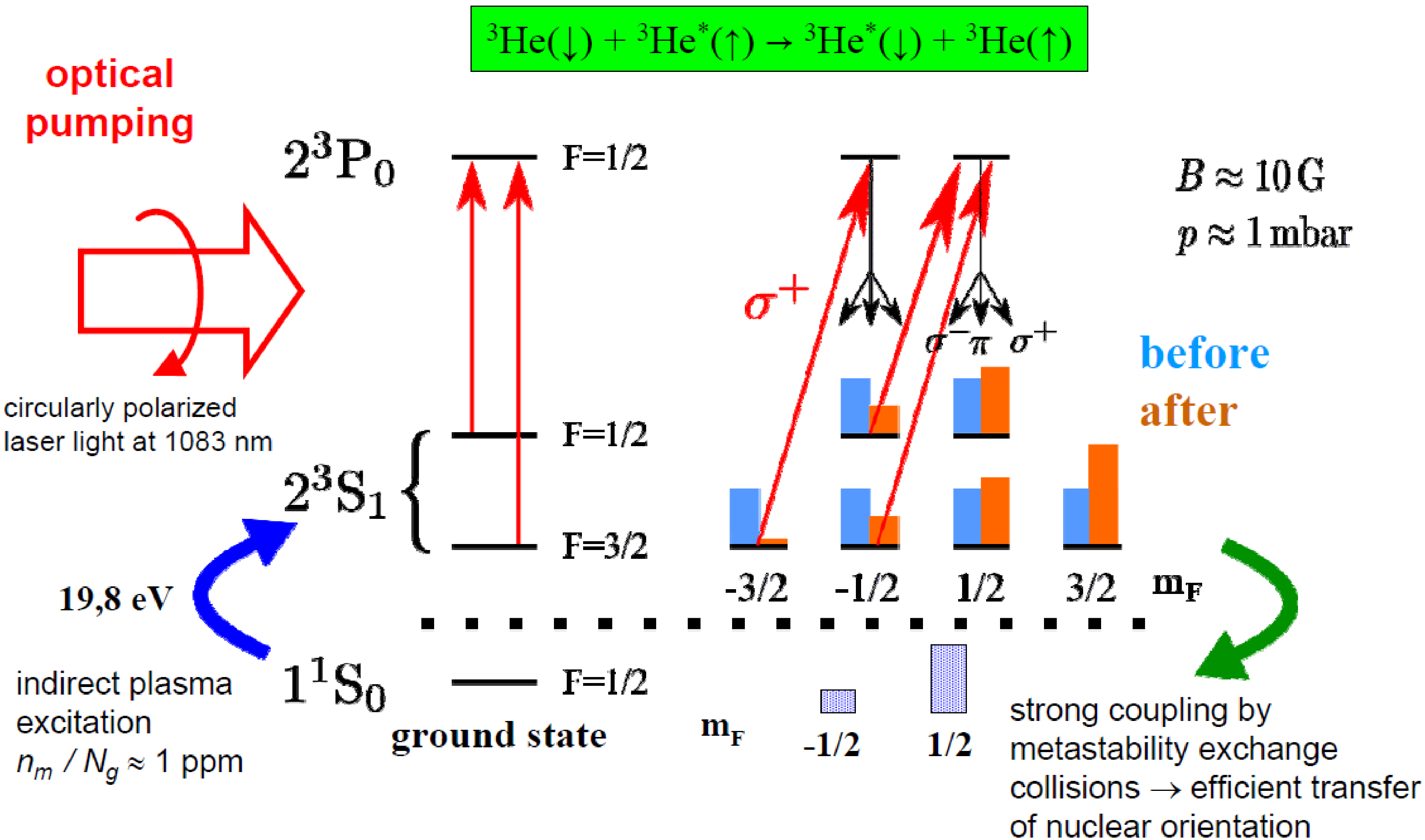


Electron beams up to 6 A were successfully propagated through the assembly consisting of a 46 cm, 10mm gas cell with a 3 cm long, 10 mm upstream barrier electrode and a 3 cm long, 5 mm diameter downstream barrier electrode.

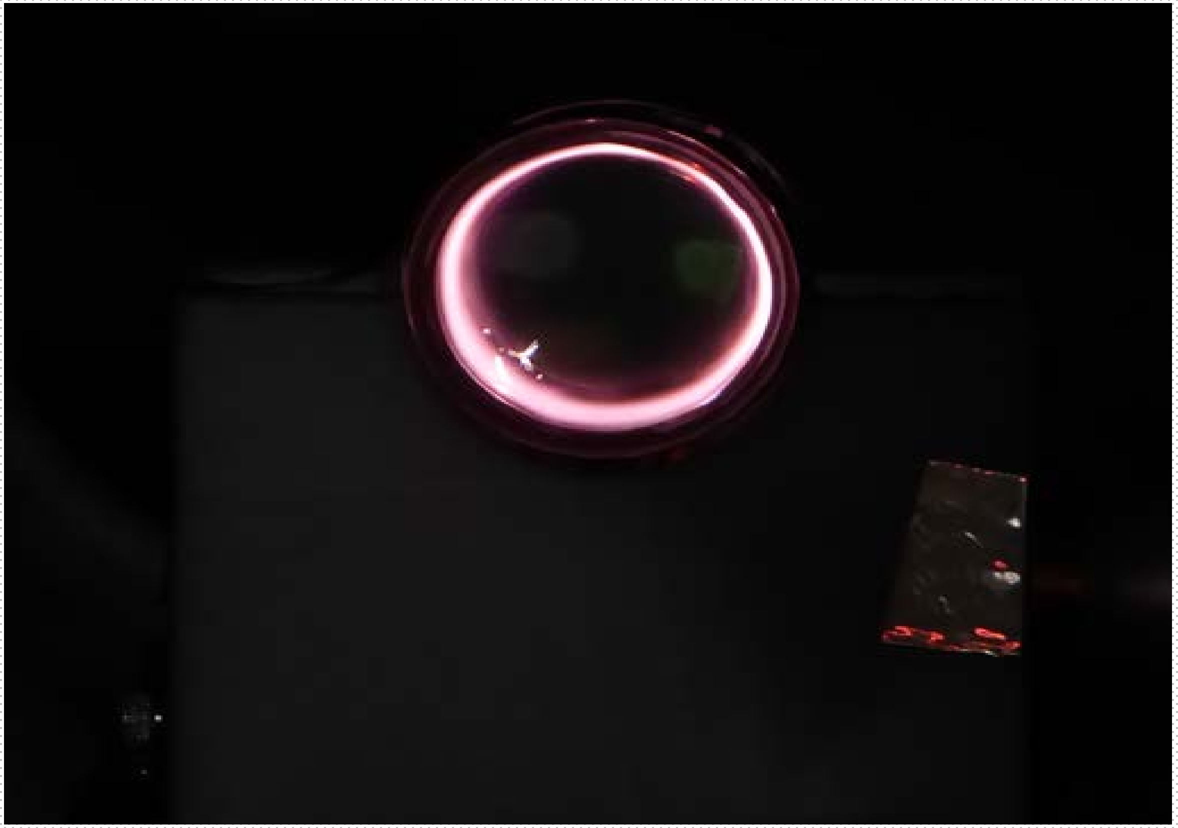
3He pulsed valve development



Principle of Metastability Exchange Optical Pumping (MEOP) in ^3He



RF-discharge in 2.0 T magnetic field.
3He-cell diameter-25mm

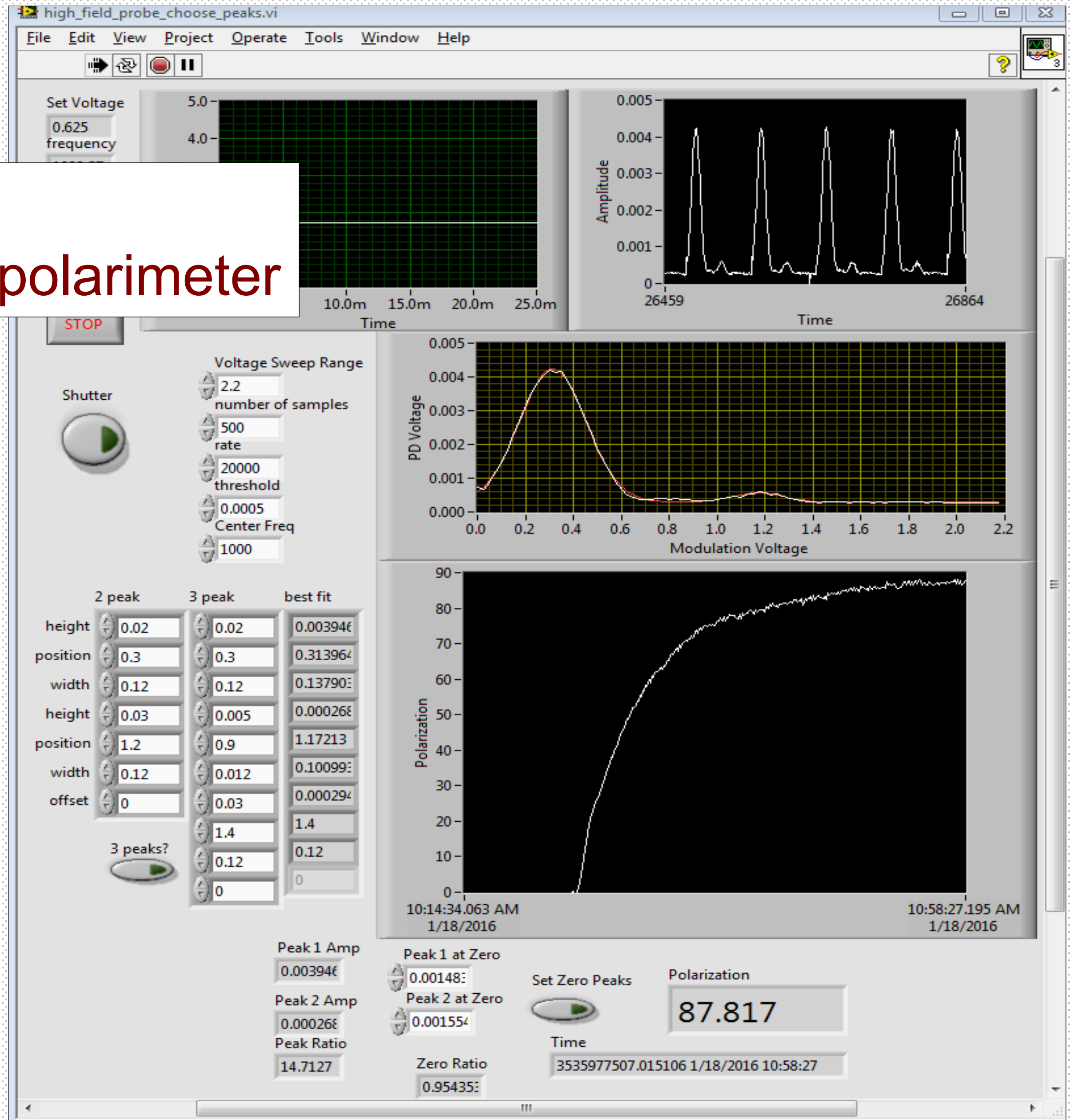


RF-discharge parameters strongly affect maximum polarization.

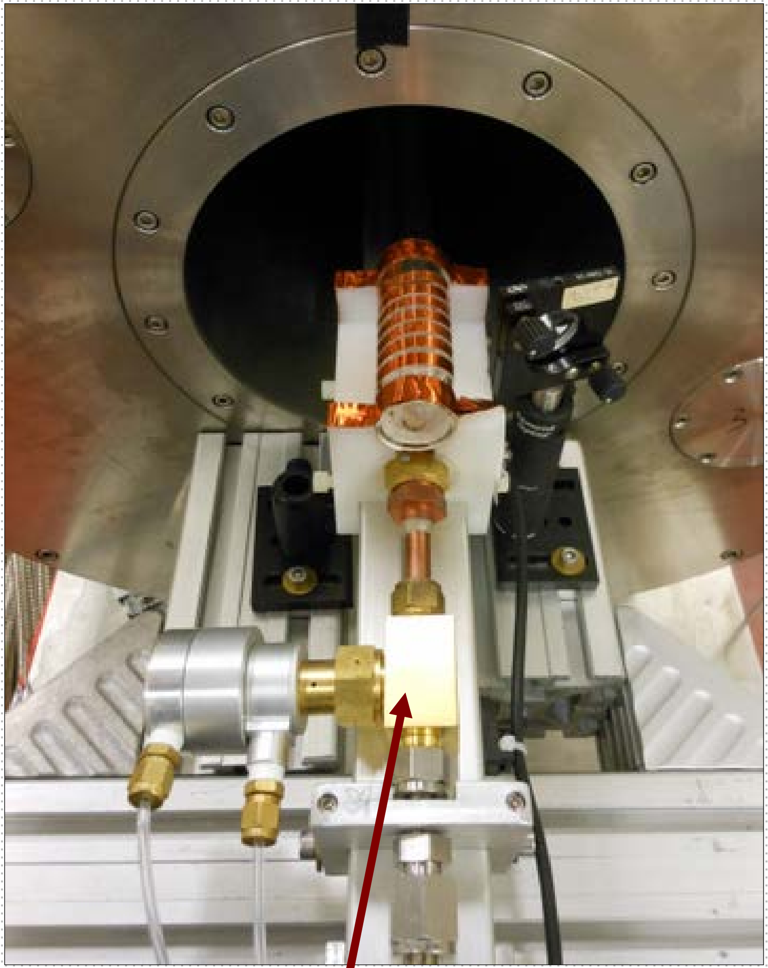
Optimization of the 3He -cell geometry (smaller diameter?) and electrodes for RF input should improve polarization.

Jan18,2016, Sealed cell, OD-30 mm-Pol.- 88%, Field-2.0 T

Probe laser
absorption polarimeter

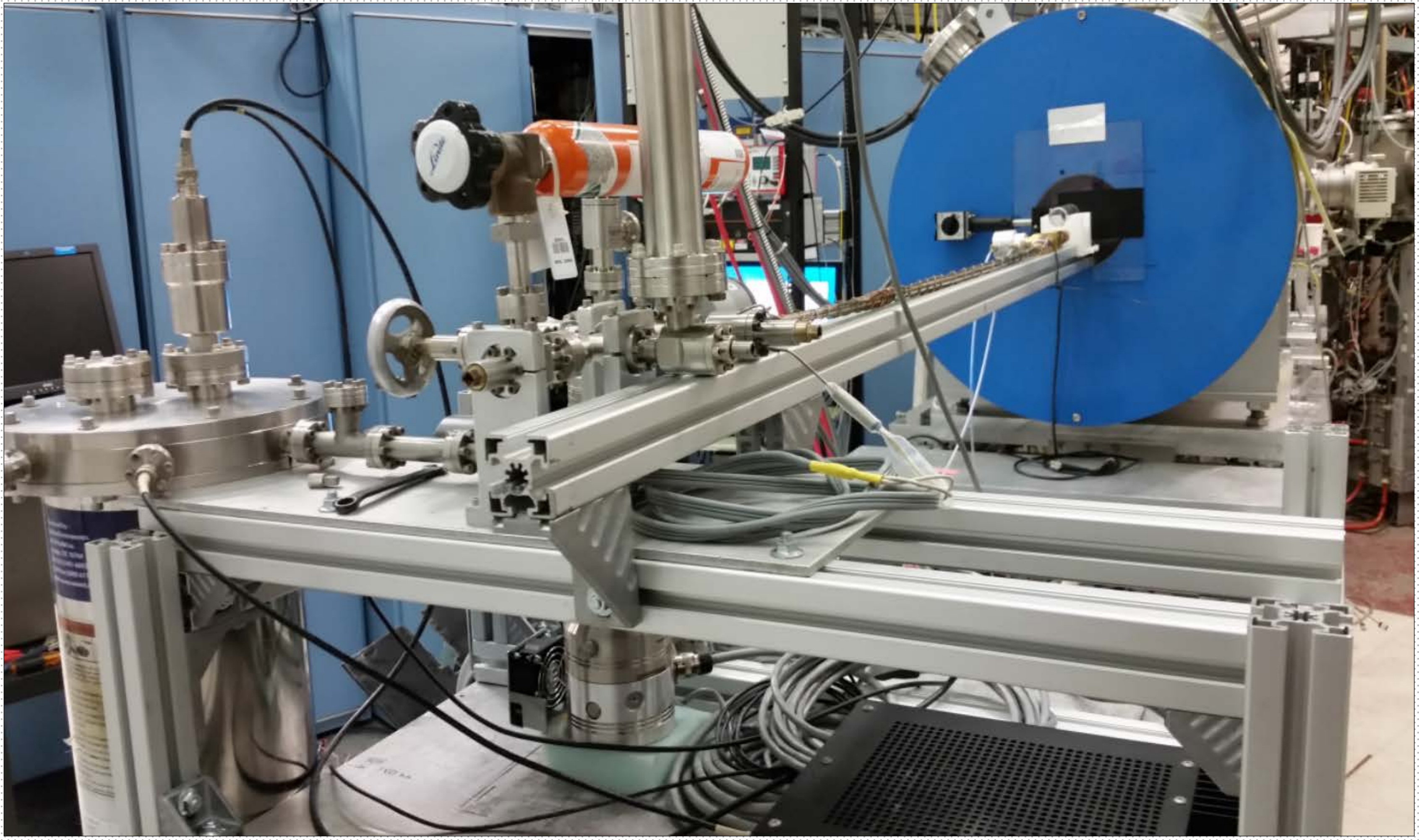


3He-gas purification and filling system



Non-magnetic brass pneumatic remotely controlled Isolation Valve

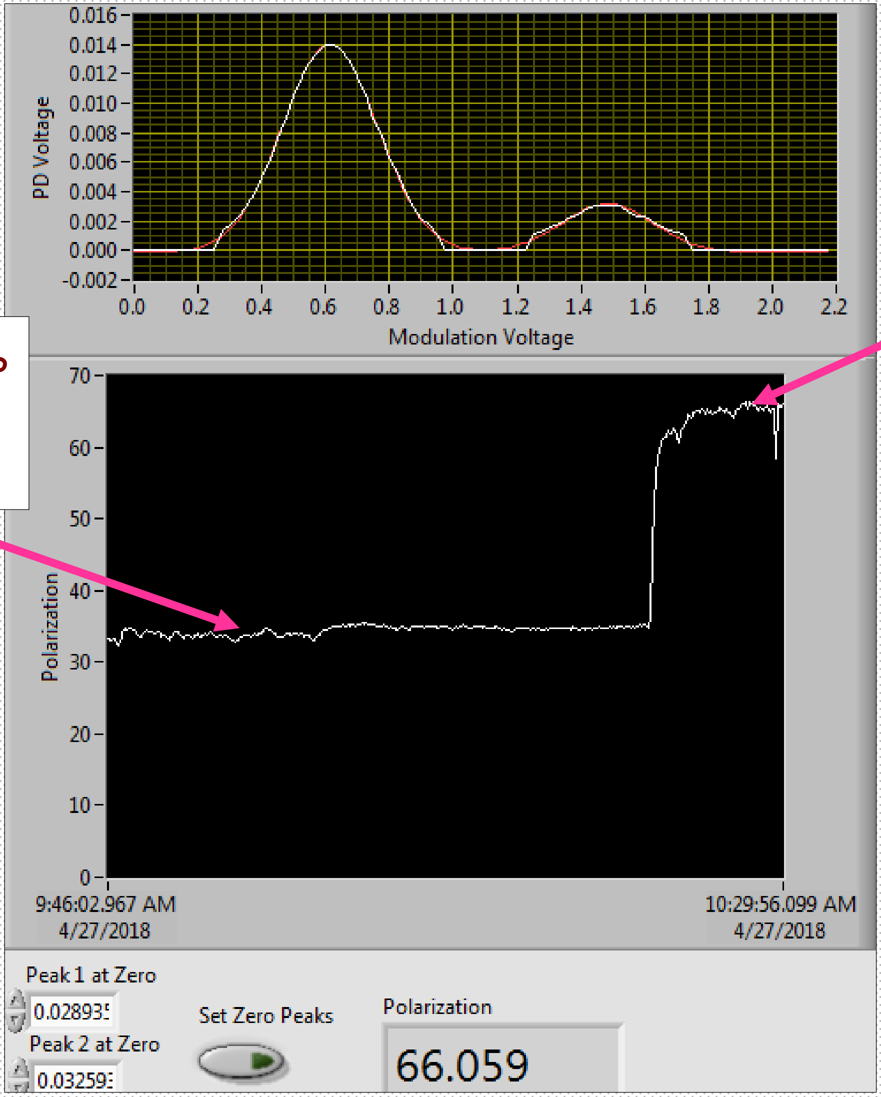
3He polarization setup using OPPIS 3.0 T solenoid
Septemer, 2017



Optical pumping of 3He in the "open cell" geometry

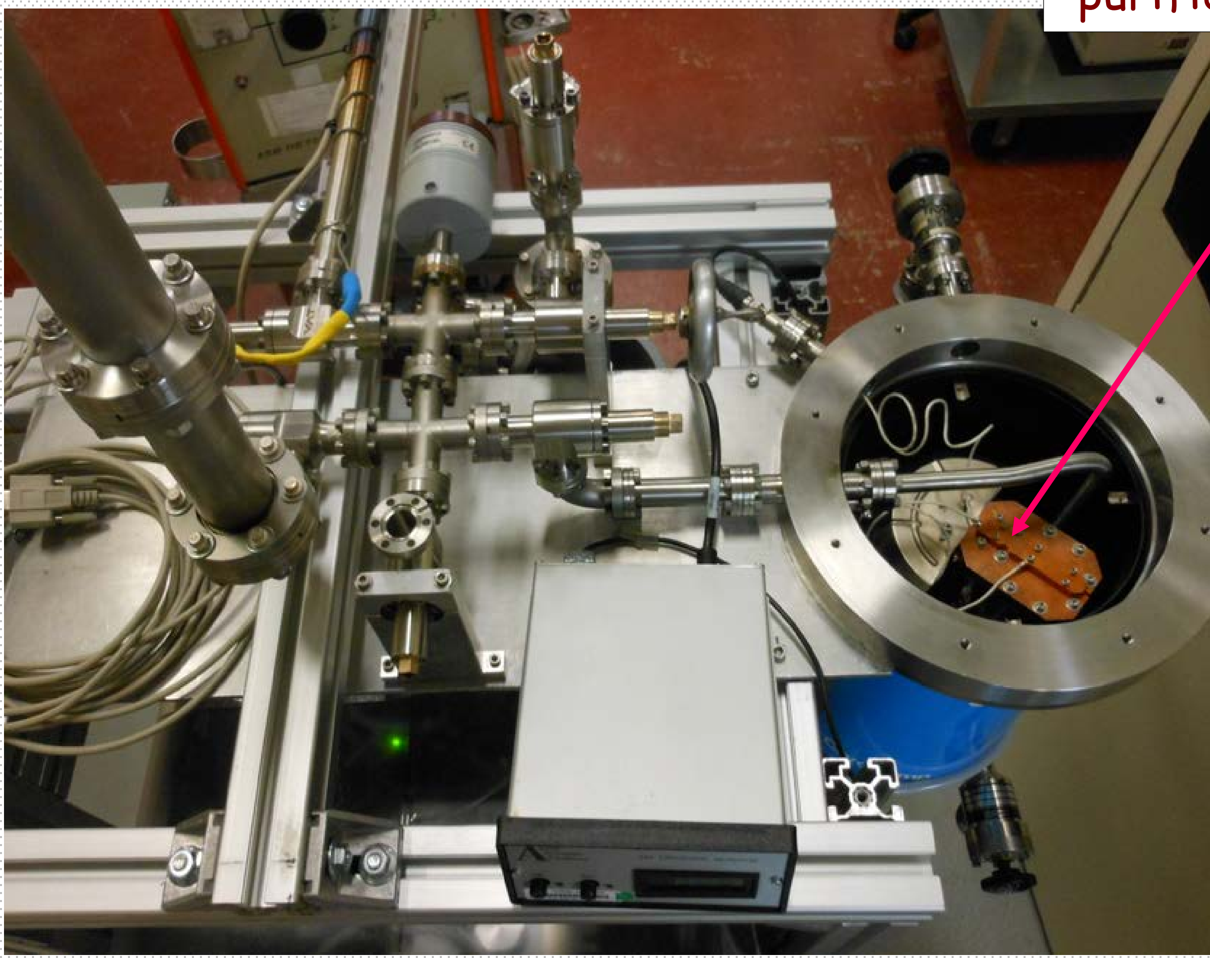
Polarization -66%
With closed
Isolation valve

Polarization -34%
With open
Isolation valve

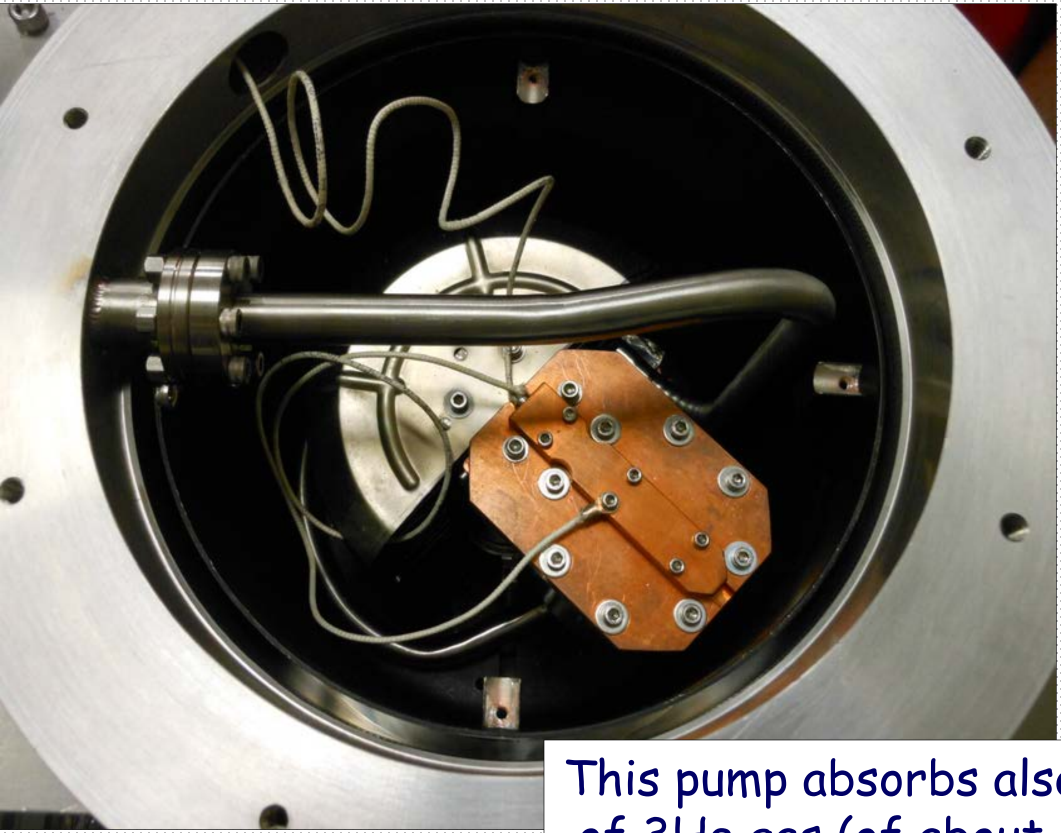


3He-gas purification and filling system

Modified Cryo-pump for 3He purification and storage



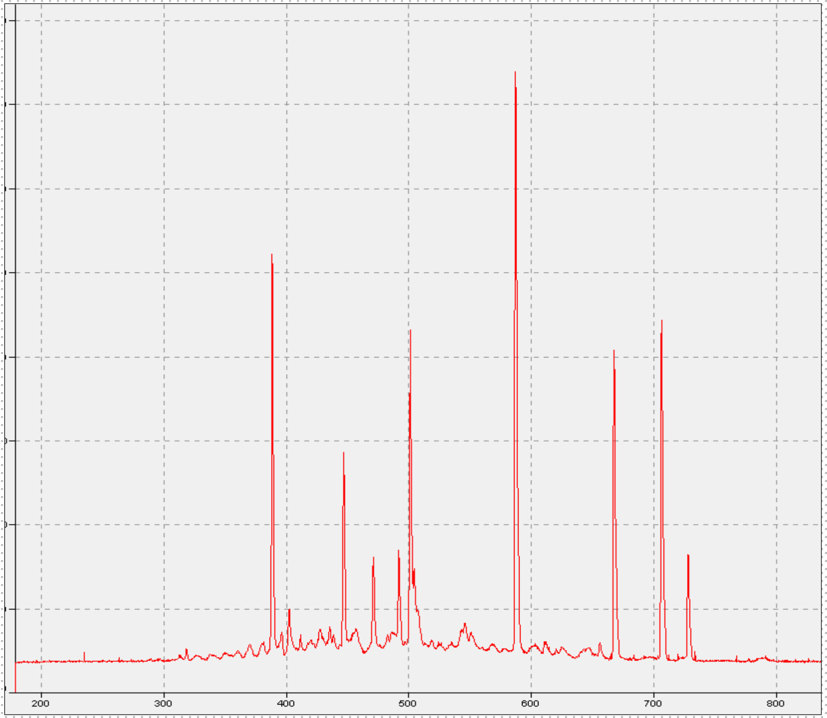
3He cryo- purification system built-in CTI-8 cryo-pump. This pump is pumping all gases except for helium to the level below 10^{-7} torr



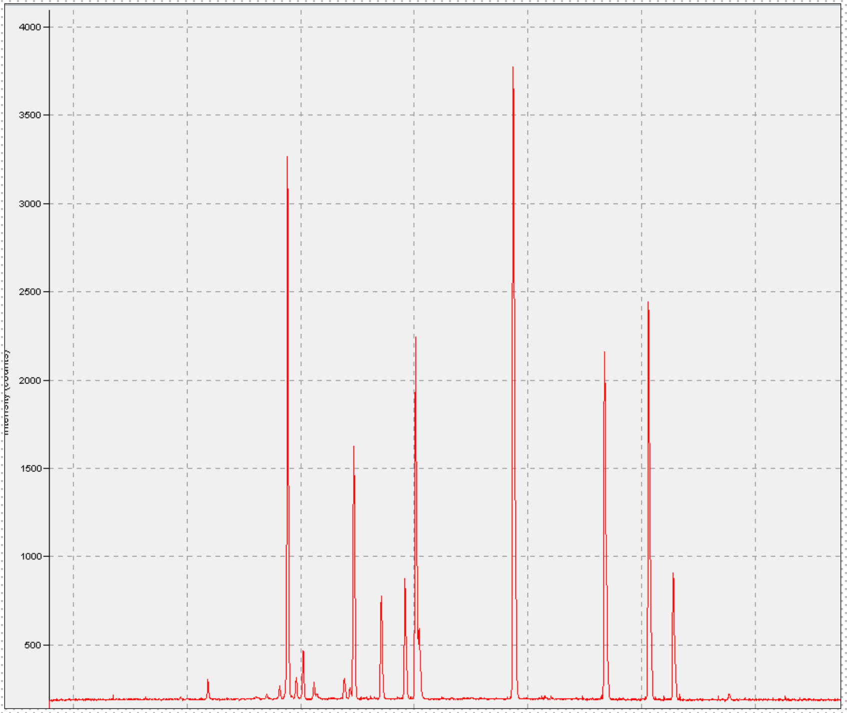
This pump absorbs also quite a significant amount of 3He gas (of about 100 sccm).
The absorbed gas is released by the pump vessel heating.
This provides gas storage and supply for 3He-cell operation at the optimal pressure value.

Discharge cleaning by RF discharge.

Impurities in 3He gas from the cell walls out-gassing



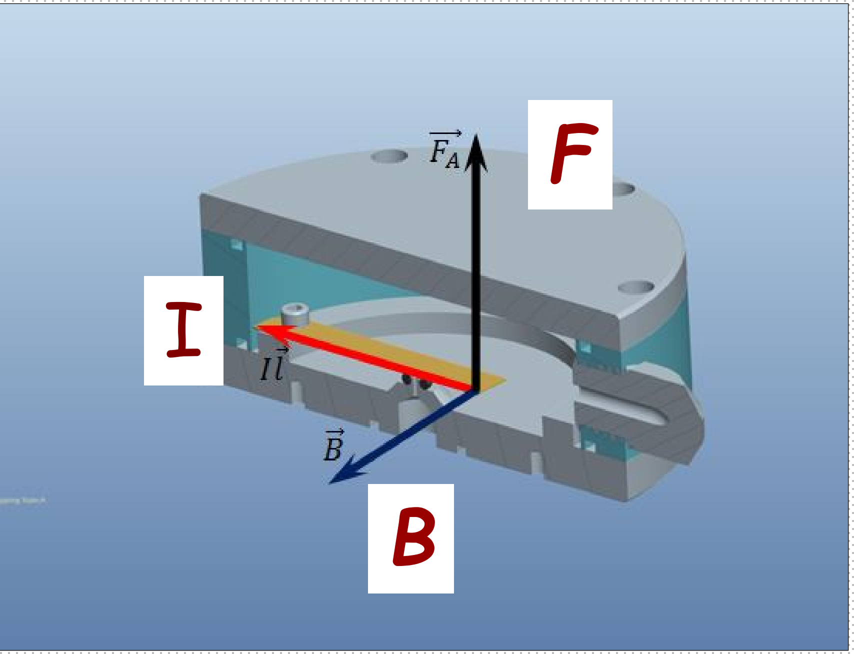
After 20 hrs Rf –discharge cleaning



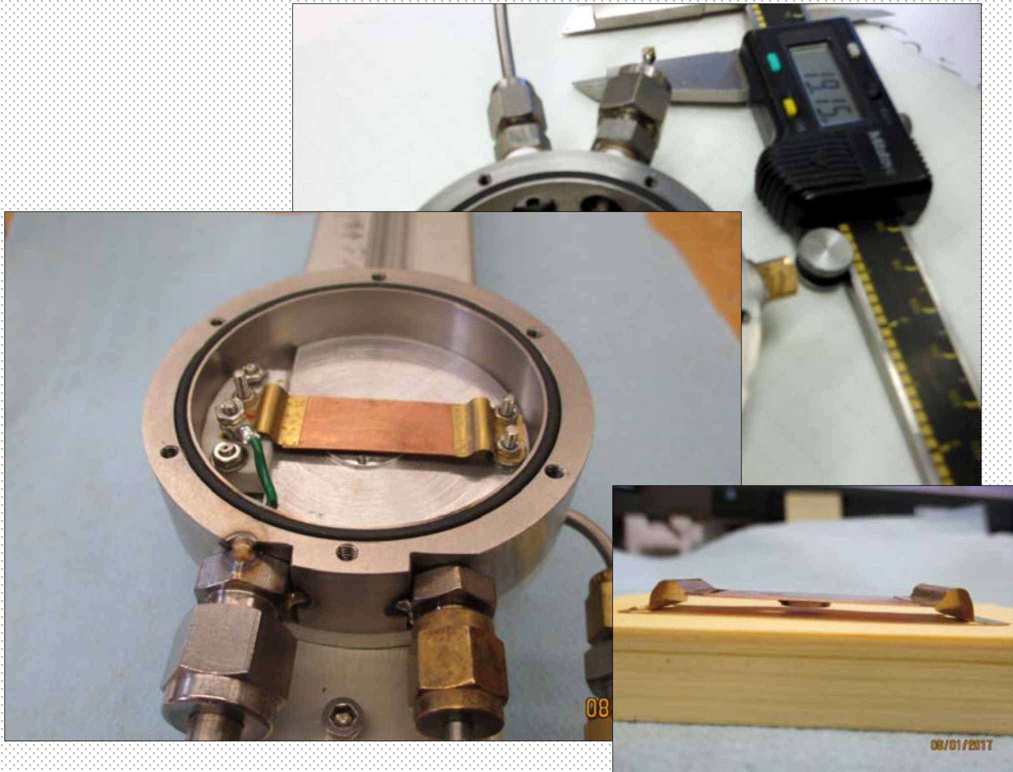
3He optical spectra

"Electro-dynamic" valve operation principle.

Lorentz (Laplace) force to the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=100 A, L=5 cm, F=15 N. Current pulse duration ~100 us

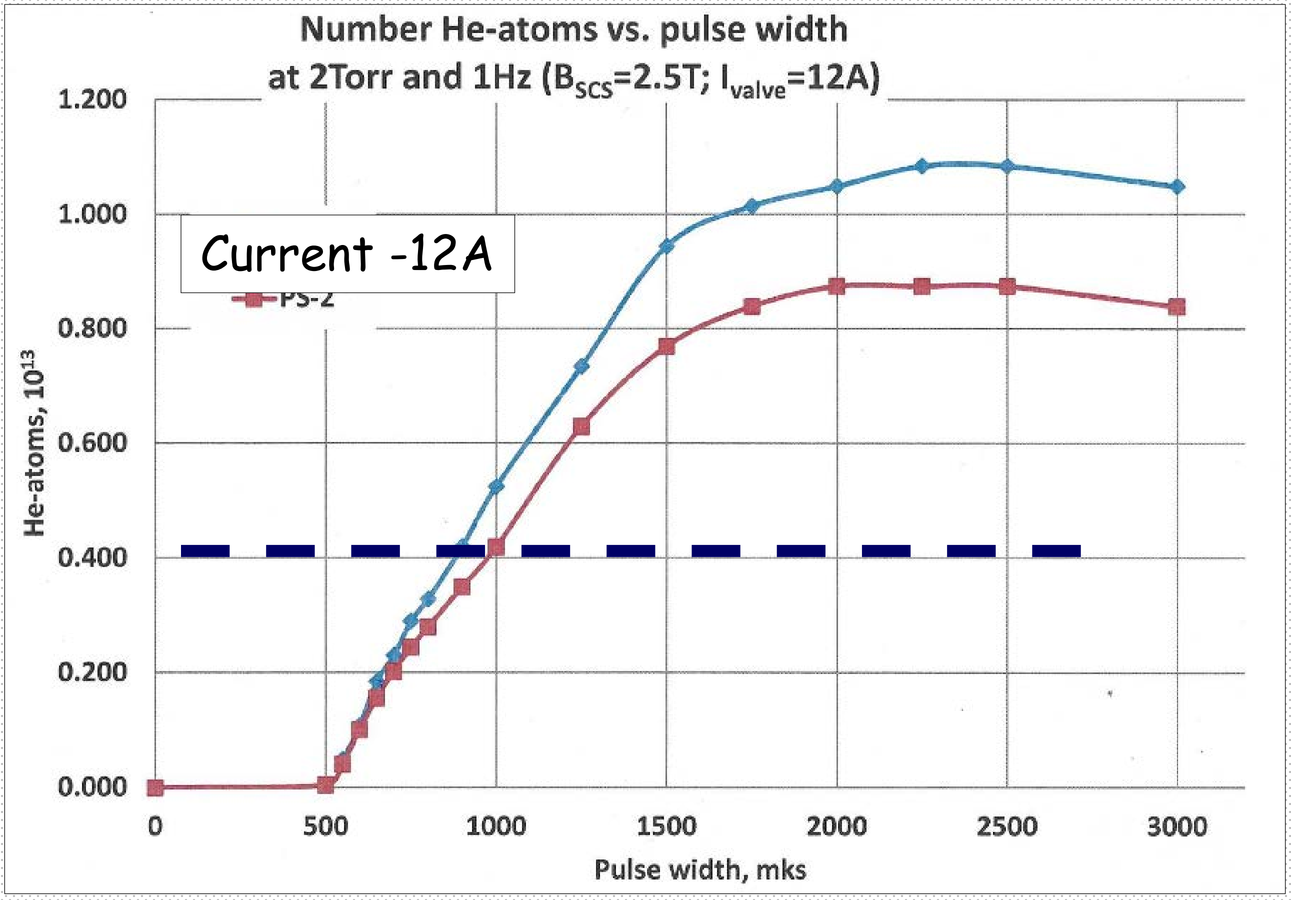


$$d\vec{F_A} = I\,[d\vec{l}\,\vec{B}]$$



Pulsed 3He valve operation in 2.0T solenoid.
He-flow vs. pulsed current width

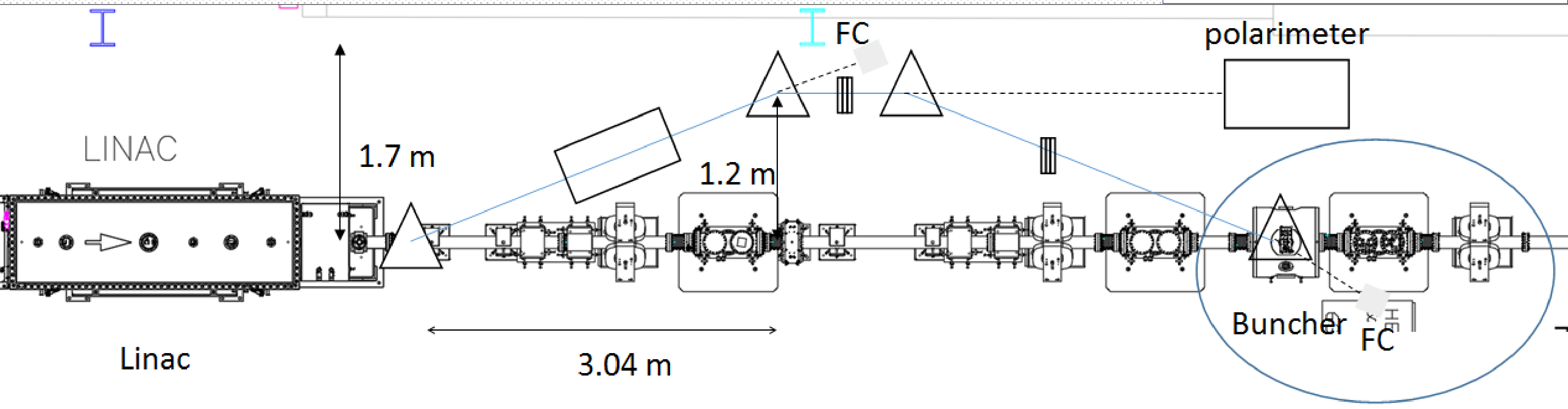
$4*10^{11}$ Atoms per/pulse



Pulsed current width (us)

3He^{++} spin rotator and polarimeter in the EBIS HEBT line at 6.0 MeV beam energy

3He-4He-scattering



The development of the 3He polarizing apparatuses, the spin-rotator, and the nuclear polarimeter at the 3He++ ion beam energy 6.0 MeV (in the high-energy beam transport line after the EBIS drift-tube Linac) is funded by the DOE Research and Development Funds for the Next Generation Nuclear Physics Accelerators Facilities.

Summary

- The RHIC high intensity polarized H^- source provides required beam intensity for present RHIC and future high-luminosity eRHIC collider operation.

- The polarized $^3He^{++}$ ion source (on the basis of extended EBIS) is under development at BNL for future eRHIC collider.