The RHIC Optically Pumped Polarized H^- Ion Source

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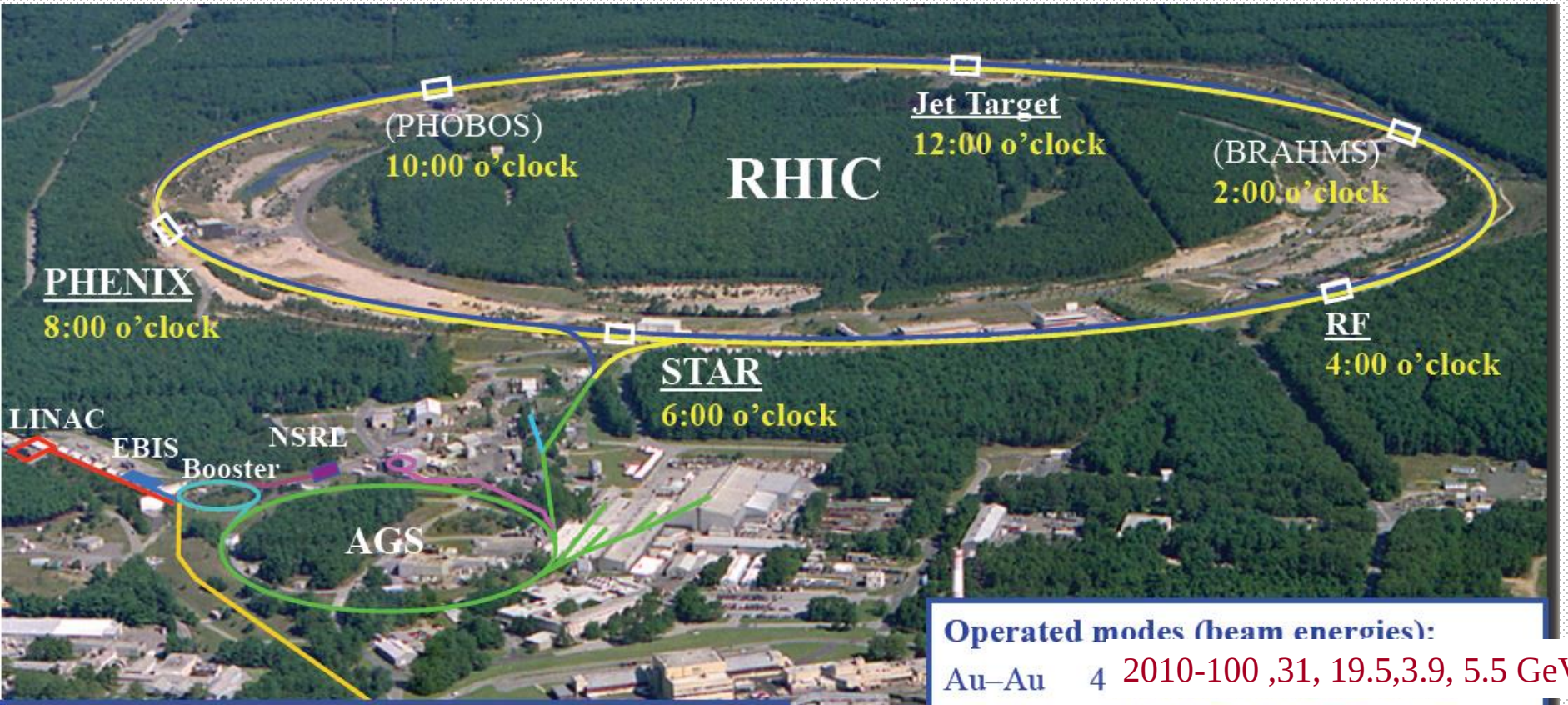
- Optical pumping polarization technique
- Charge-exchange spin-transfer collisions
- High-brightness atomic beam source
- High-intensity polarized H^- ion source at RHIC
- Polarized 3He++ source development at RHIC
- Summary

ICIS 2017 GENEVA
17th International Conference on Ion Sources
October 15-20 2017
CERN - CICG - Geneva

October 18

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):

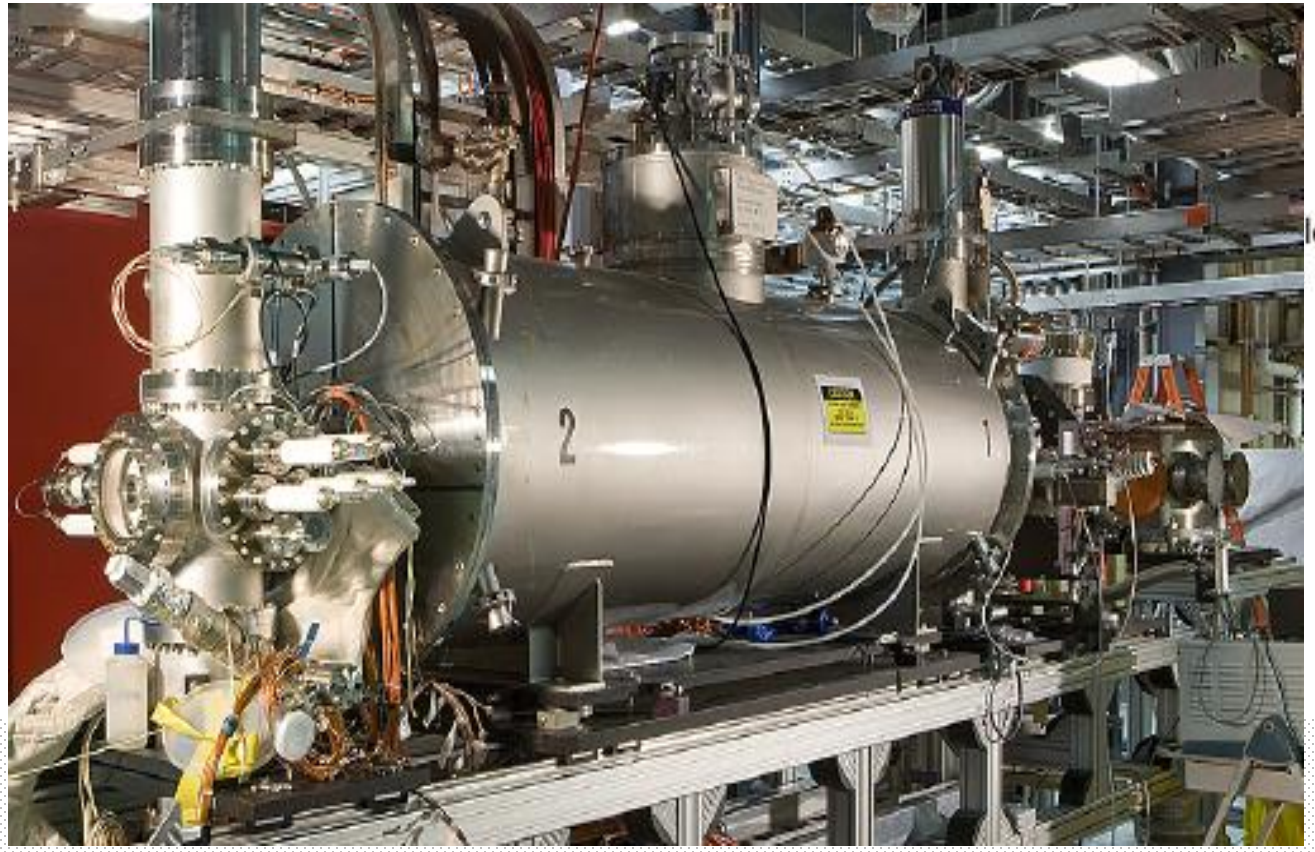
Au–Au	4 2010-100 ,31, 19.5,3.9, 5.5 GeV
d–Au*	100 GeV/n
Cu–Cu	11, 31, 100 GeV/n
p↑–p↑	11, 31, 100, 250 GeV

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) 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

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

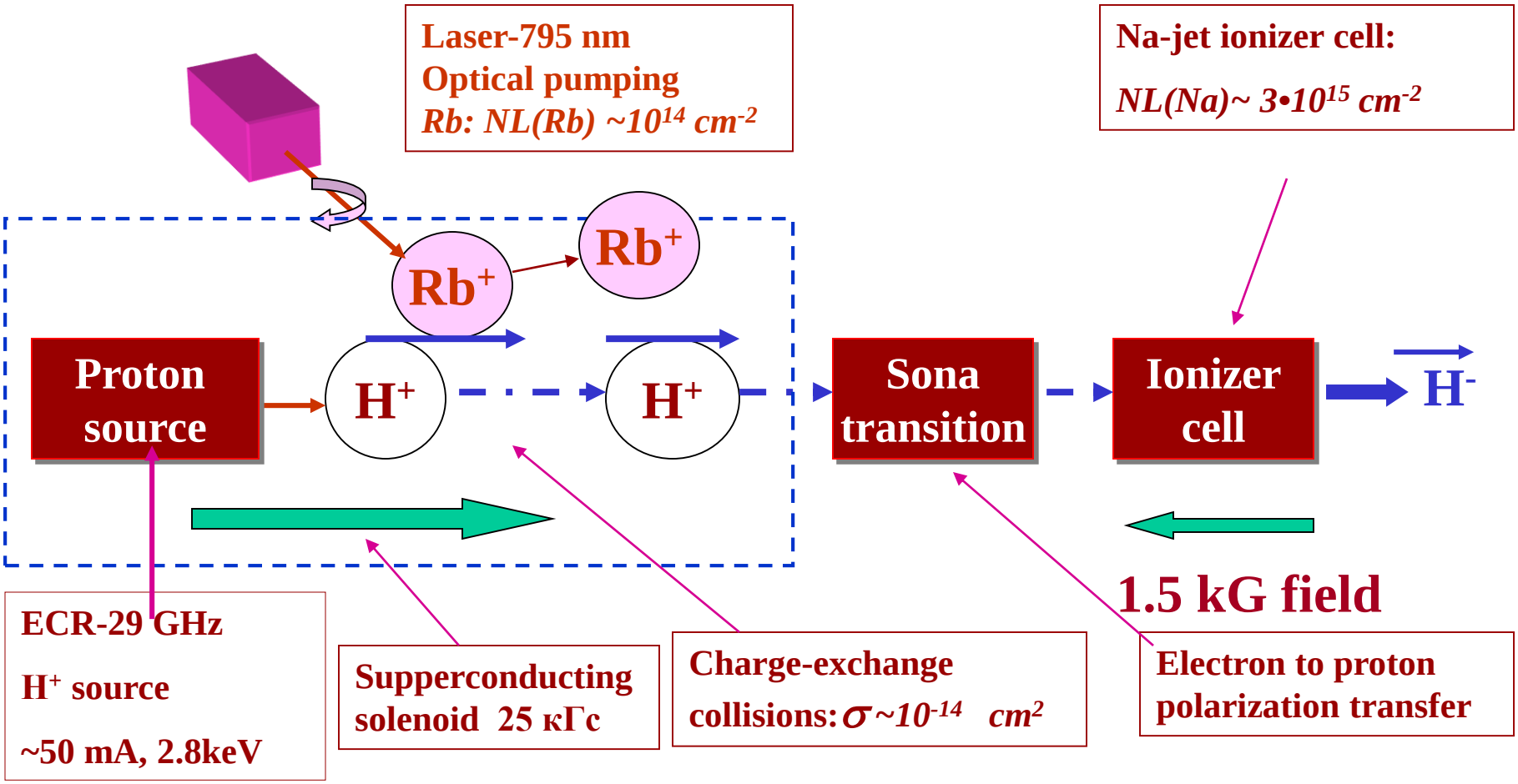
BNL - BINP, Novosibisk, INR, Moscow- collaboration

High intensity polarized H^- ion source and "Siberian Snakes" made possible the high luminosity RHIC operation with colliding polarized protons beams to study:

- proton spin structure,

- fundamental tests of QCD and electro-weak interaction.

SPIN -TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS

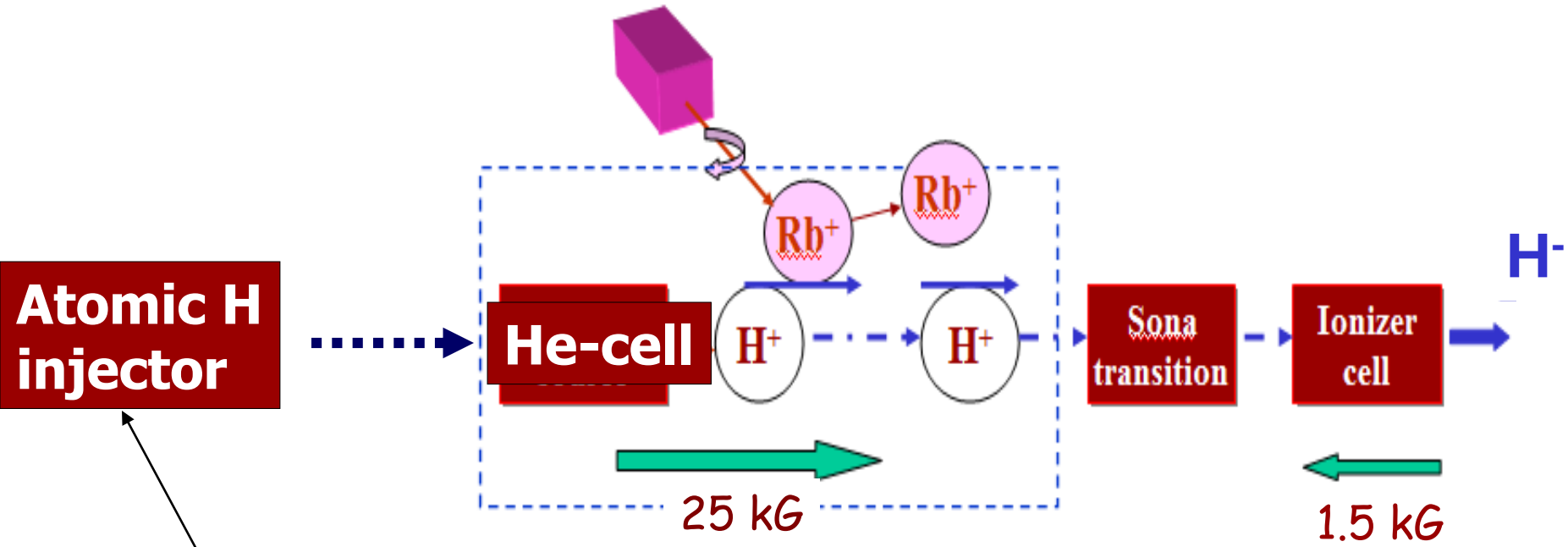


Laser beam is a primary source of angular momentum:

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

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

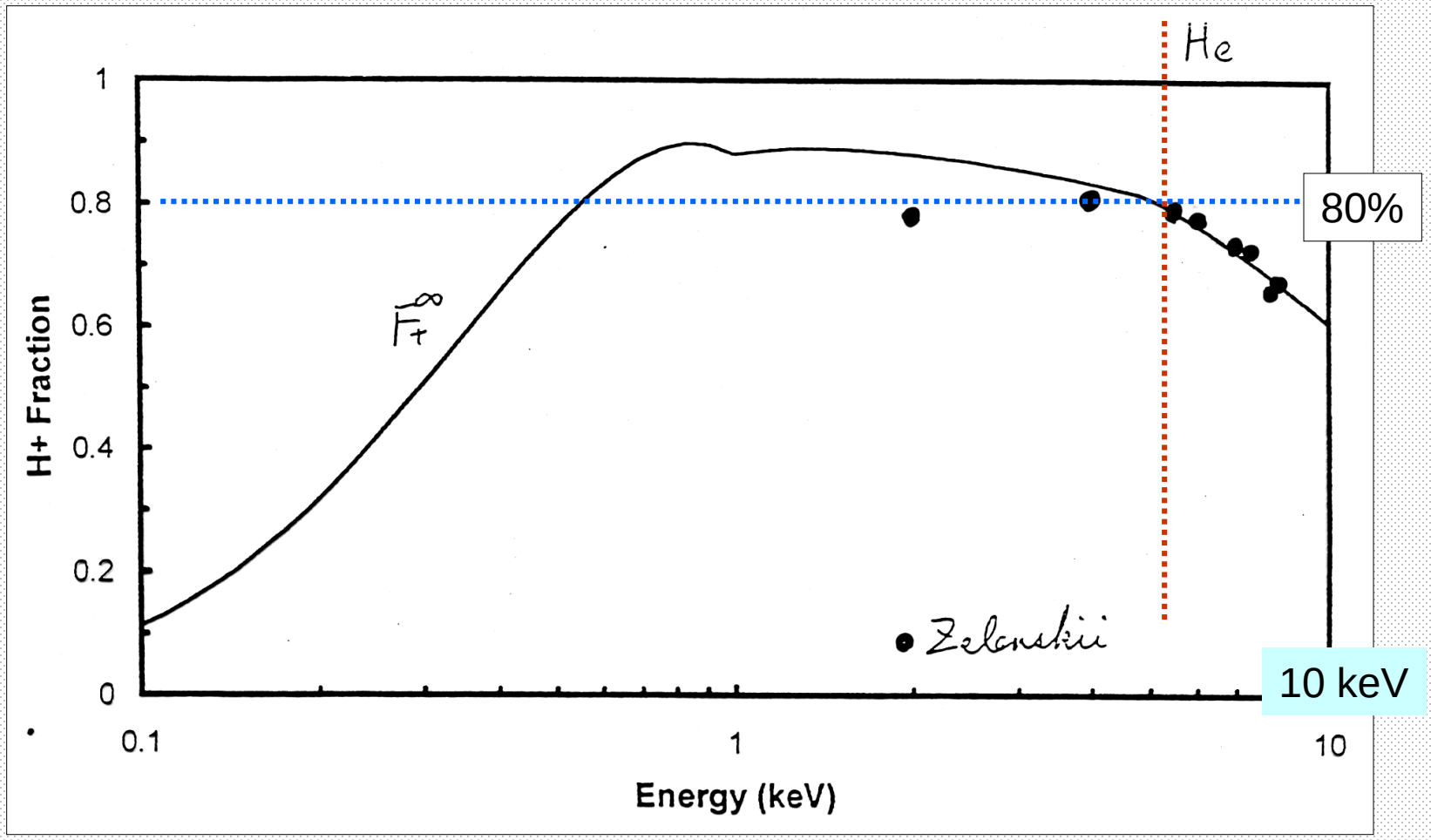
High-brightness proton beam inside strong 2.5 T solenoid field produced by atomic H beam ionization in the He-gas ionizer cell



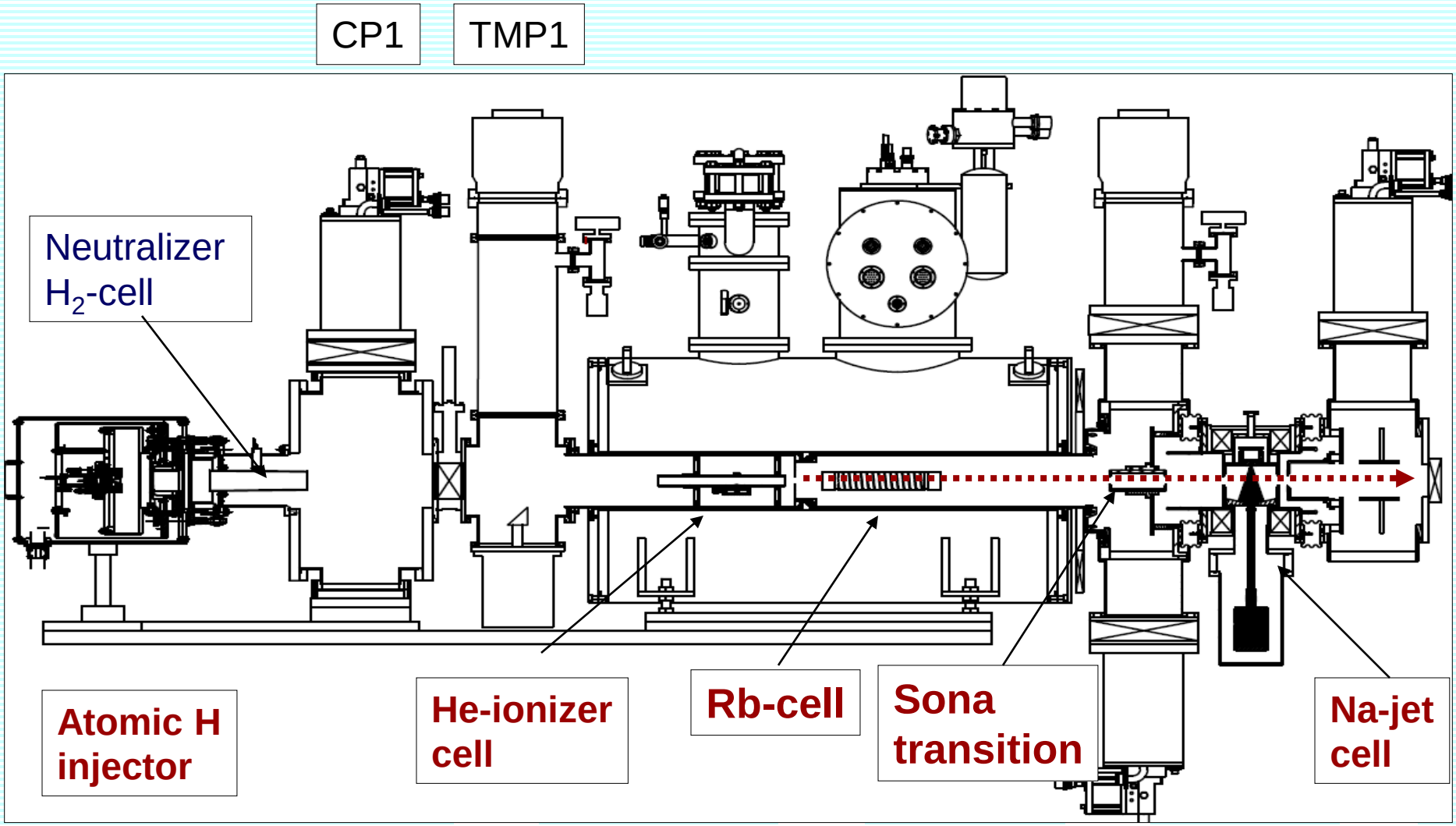
The primary proton beam and Equivalent atomic H intensity current is 2.5 A at 6.5 keV beam energy !

Hydrogen atomic beam ionization efficiency in the He- cell

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

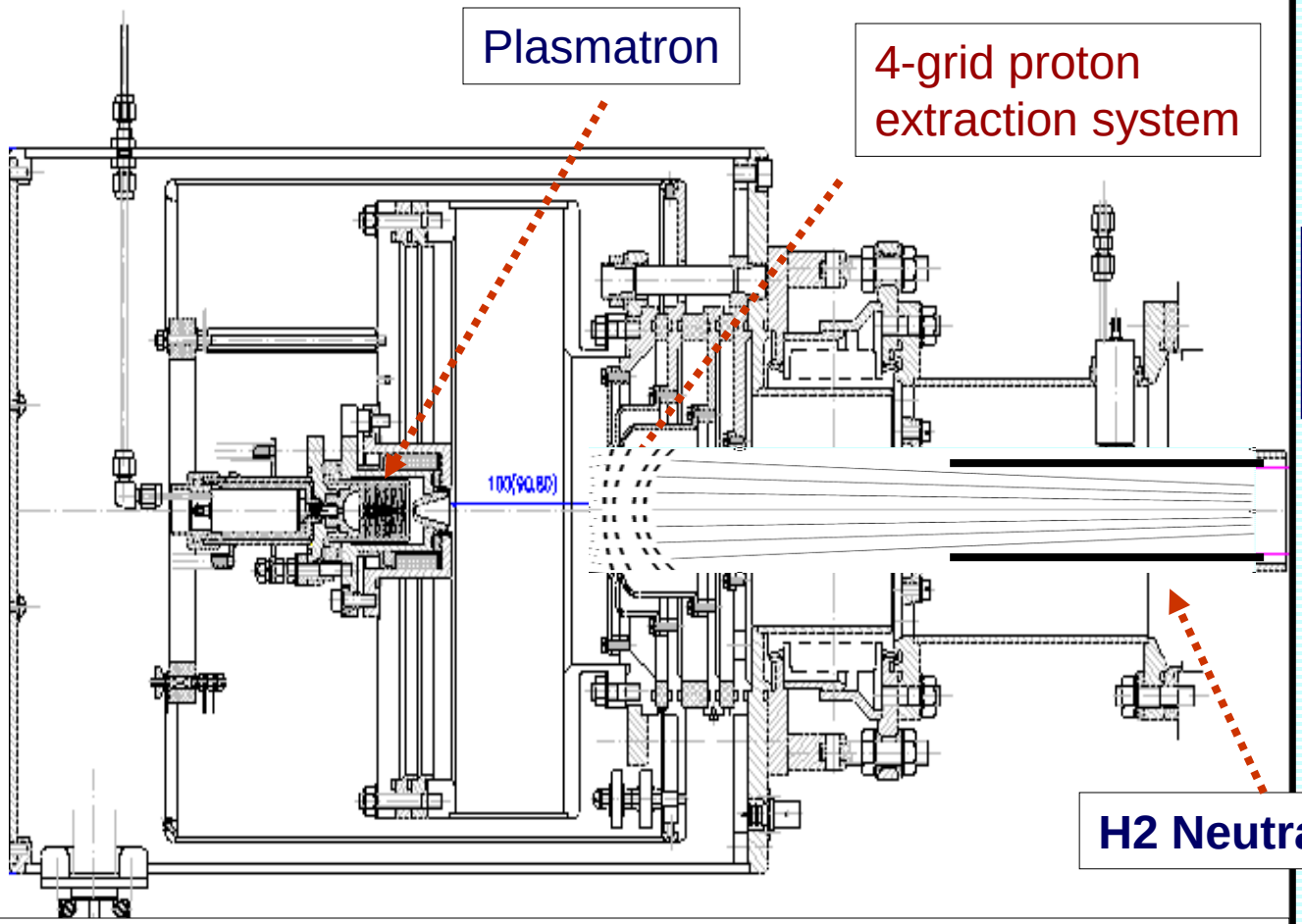


OPPIS with atomic H^0 injector layout, 2013-17



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

"Fast Atomic Beam Source", FABS, BINP, Novosibirsk



~ 2.5 A equivalent H^0 beam

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

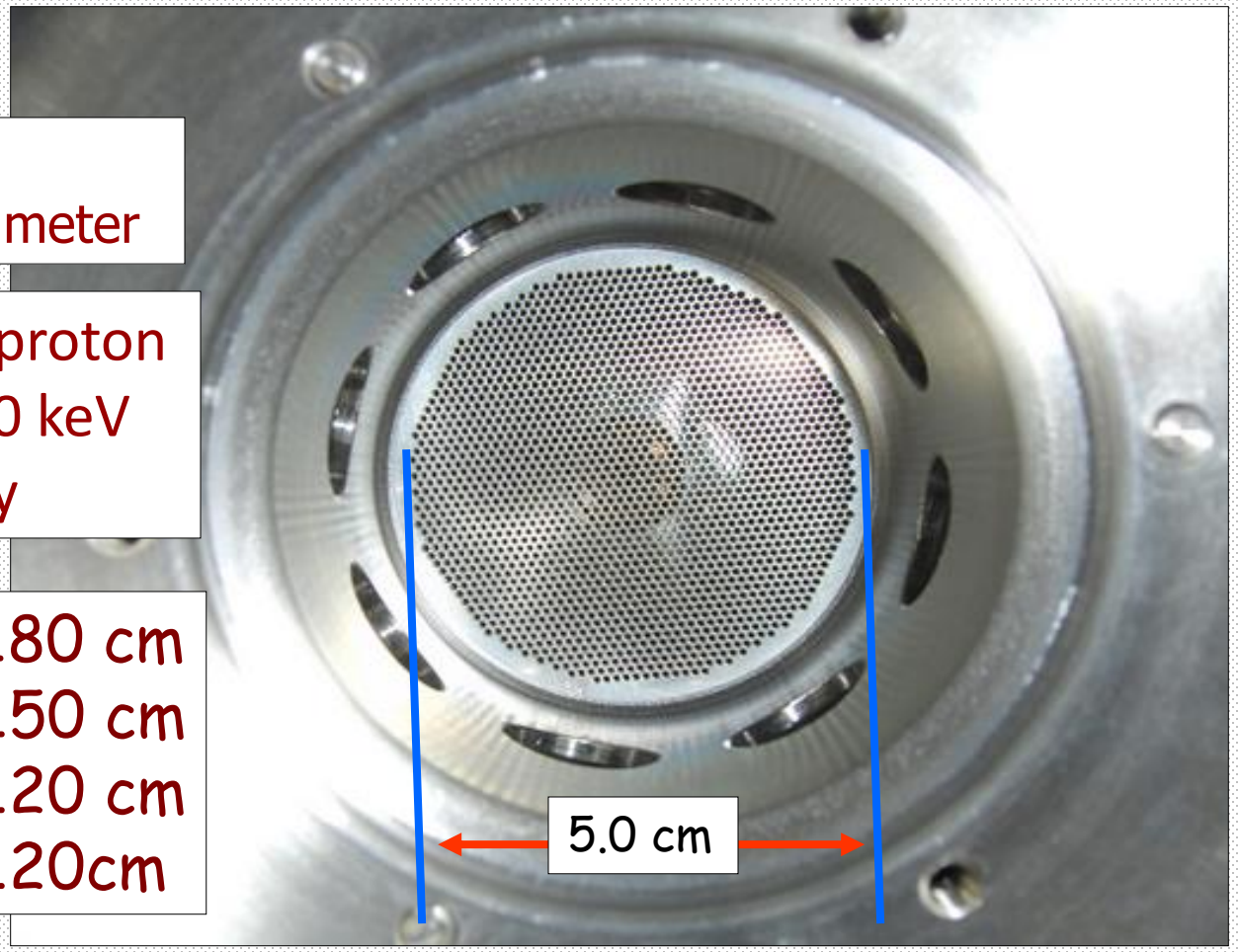
4-grid spherical Ion Optical System

F ~200 cm, δα -10 mrad

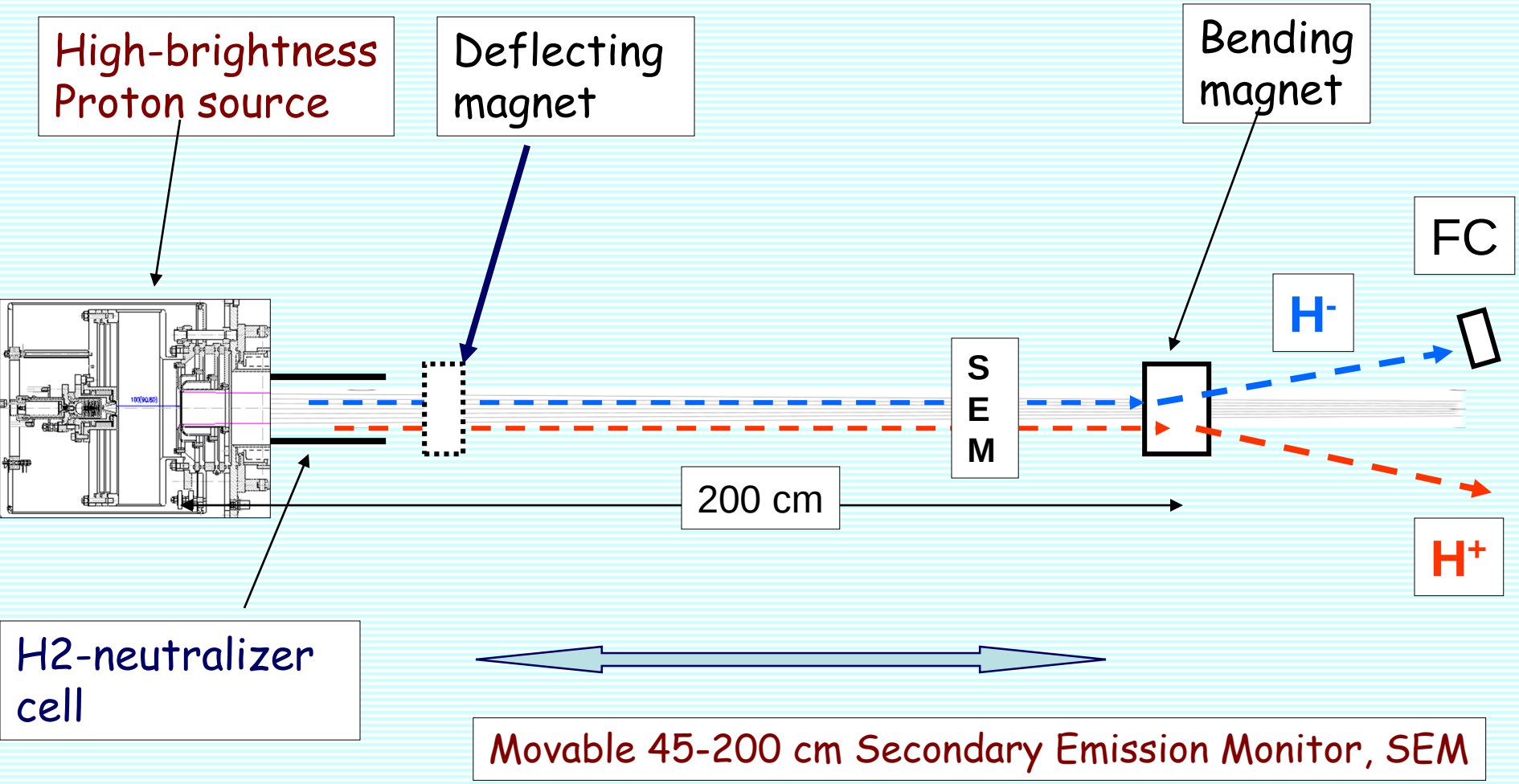
1820 holes ,
1.0 mm in diameter

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



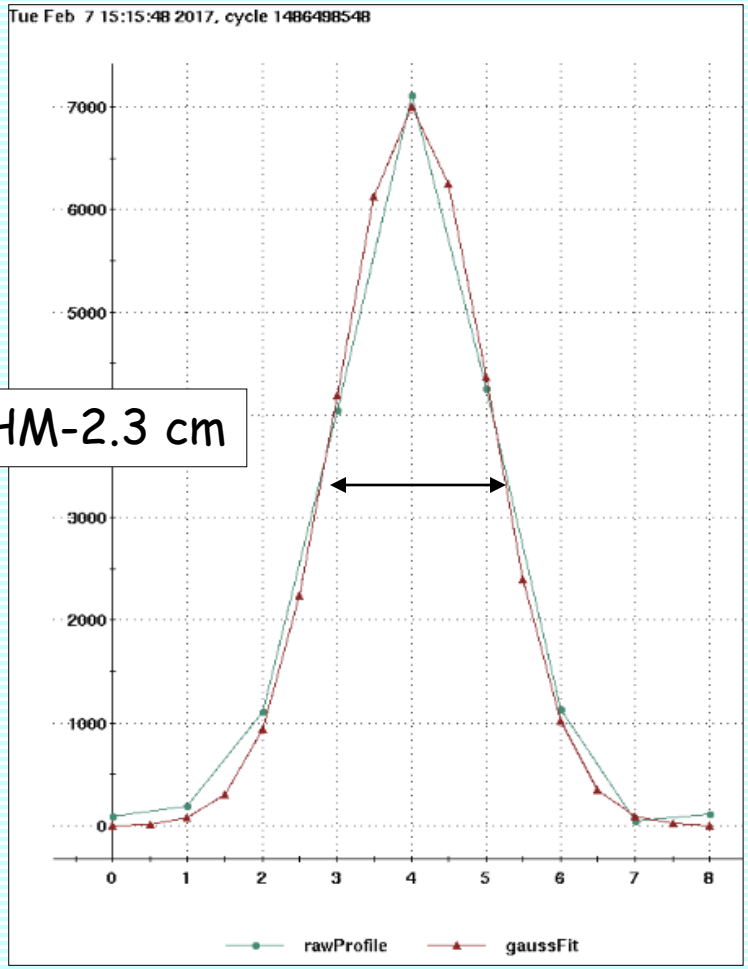
Atomic beam profile measurements



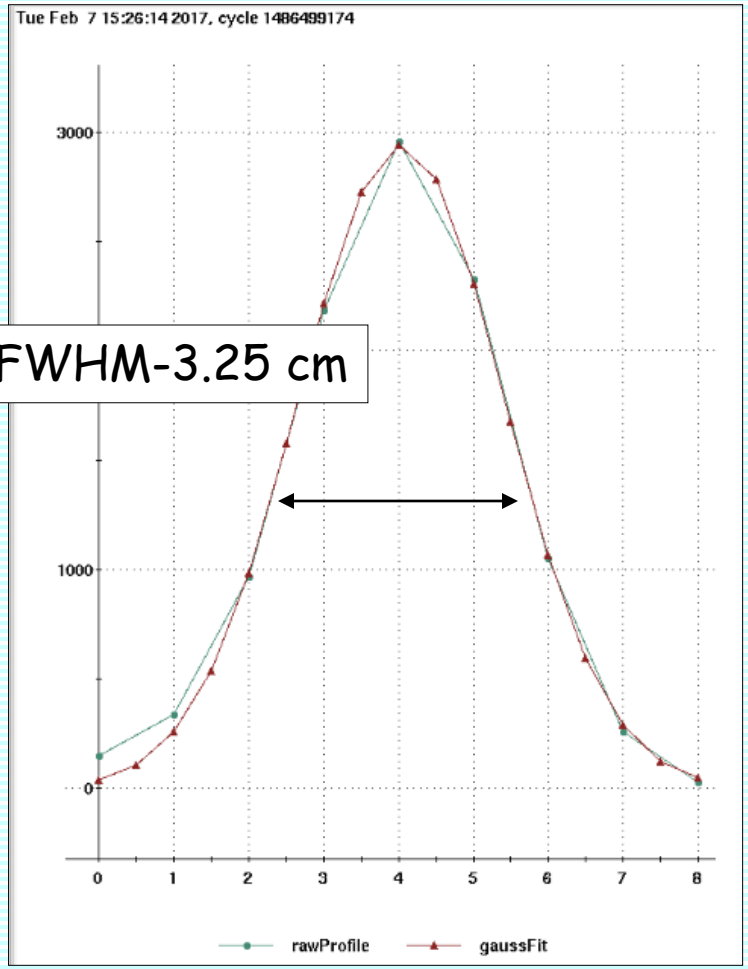
Atomic beam intensity profile vs. distance from the source.

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

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



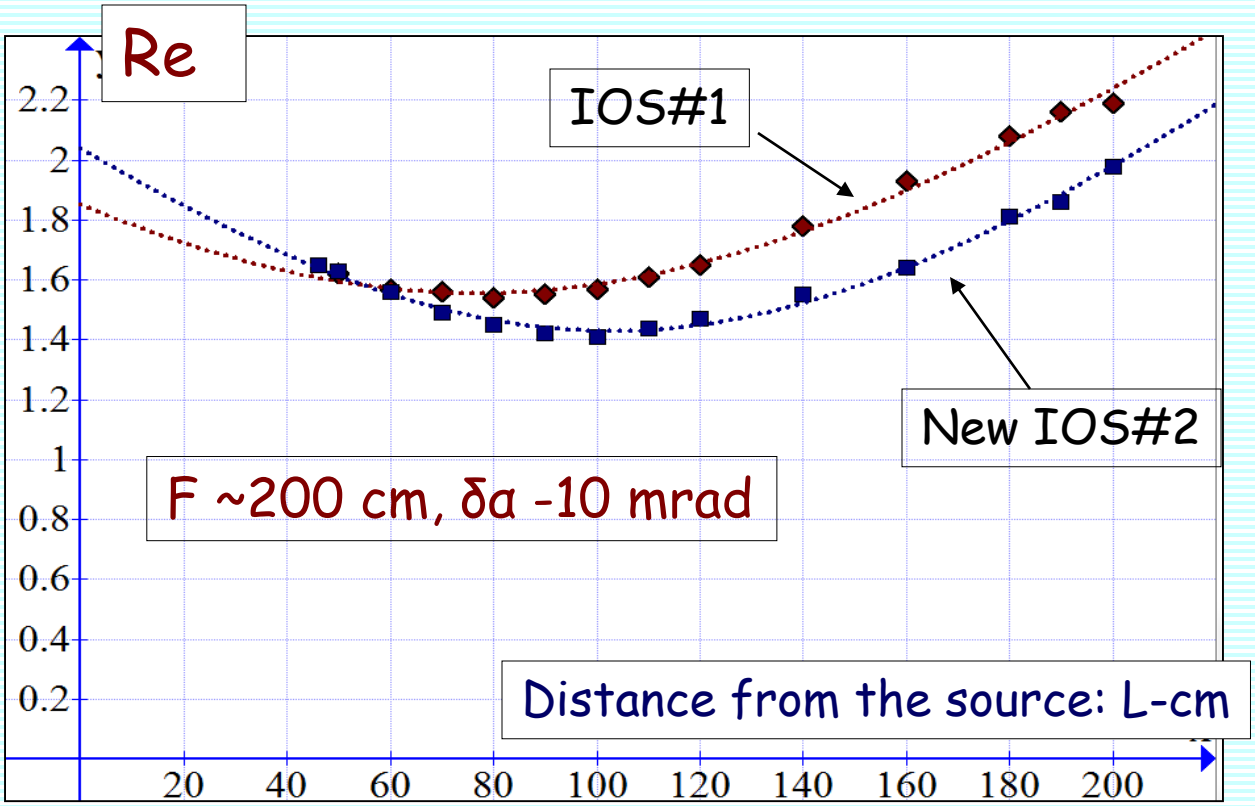
FWHM-2.3 cm



FWHM-3.25 cm

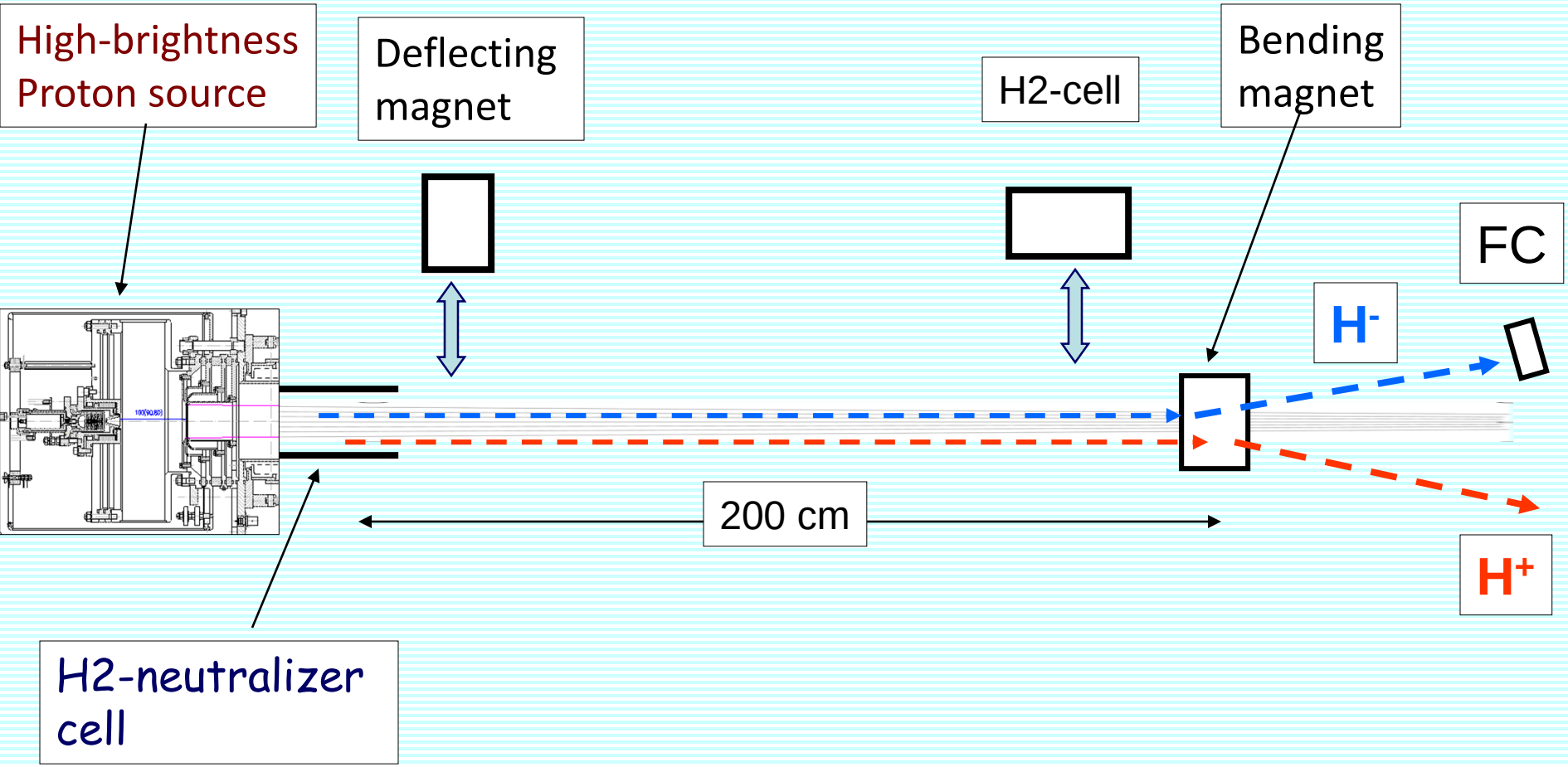
Atomic beam intensity profile vs. distance from the source measured with the movable secondary emission monitor.

Total equivalent H beam intensity 2.5A

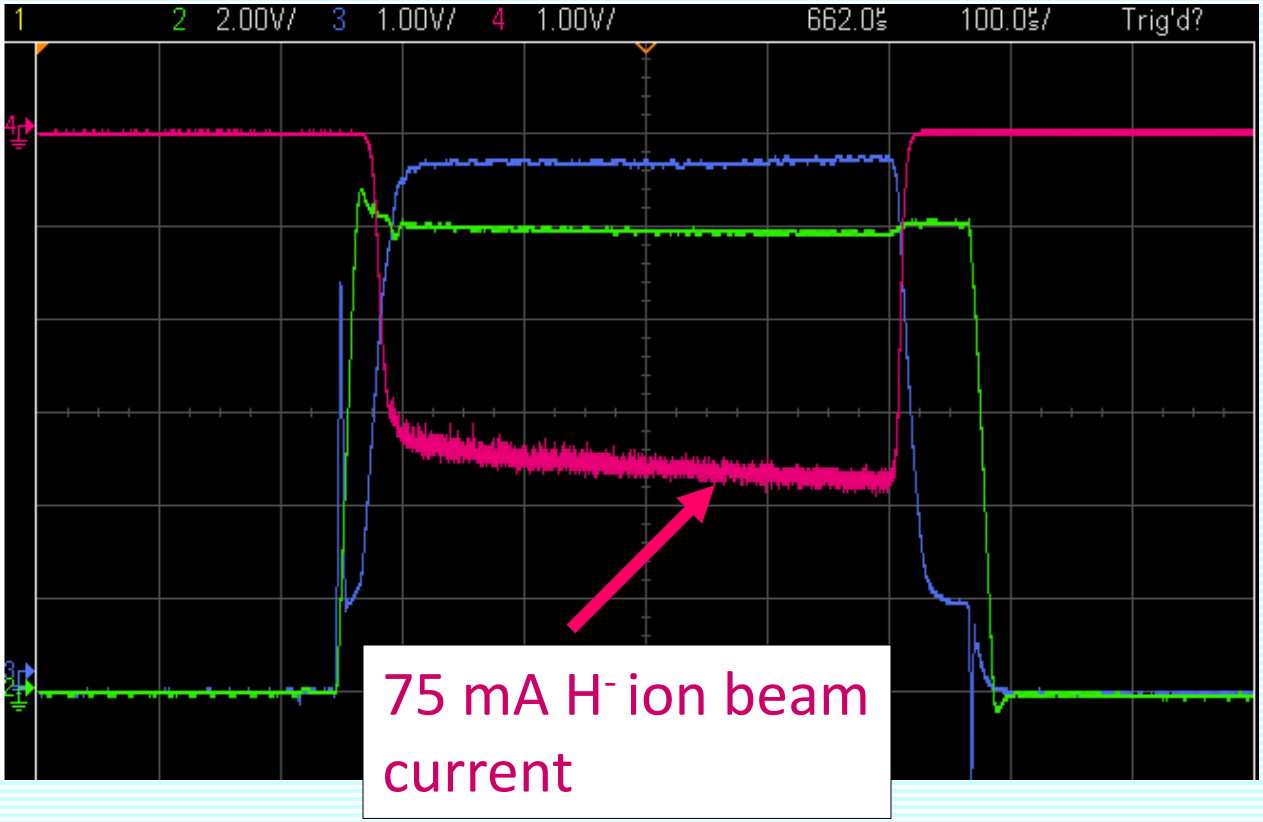


Re- half-width of beam intensity profile at -1/e level.
Beam profile FWHM = 1.67 Re

H^- ion beam production in the H2 neutralizer cell

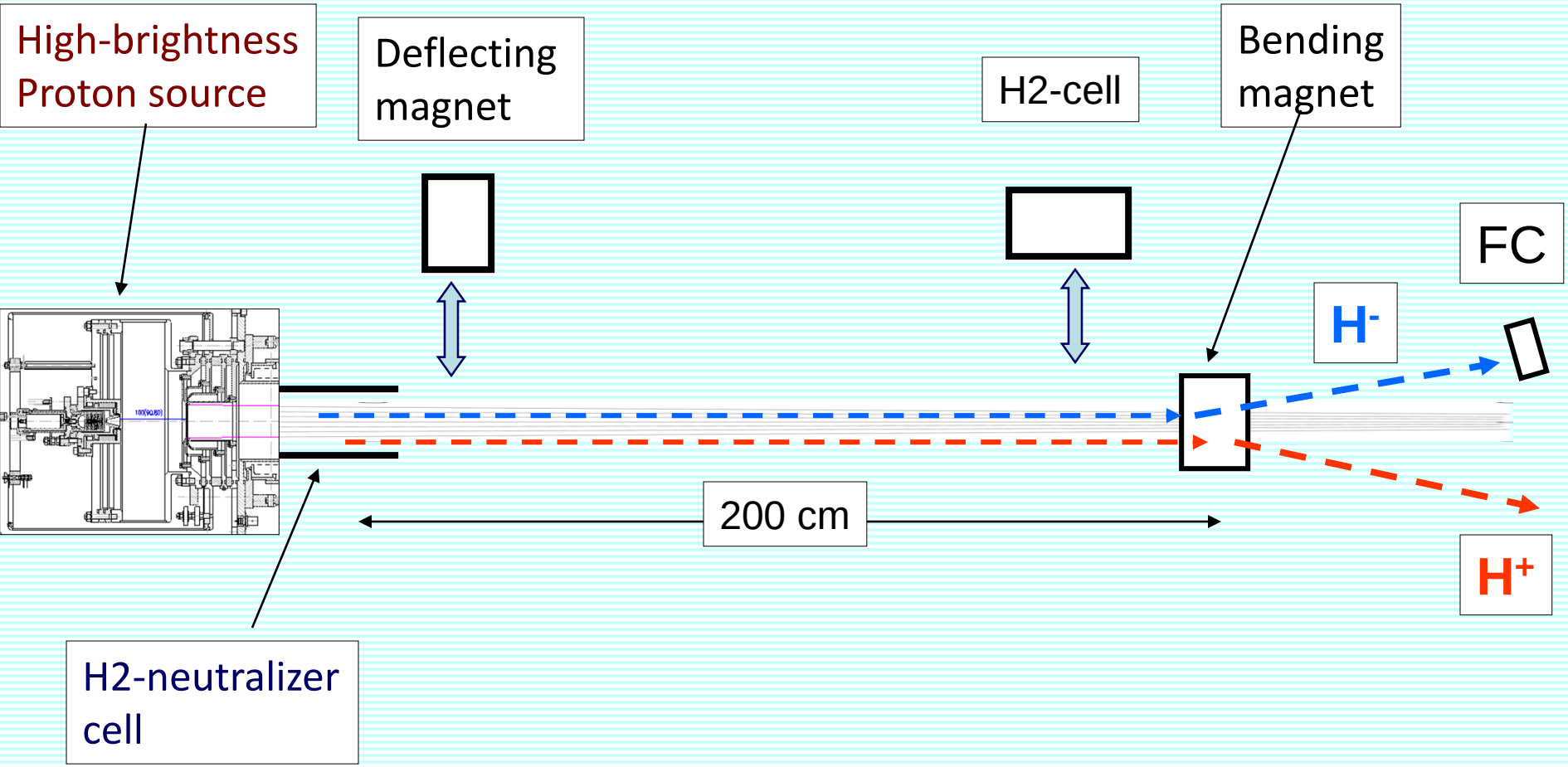


75 mA H^- ion beam current at 10 keV in FC at the distance 200 cm from the source. IOS #3

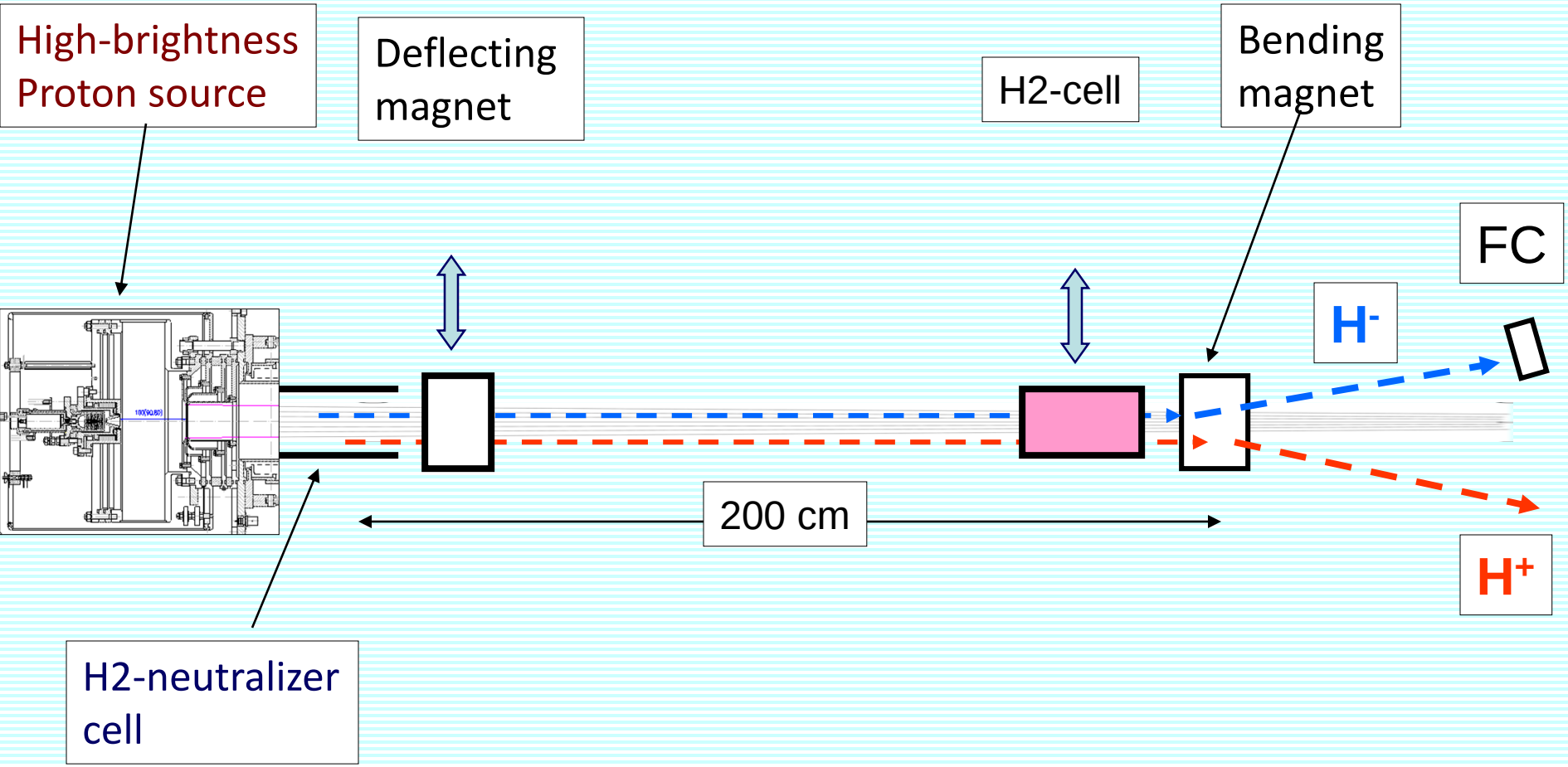


Total proton beam current - 4.7 A. With 2.0% H^- ion beam yield total H^- beam current is 94 mA. Time scale 100 us/div

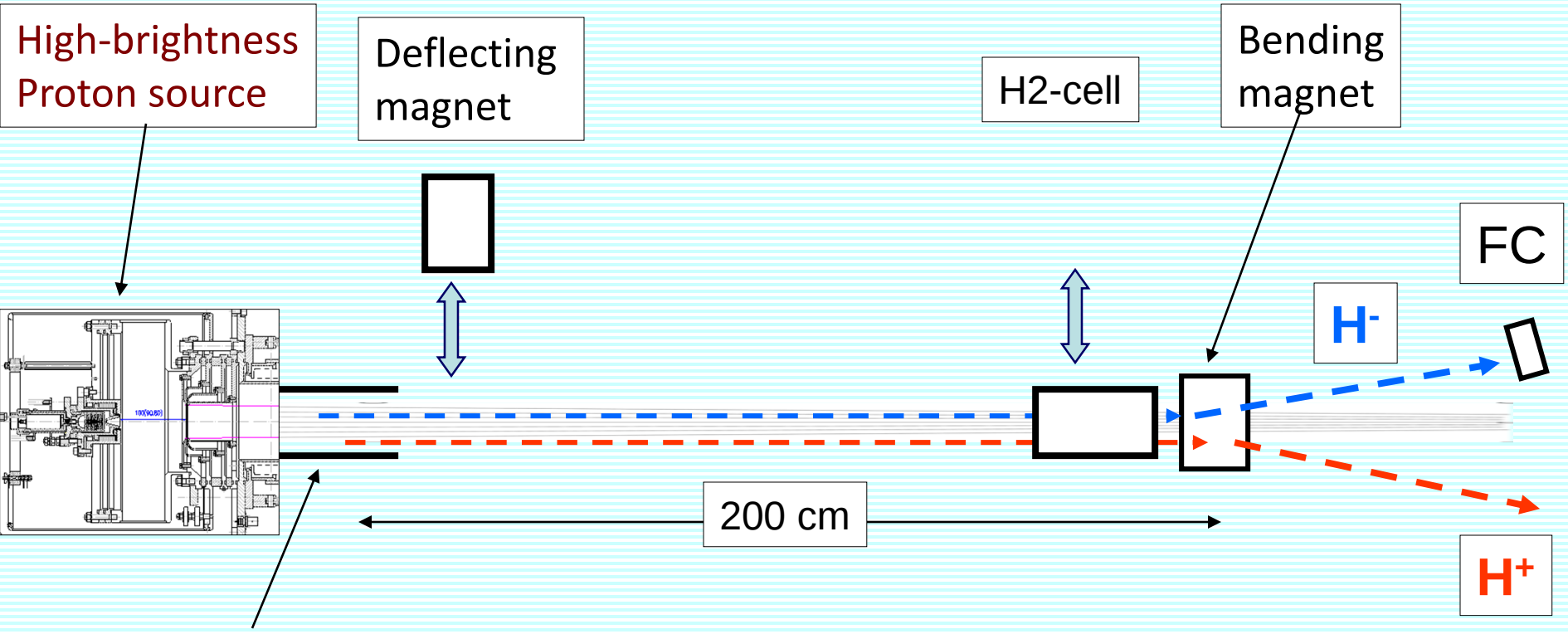
H^- ion beam production in the H2 neutralizer cell



H^- ion beam production in the H2 neutralizer cell



H^- ion beam production in the H2 neutralizer cell



H^- ion beam is transported 2.5 times better than H0 beam due to additional focusing by space-charge of H+ beam!!!

A.Kolmogorov poster, We09

H^- ion beam production in the H2 neutralization cell.

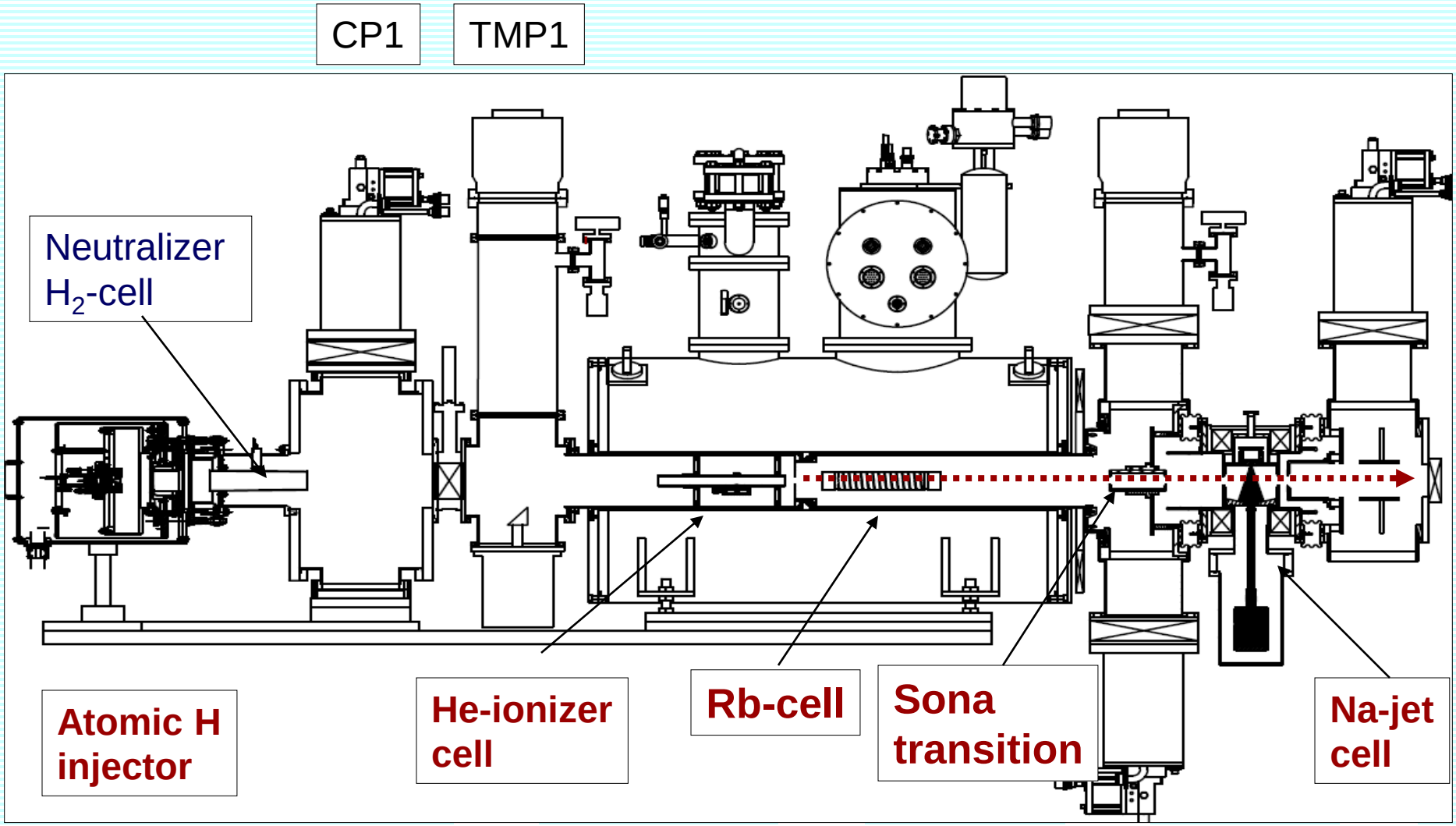
A.Kolmogorov poster, We09

An energy dependence of the H- ion beam yield drops to 1.8% at 20 keV (and 1.4% at 30 keV). The primary proton beam current strongly increases with the beam energy (from 3,2 A at 8.0 kev to 4.7 A at 10 keV). And H^- ion beam current increases from 50 to 75 mA.

Therefore, it is expected at 20-30 keV beam energy it is possible to produce a 100-200 mA of the H^- ion beam intensity (in Cesium-free source), which might be useful for some accelerator applications.

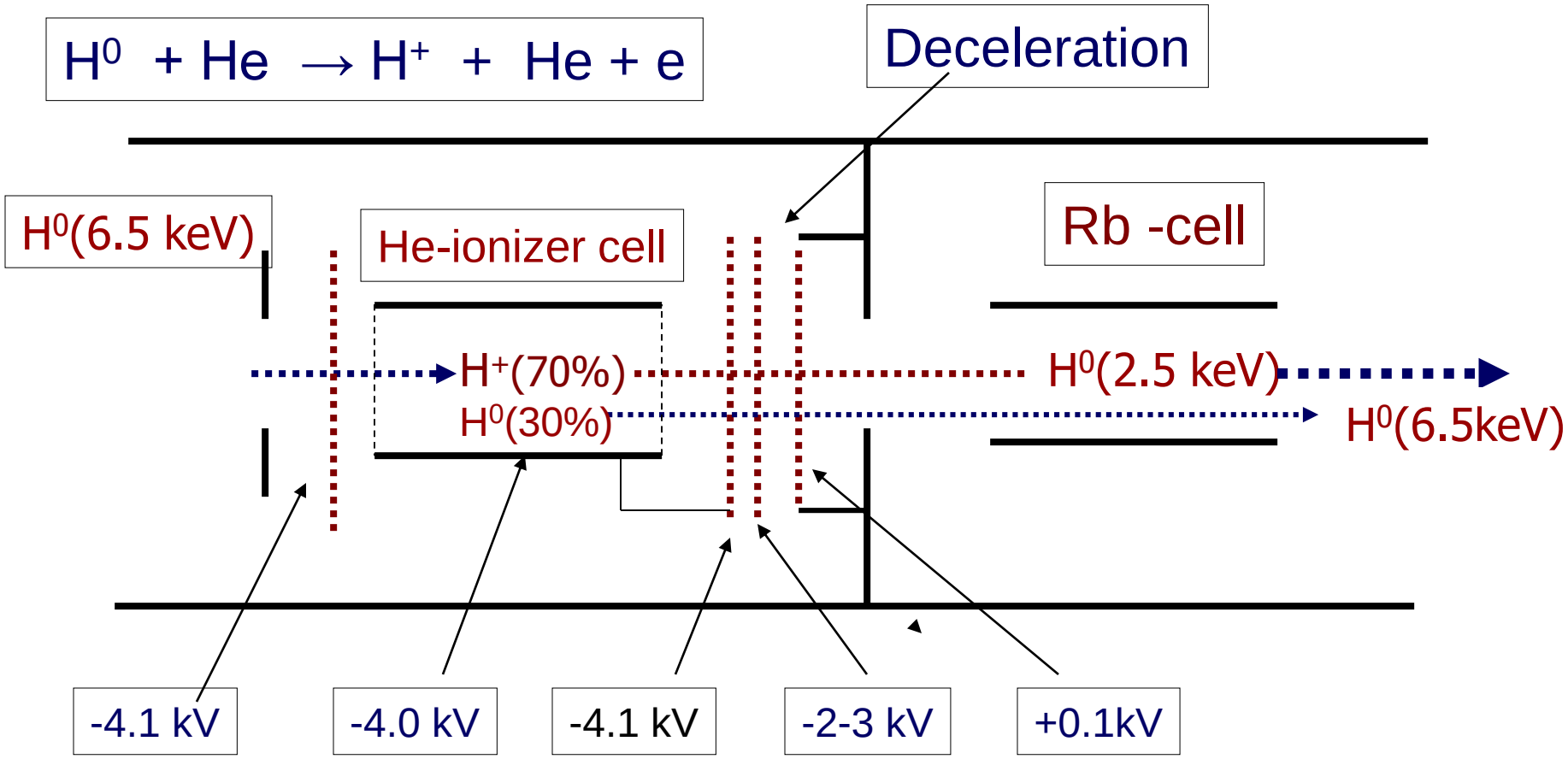
The H^- beam emittance is similar or smaller than neutral hydrogen beam emittance, which is estimated ≤ 0.5 π mm mrad.

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

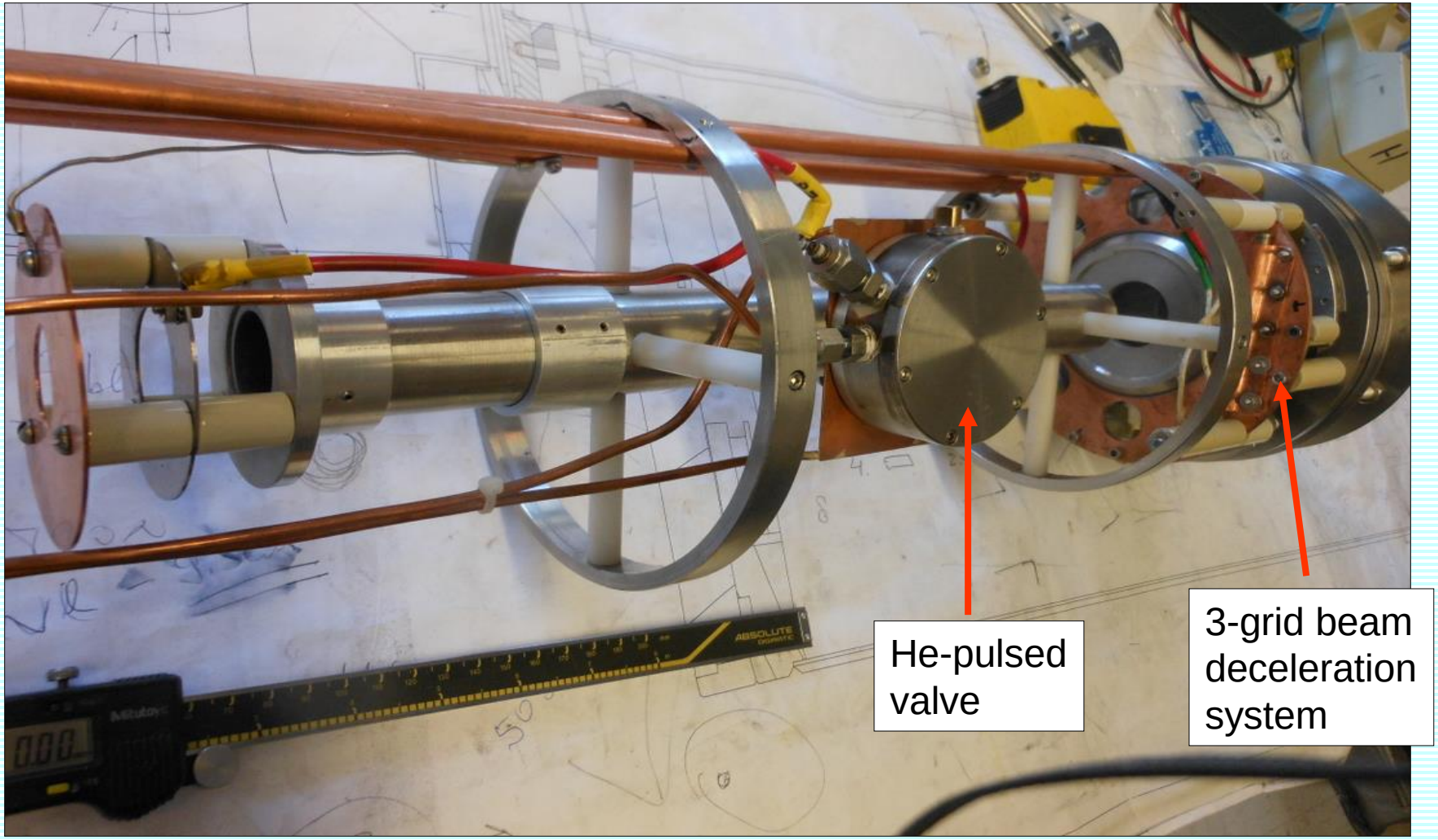


$H^+ \longrightarrow H2 \xrightarrow{H^0} He \xrightarrow{H^+} Rb \xrightarrow{H^0} Na \xrightarrow{H^-}$

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



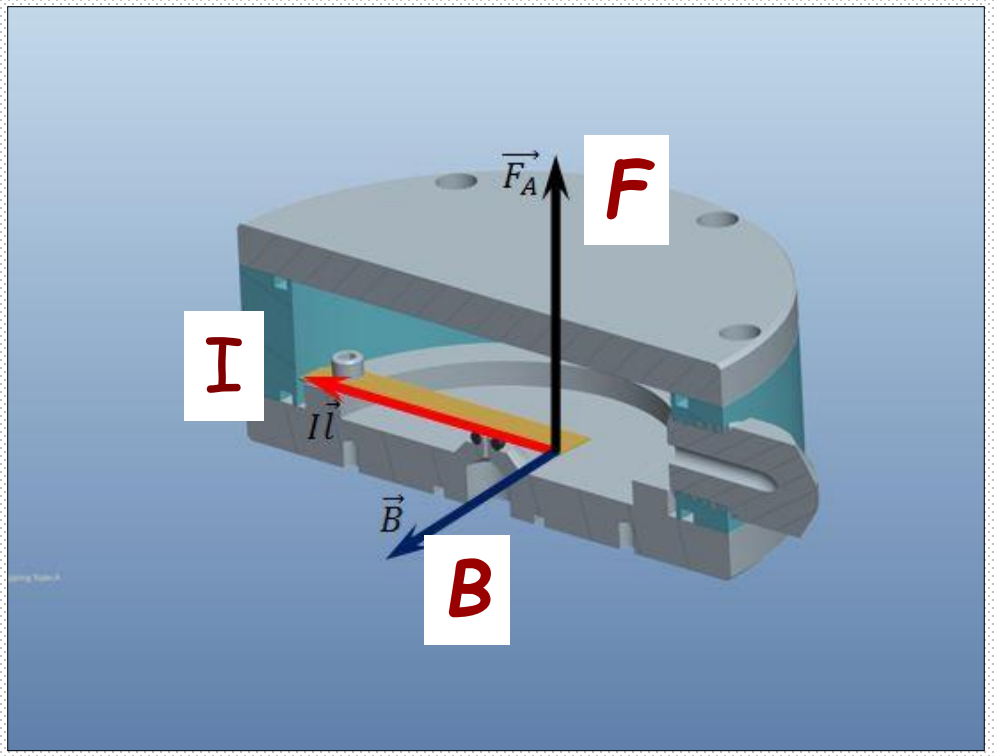
He-ionizer cell and 3-grid energy separation system.

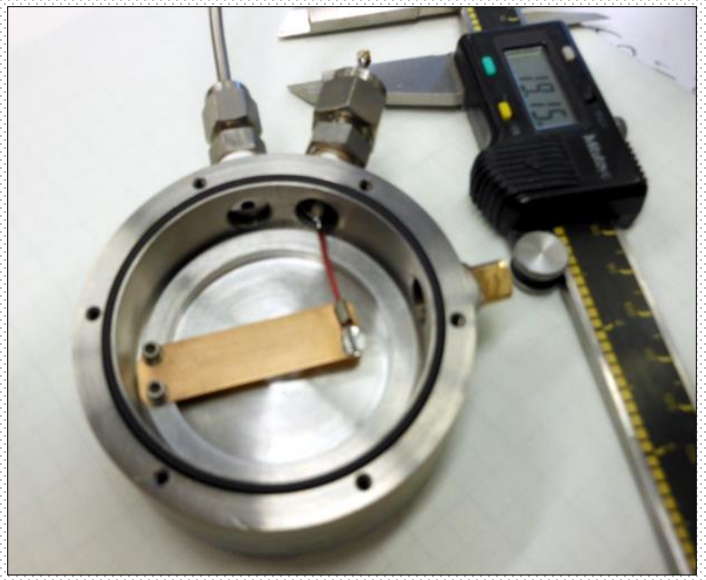


"Electro-dynamic" valve operation principle.

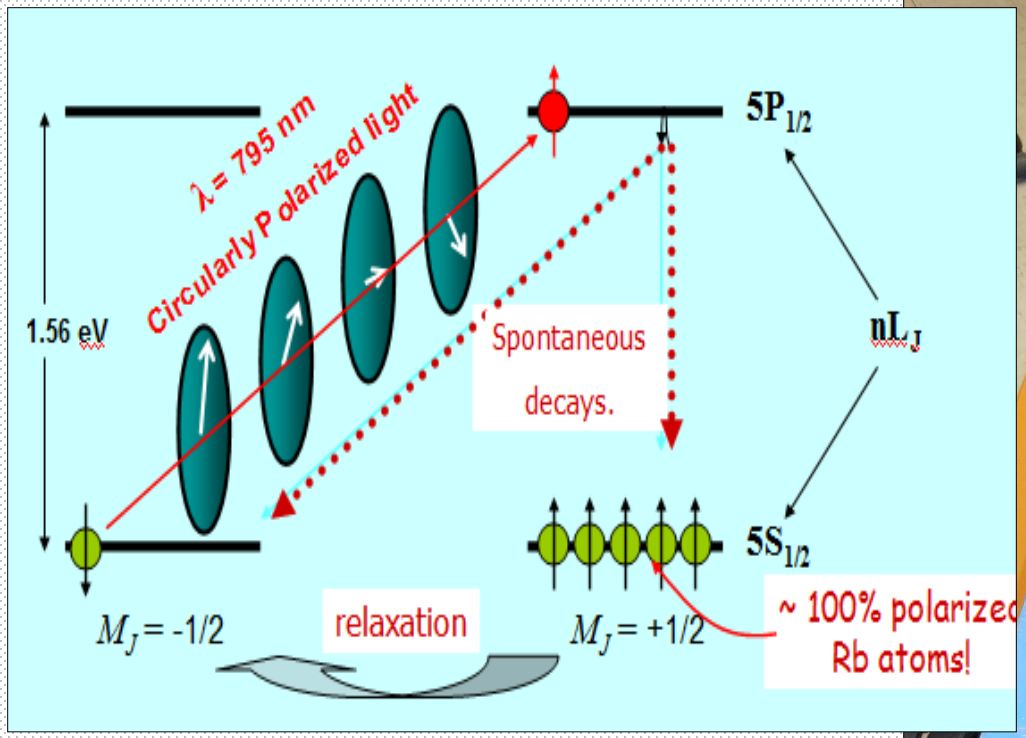
Lorentz force to the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=100 A, L=5 cm, F=15 N. Current pulse duration ~100 us

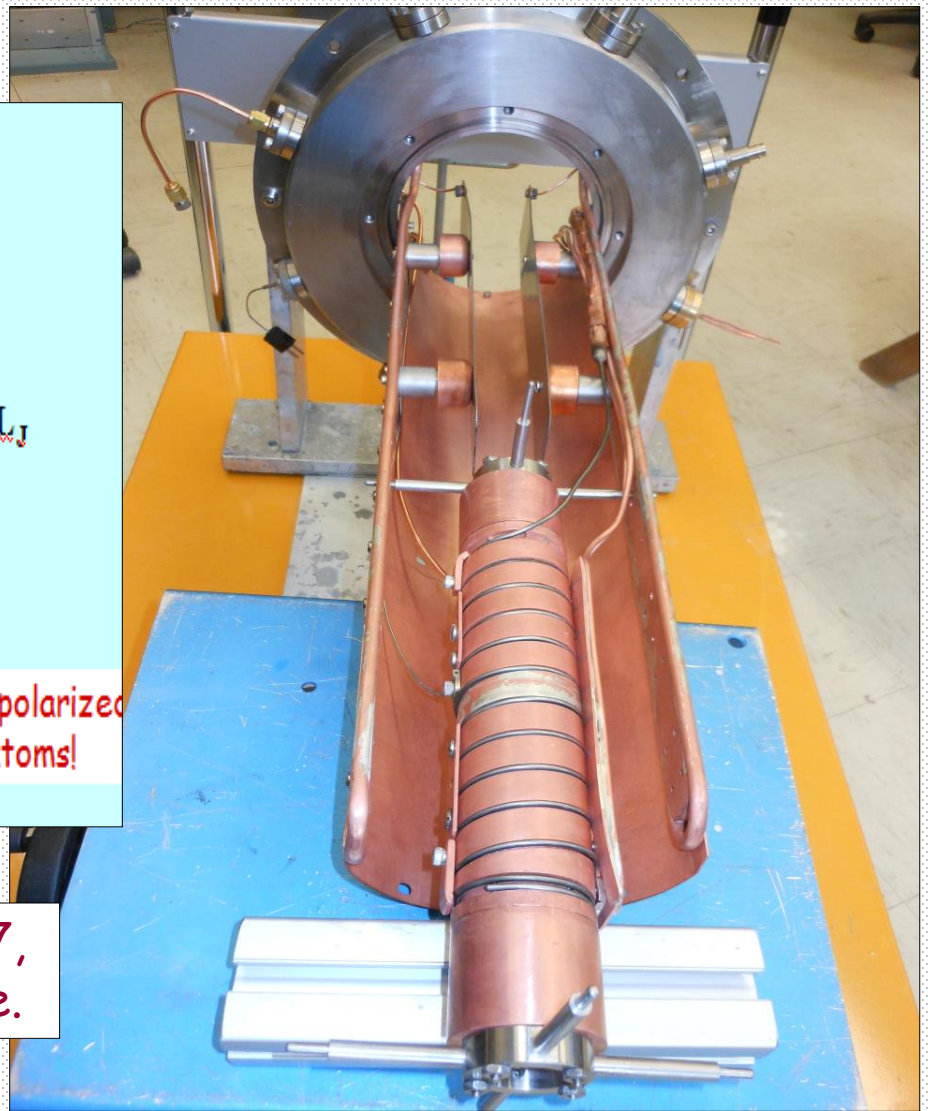
$$d\overrightarrow{F_A} = I[d\vec{l}\,\vec{B}]$$





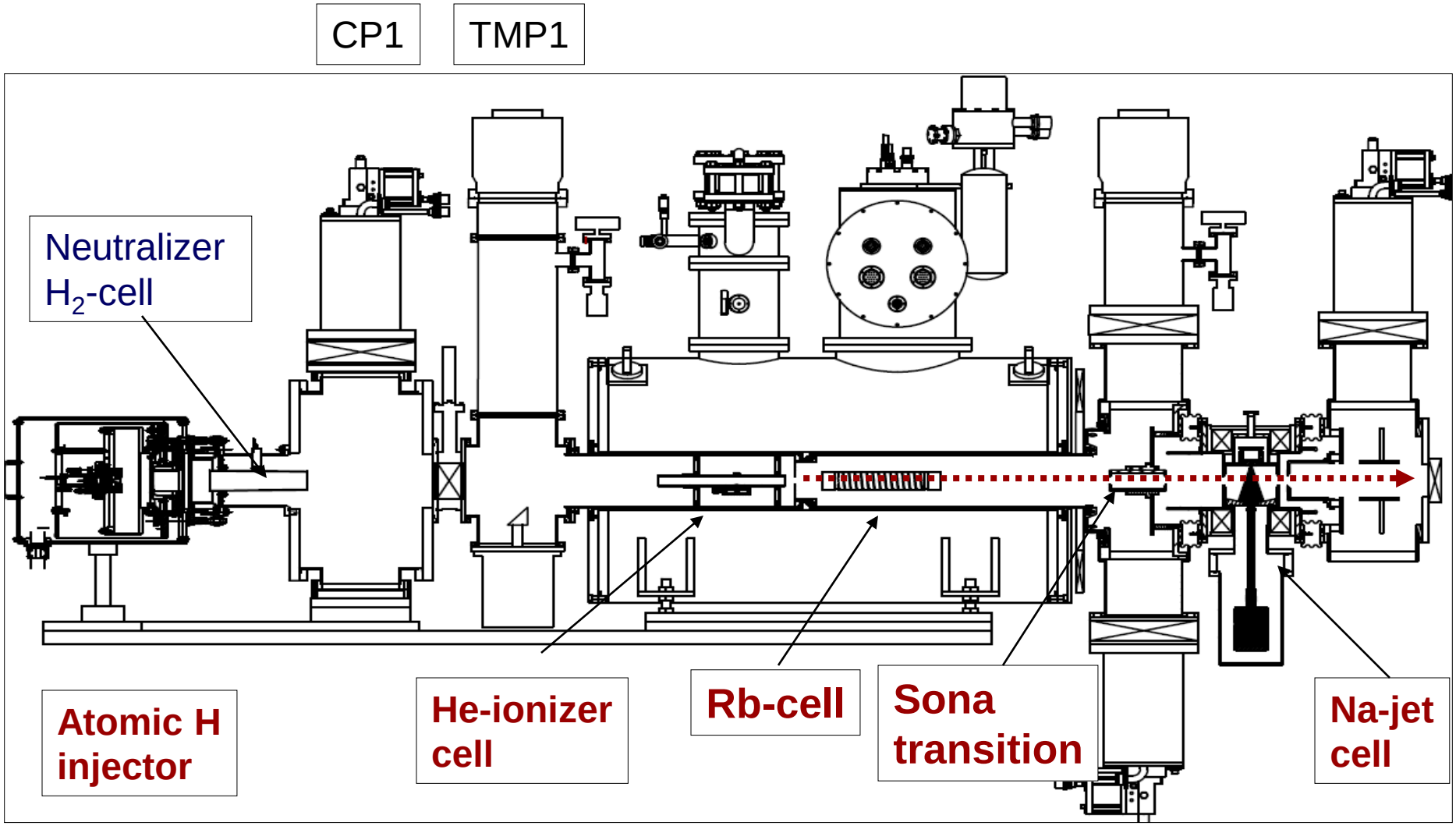
Optically-pumped Rb-vapor cell





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

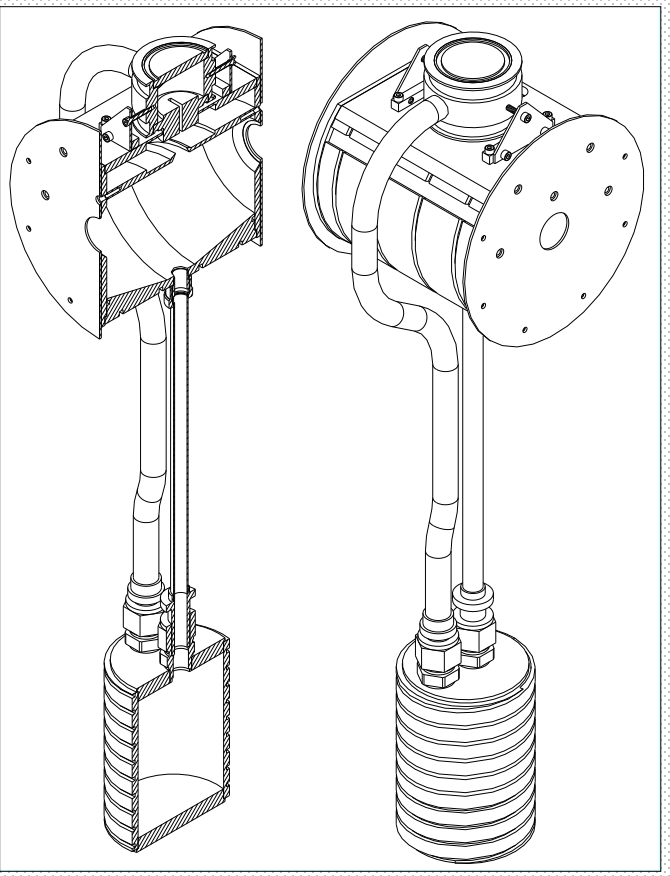
New OPPIS with atomic H^0 injector layout, 2013-17



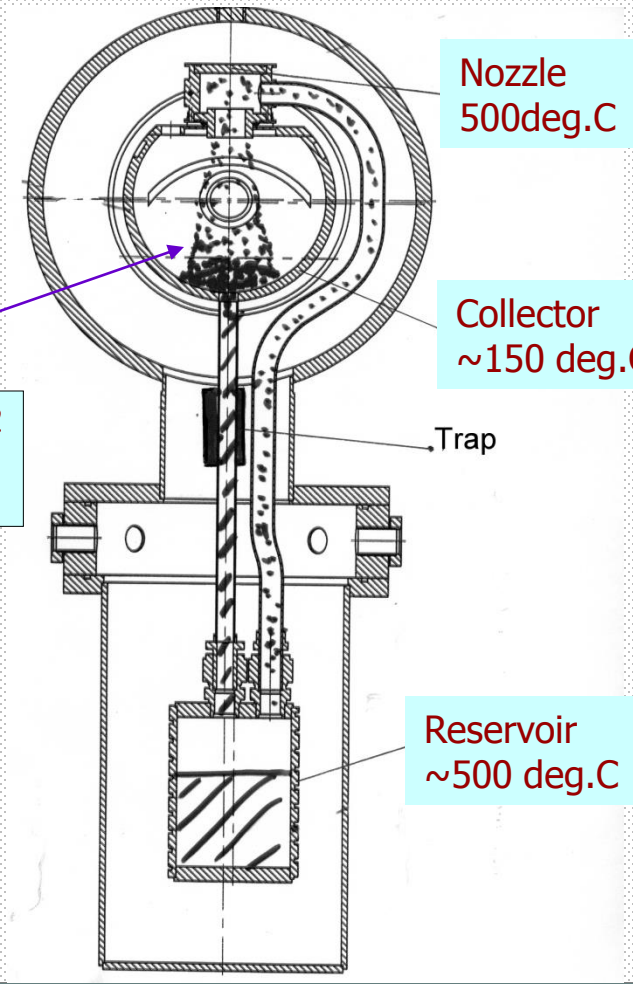
$H^+ \longrightarrow$ H2 $\xrightarrow{H^0}$ He $\xrightarrow{H^+}$ Rb $\xrightarrow{H^0}$ Na $\xrightarrow{H^-}$

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 .

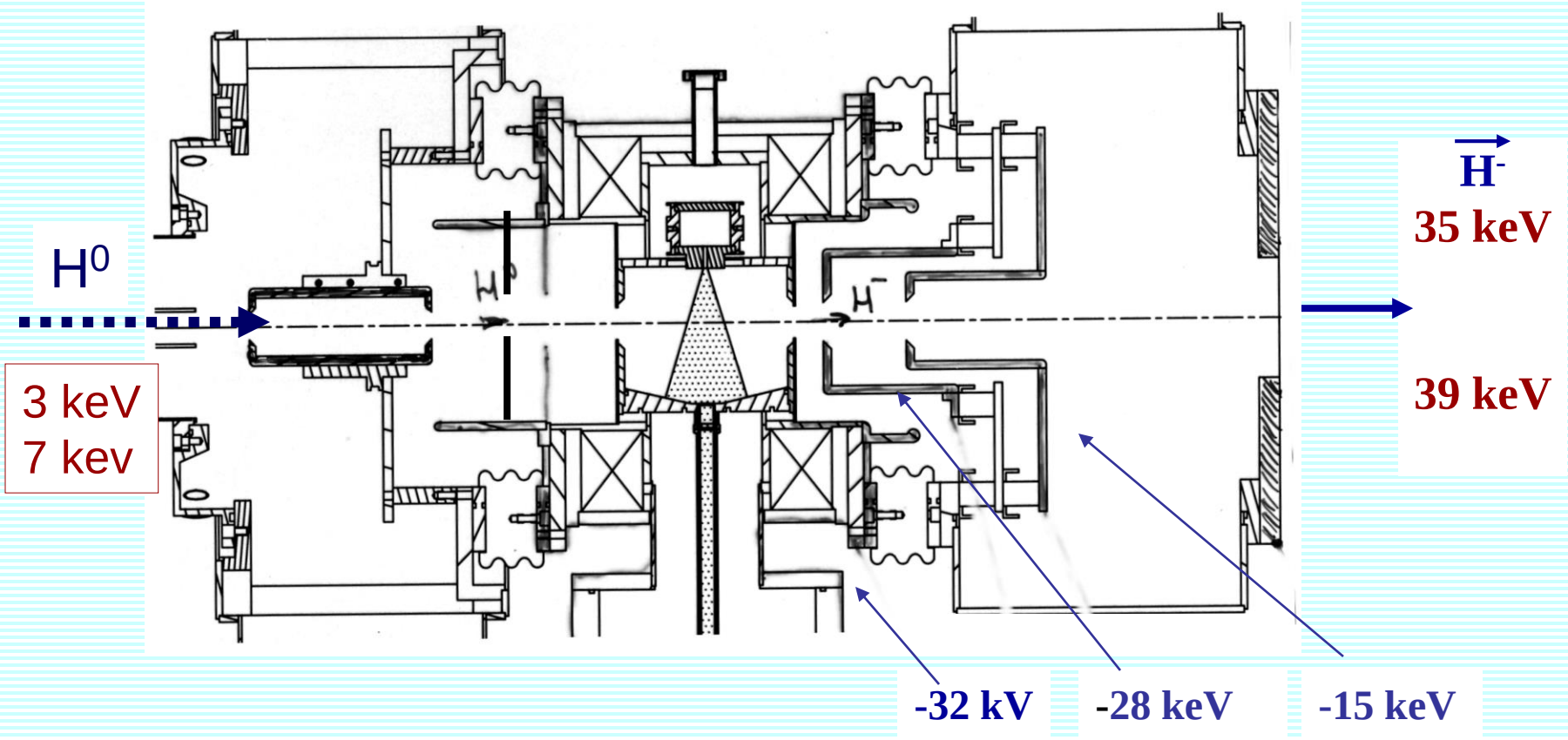


NL ~$2 \cdot 10^{15}$ atoms/cm^2
L ~ 2-3 cm



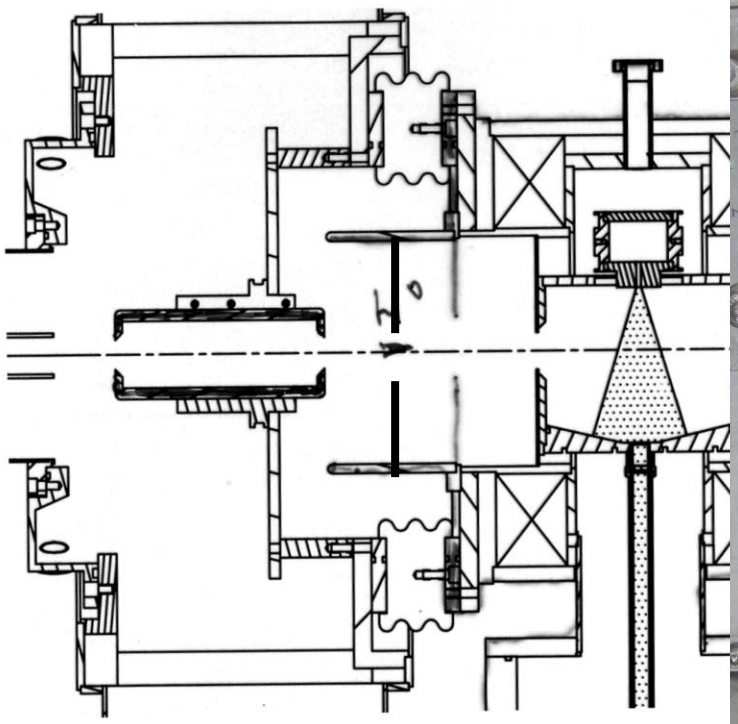
Reservoir– operational temperature. Tres. ~500 °C.
Nozzle – Tn ~500 °C.
Collector- Na-vapor condensation: Tcoll.~120°C
Trap- return line. T ~ 120 – 180 °C.

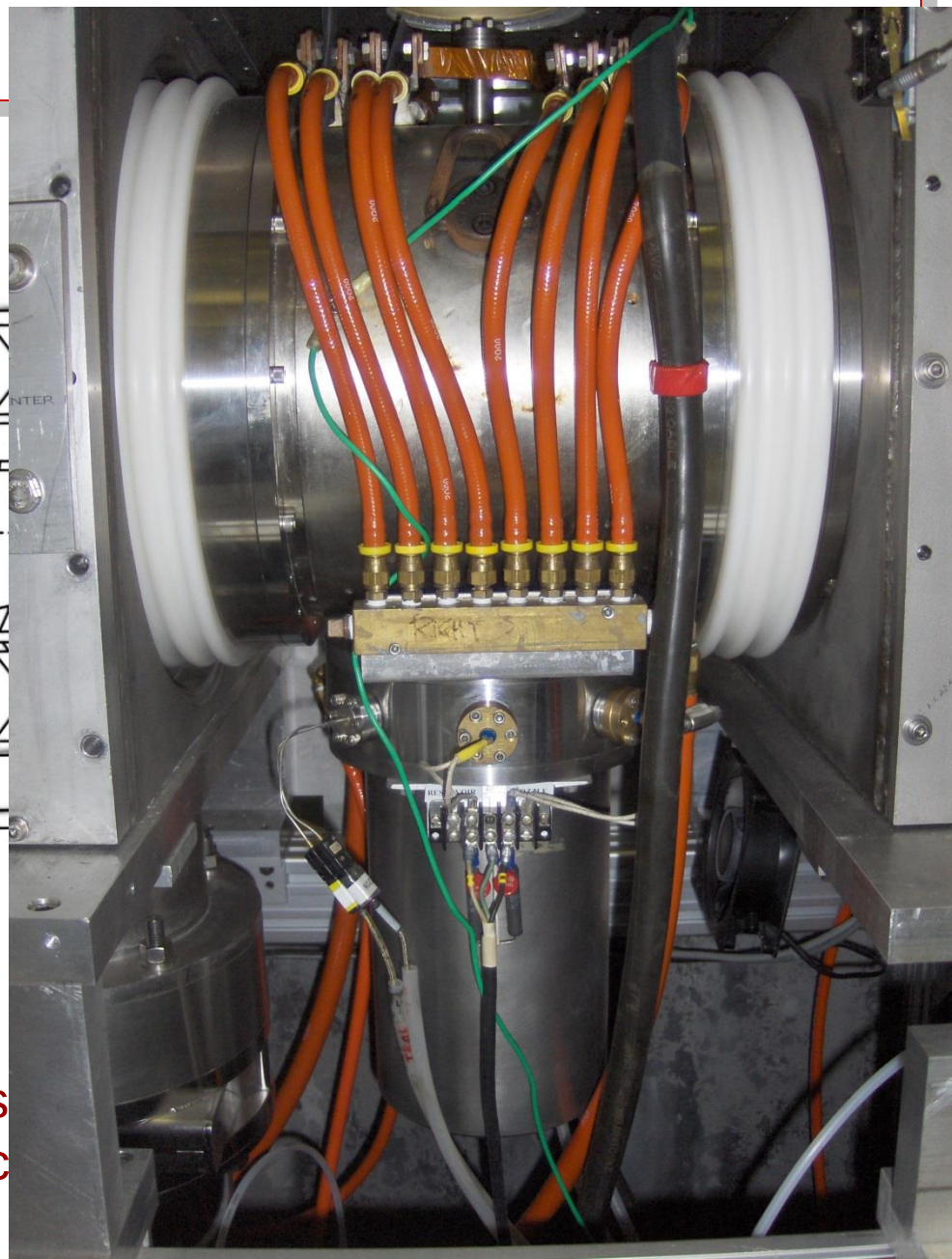
H^- beam acceleration to 35 keV at the exit of Na-jet ionizer cell



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

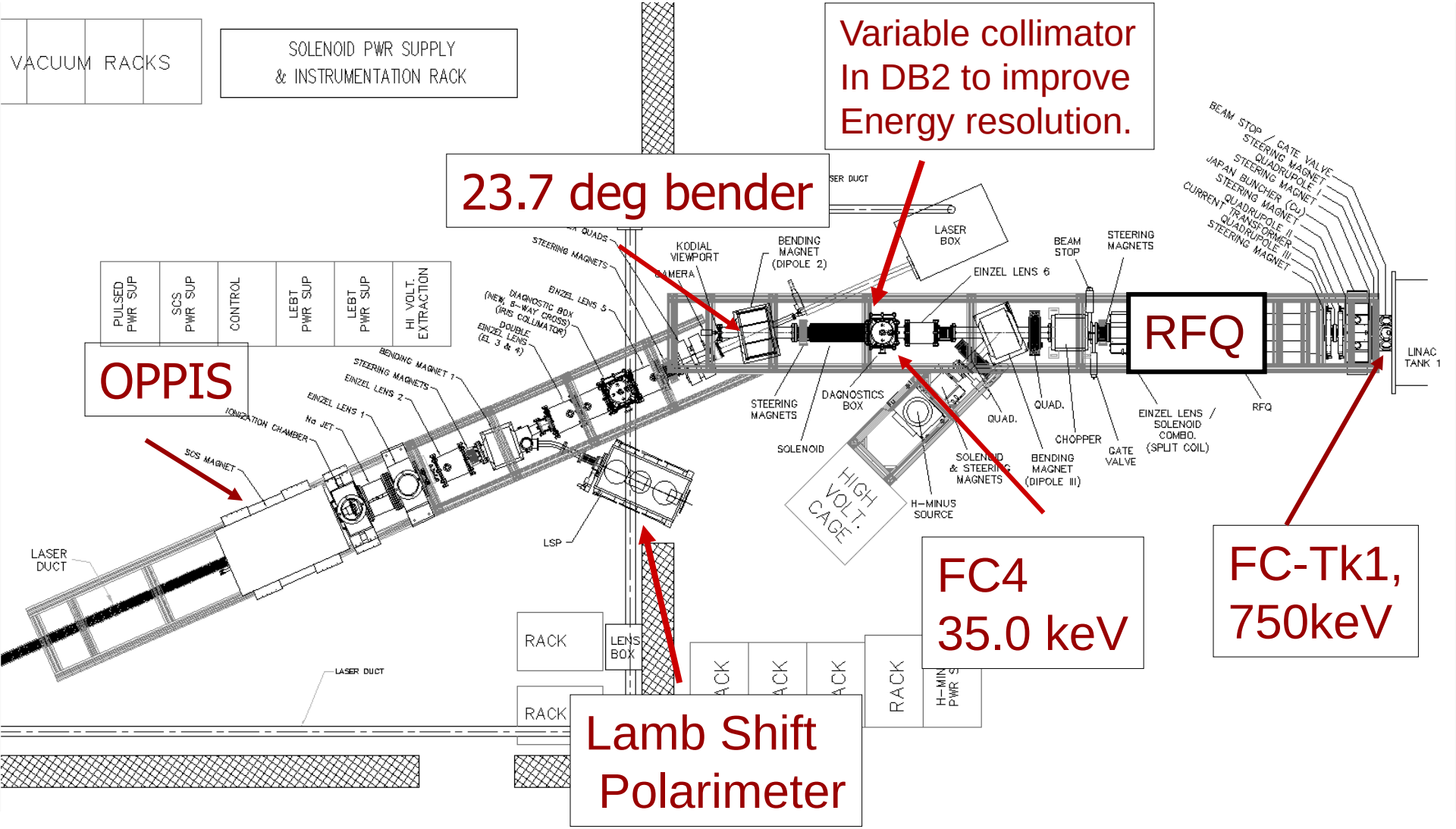
H^- beam acceleration to 35 keV at the exit of Na-jet





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

Low Energy Beam Transport line.



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.

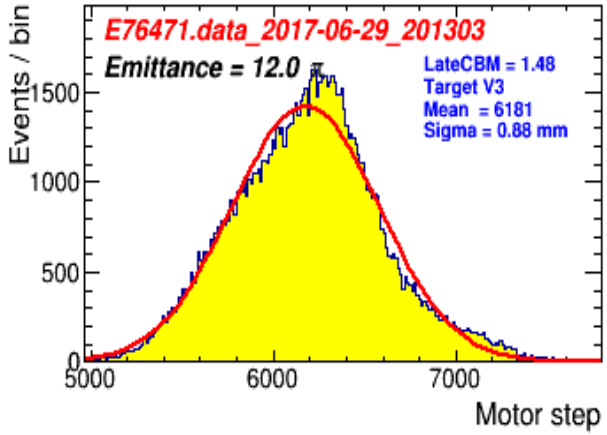
Rb-cell thickness-NL	4.5	5.5	7.5	10.4
Linac Current, μA	440	520	740	950
Booster Input $\times 10^{11}$	10.0	12.0	14.0	17.1
Pol. %, at 200 MeV	86	86	84.5	83

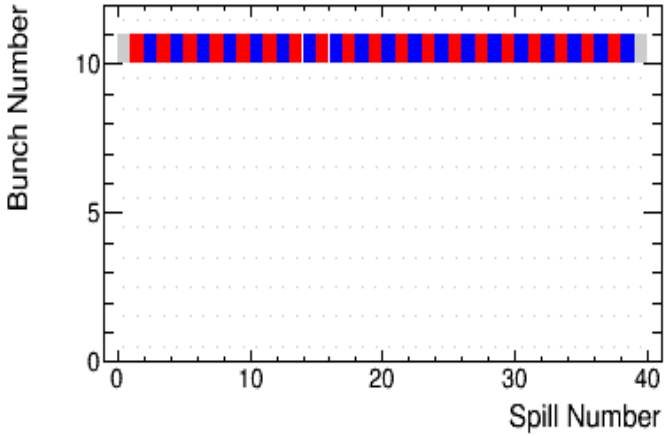
Rb-cell thickness ,NL $\times 10^{13}$ atoms/cm^2

Polarization in AGS, 23 GeV, Run-2017

Thu Jun 29 20:13:48 2017 | Thu Jun 29 20:16:40 2017

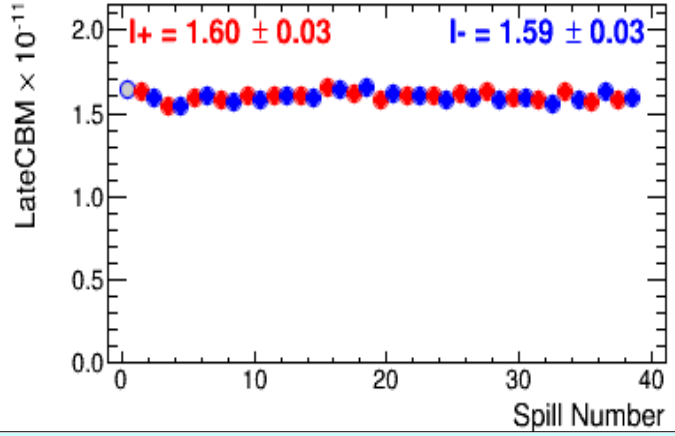
Run 76471 V3 I=1.60 Stat=38.5 (41.0) P = 78.3 ± 2.3%



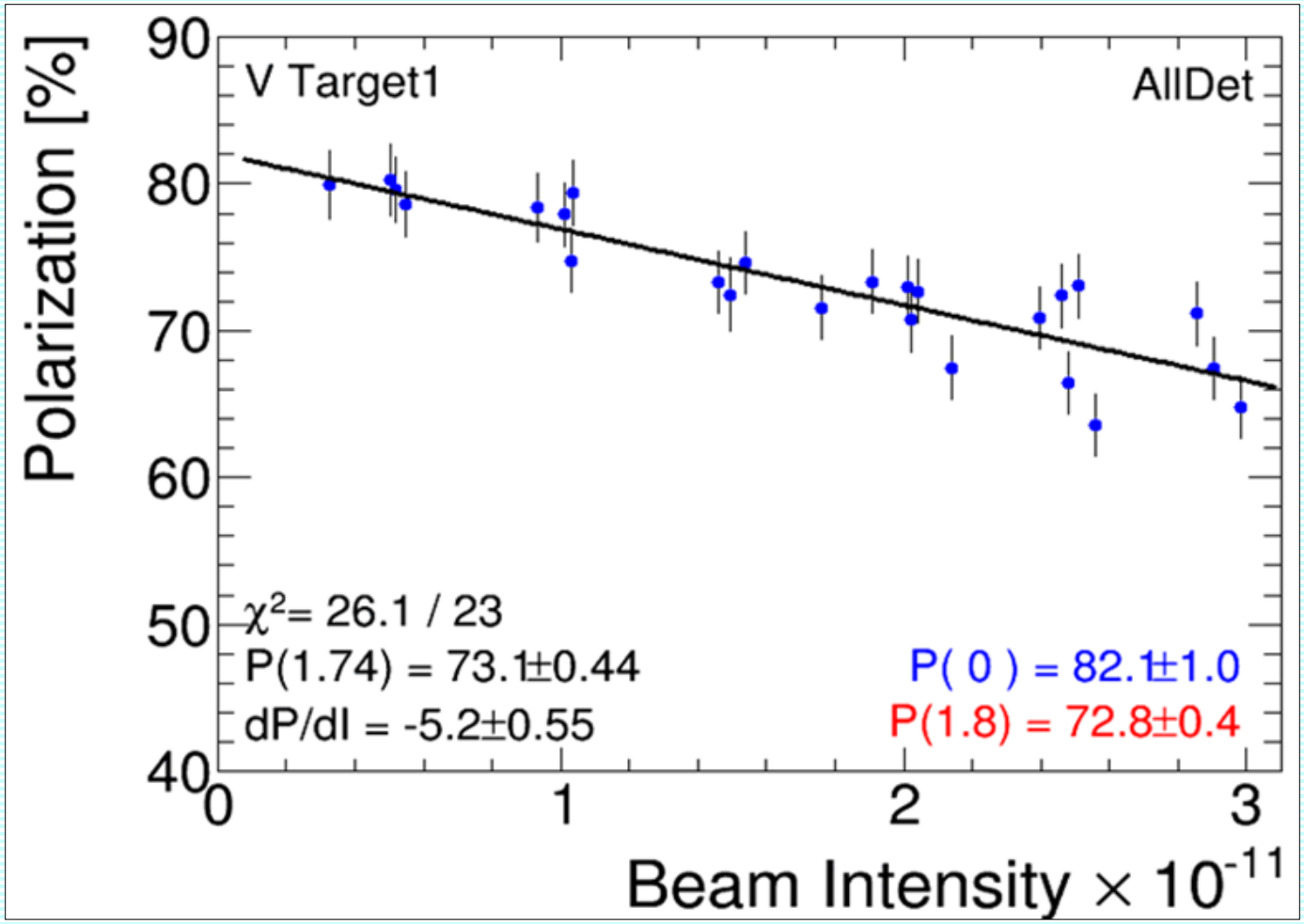


Detectors	Stat.	Polar.	(no corr.)
All	19.3	78.3±2.3	(73.6±2.3)
90deg	6.6	77.9±3.2	(73.2±3.3)
90degUp	6.6	77.9±3.2	(73.2±3.3)
90degDn			
45deg	12.7	78.9±3.3	(74.3±3.3)
45degUp	6.3	84.5±4.7	(79.6±4.8)
45degDn	6.4	73.5±4.5	(69.2±4.7)

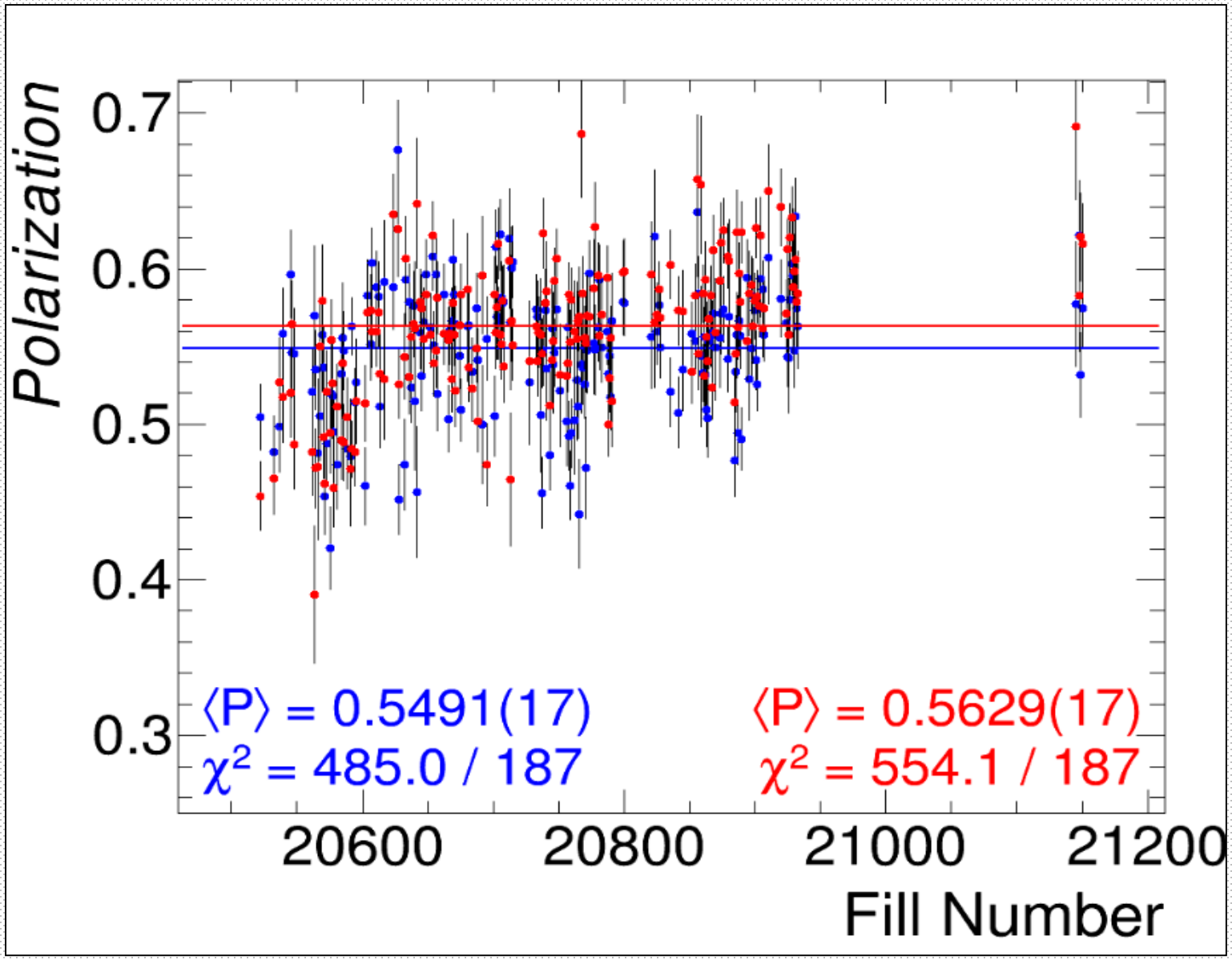
Det.Mask=0xFF R.C.=1.00



Polarization at 23 GeV in AGS



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



RHIC Polarized beam in Run 2013-17

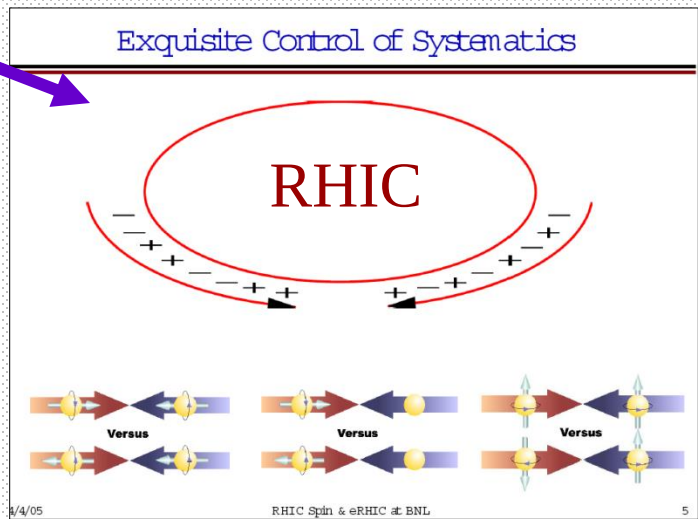
OPPIS → 1.0 mA x 300us→$18 \cdot 10^{11}$ polarized H^- /pulse.

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

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

AGS → $(2.0\text{-}2.5) \cdot 10^{11}$ p/bunch, P-70%

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



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

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

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

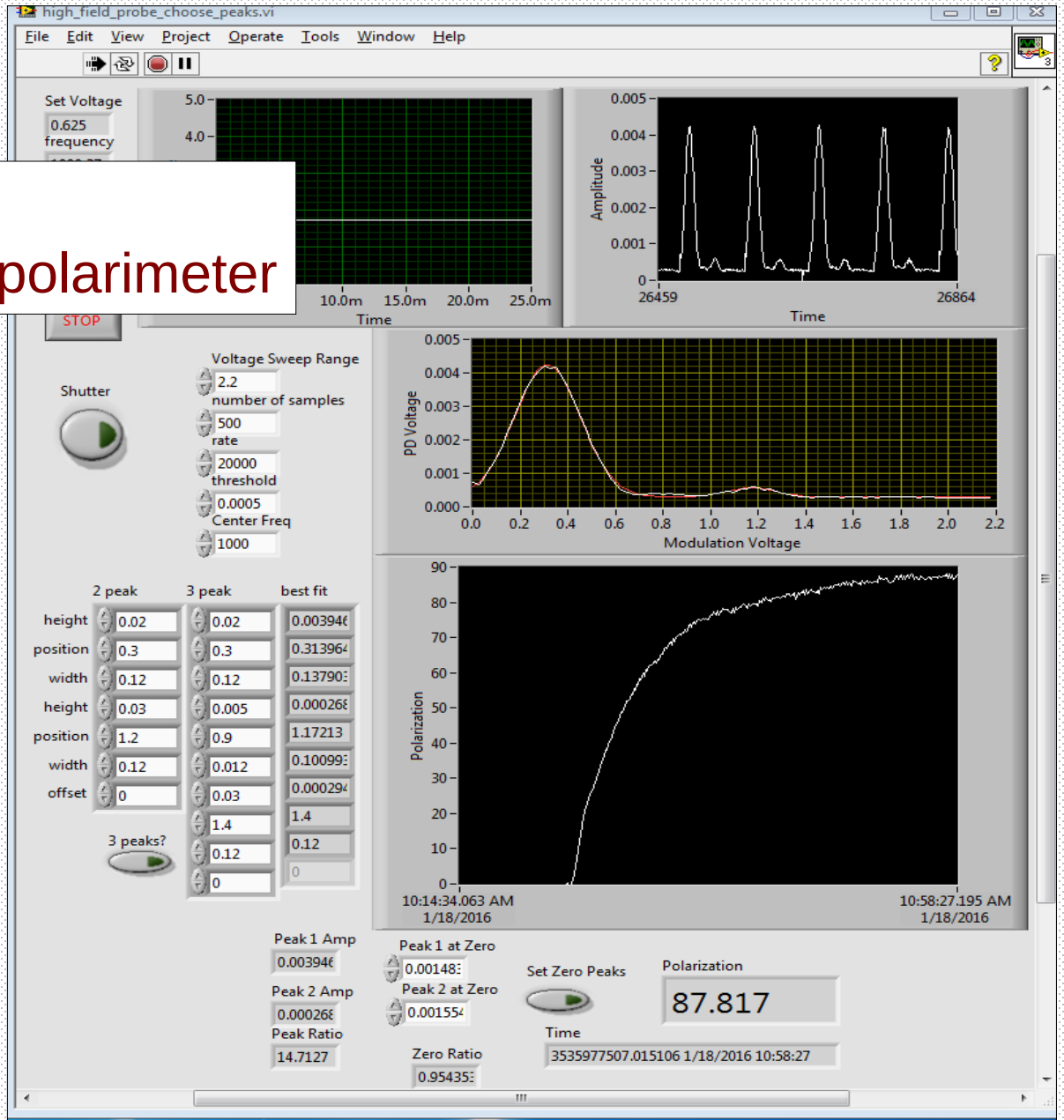
- EBIS is used for <u>efficient ionization</u> and <u>accumulation</u> of polarized $3He^{++}$ ions to the full capacity 10^{12} total charge ($5 \cdot 10^{11}$, $3He^{++}$ ions).

3He-gas purification and filling system

Non-magnetic brass pneumatic remotely controlled Isolation Valve

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

Probe laser absorption polarimeter

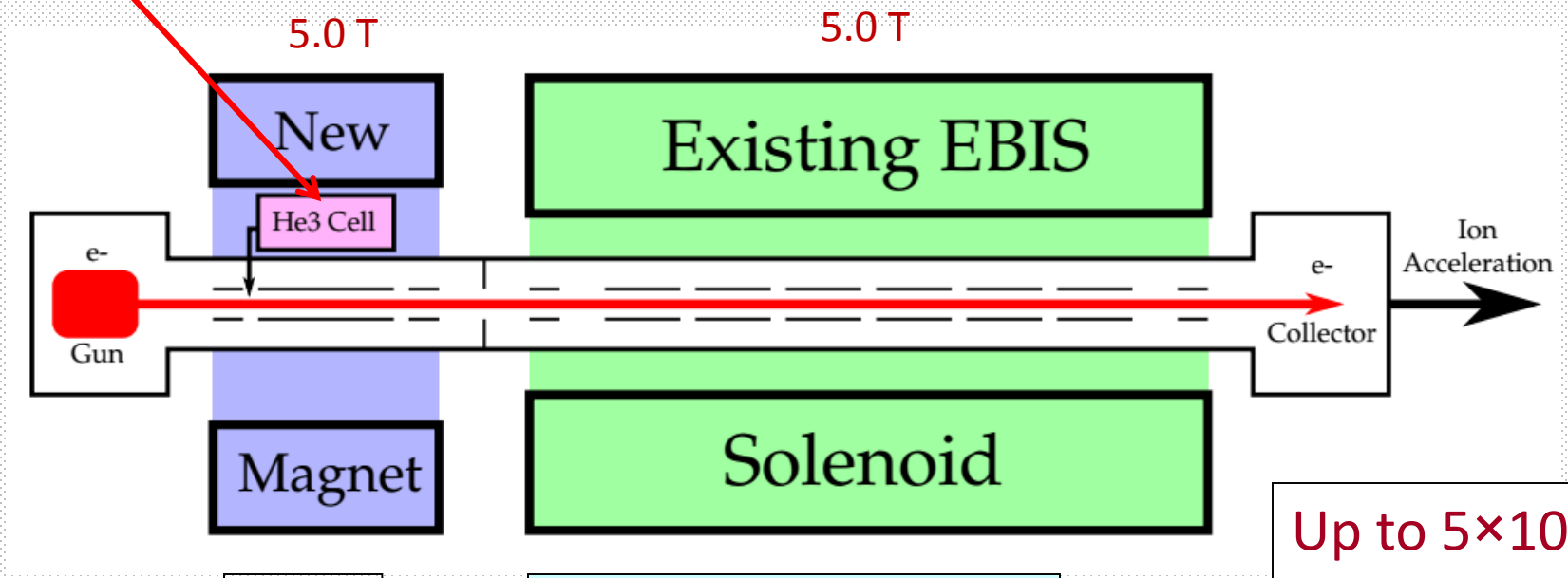


EBIS upgrade with new "injector" solenoid for polarized $3He^{++}$ ion production, 2017-2019.

BNL-MIT collaboration

Optical pumping in High magnetic field

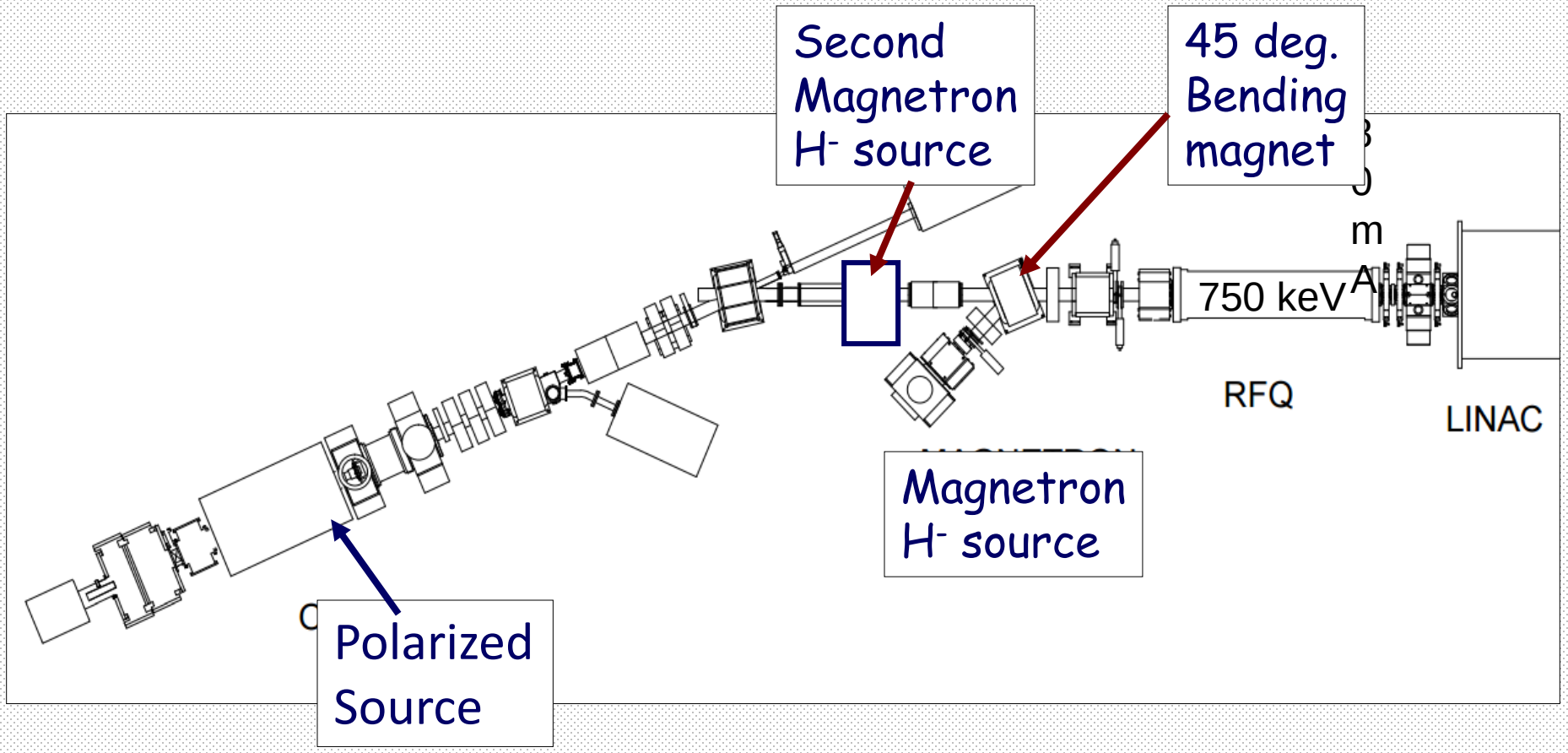
Polarization and ionization in high magnetic field will produce $3He^{++}$ ion beam with $P \geq 80\%$



$3He^{+}$ → Ionization to $3He^{++}$ → Up to 5×10^{11} $3He^{++}$ ions/pulse

Injector upgrade with the second magnetron H^- ion source in 2017, as a part of high intensity Linac upgrade. The source and Linac pulse duration increase to 1000 us. Current-55-60 mA

Prototype of the advanced injector for high-energy accelerators.



BNL magnetron H^- ion source

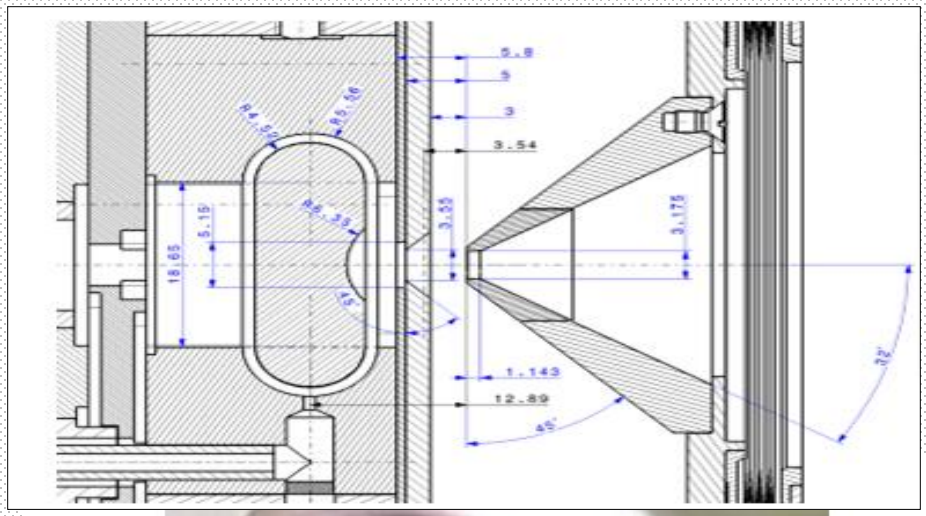


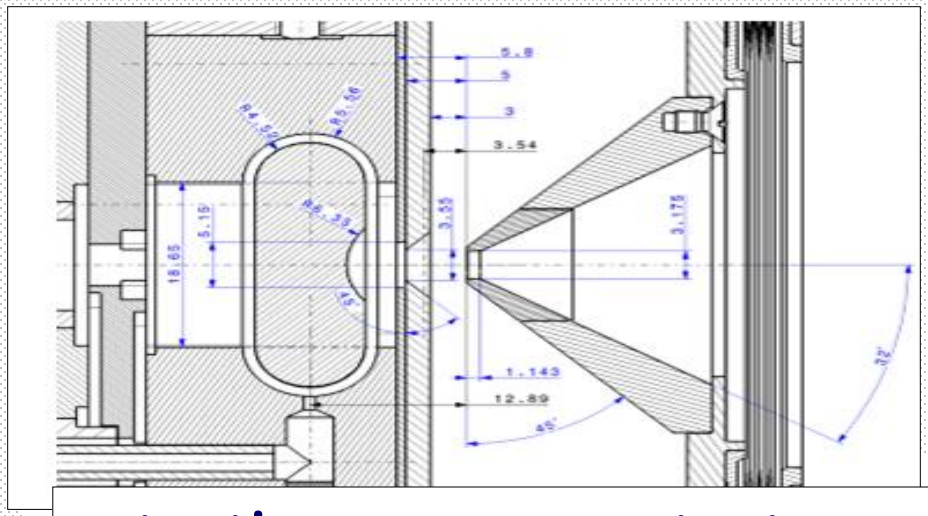
FIGURE 2. Source with the anode cover removed. Permanent magnets are visible on the sides of the source.

TABLE 1. Typical running parameters	
H- current	90-100 mA
J (H-)	1.5 A/cm^2
Extraction voltage	35 kV
Electron/H-	0.5- 1.0
Arc voltage	140 – 160 V
Arc current	8 – 18 A (see note)
Rep rate	7.5 Hz
Pulse width	700 μs
Duty factor	0.5 %
rms emittance	~ 0.4 π mm mrad
Cs consumption	< 0.5 mg / hr
Gas flow	~ 2 sccm

Power efficiency : ~ 100 mA H^-/1.5 kW arc-discharge power. Average-10W

Very reliable operation.
Typically for 6 months run.

BNL magnetron H^- ion source



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Rep rate	7.5 Hz
Pulse width	700 µs

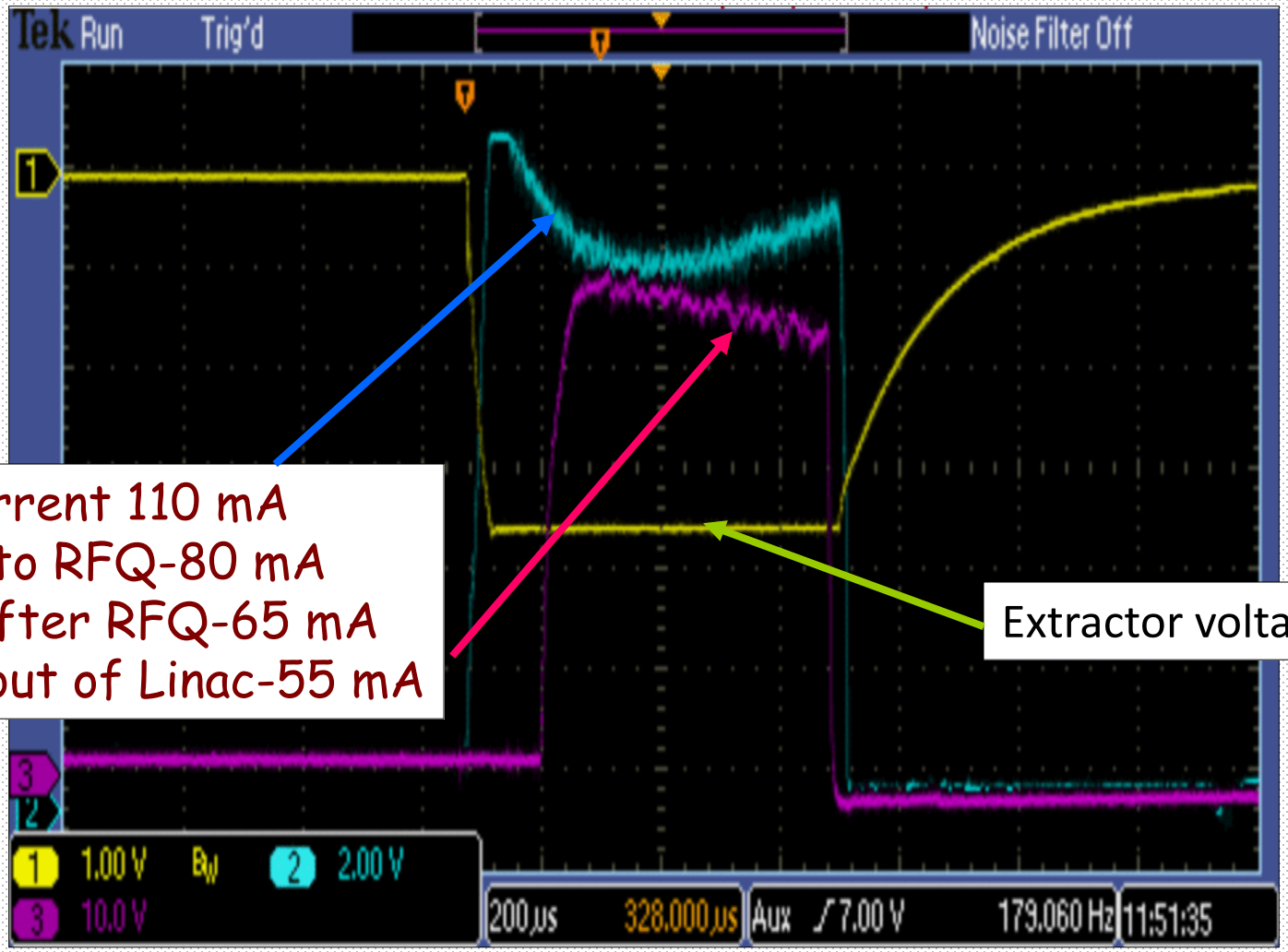
Similar source is in operation at Fermilab and was used for the long time at HERA injector

FIGURE 2. Source with the anode cover removed. Permanent magnets are visible on the sides of the source

Power efficiency : ~ 70 mA / kW arc-discharge power

Very reliable operation.
Typically for 6 months run.

H^- magnetron source current at BNL



Source current 110 mA
Injection to RFQ-80 mA
750 keV after RFQ-65 mA
200 MeV out of Linac-55 mA

Extractor voltage-35 kV

CERN-BNL magnetron ion source performance

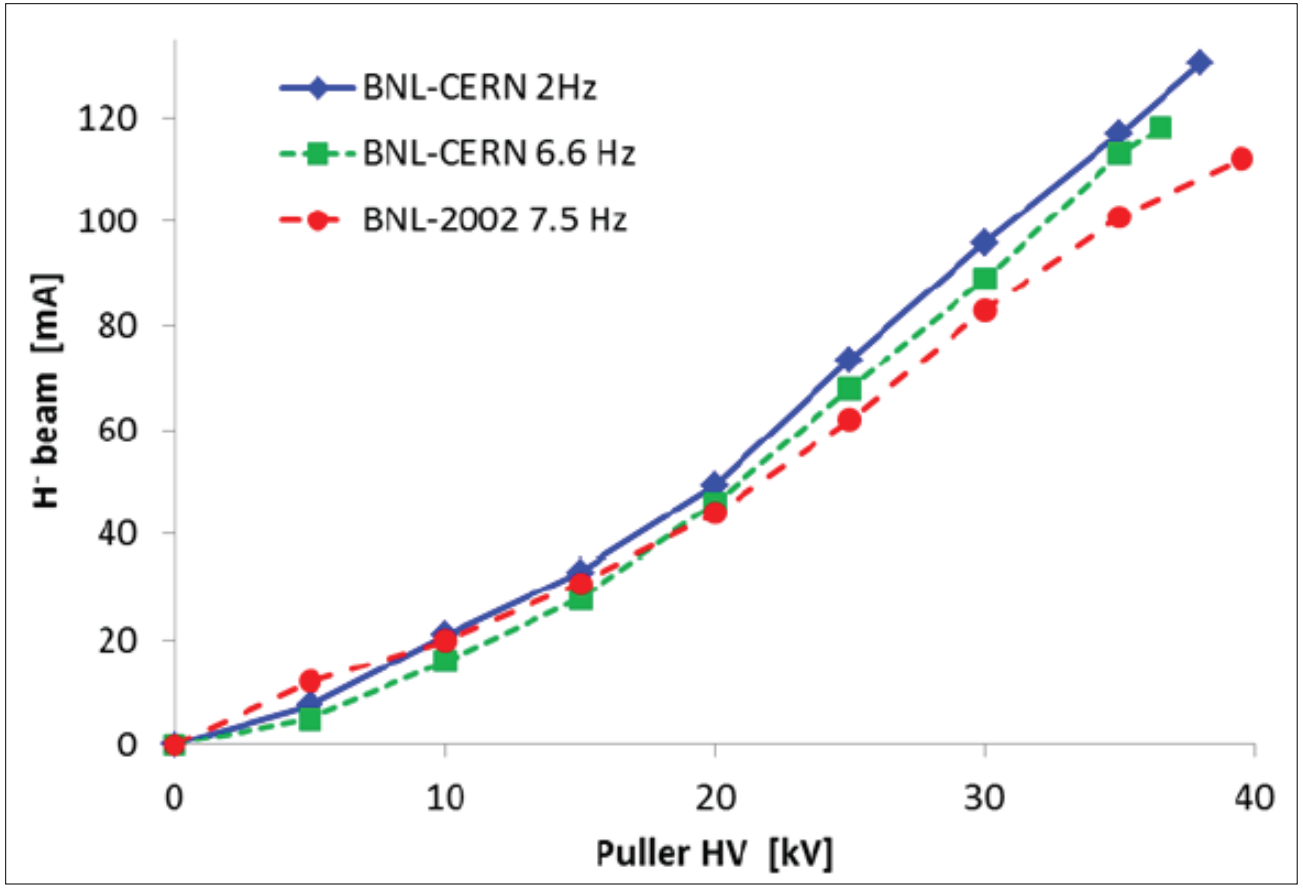


FIGURE 10. H^- beam-current – extraction-voltage characteristic measured at 2 and 6 Hz repetition rates, the reference values measured on the original Magnetron at 7.5 Hz are extracted from ref. 6.

Summary

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

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

- High intensity un-polarized H^{-} ion source development is in progress as a part of Linac intensity upgrade.