High IntensityPolarized Ion Sources

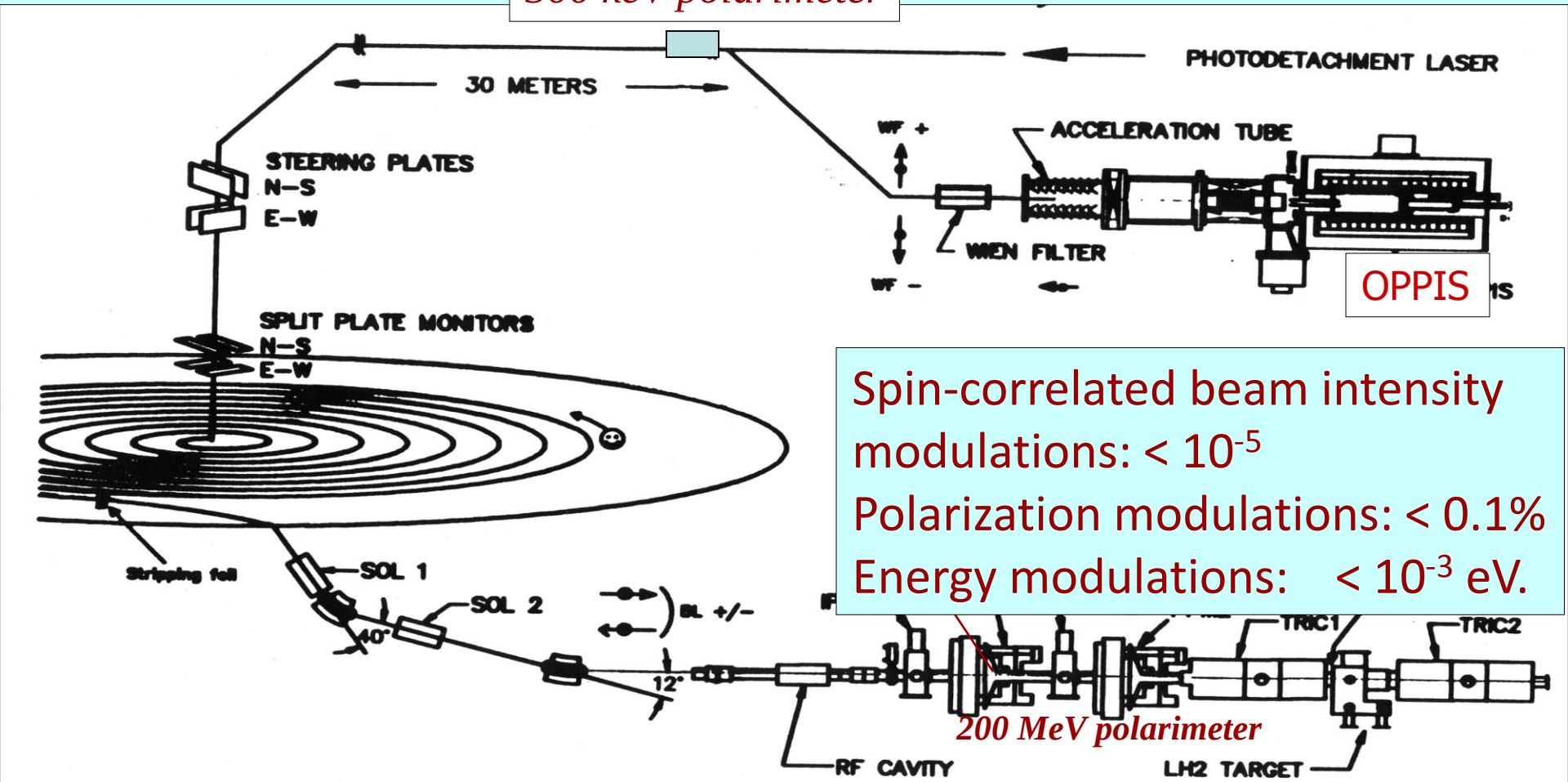
Anatoli Zelenski, BNL

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

Summary.

EDM Collaboration meeting , March 13, 2017

Parity-violation experiment at TRIUMF in pp-scattering at 221 MeV



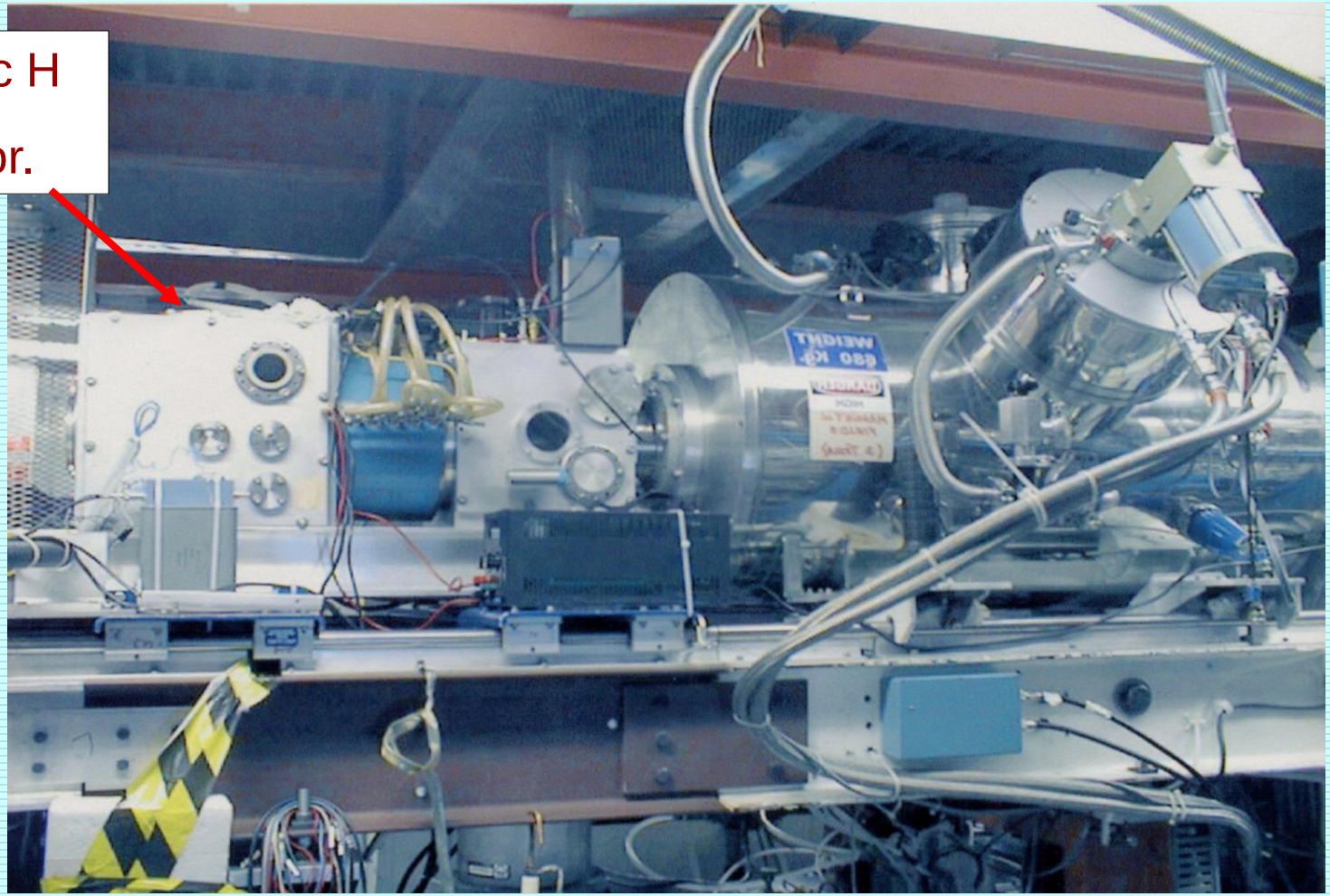
Spin-correlated beam intensity modulations: $< 10^{-5}$

Polarization modulations: < 0.1%

Energy modulations: $< 10^{-3}$ eV.

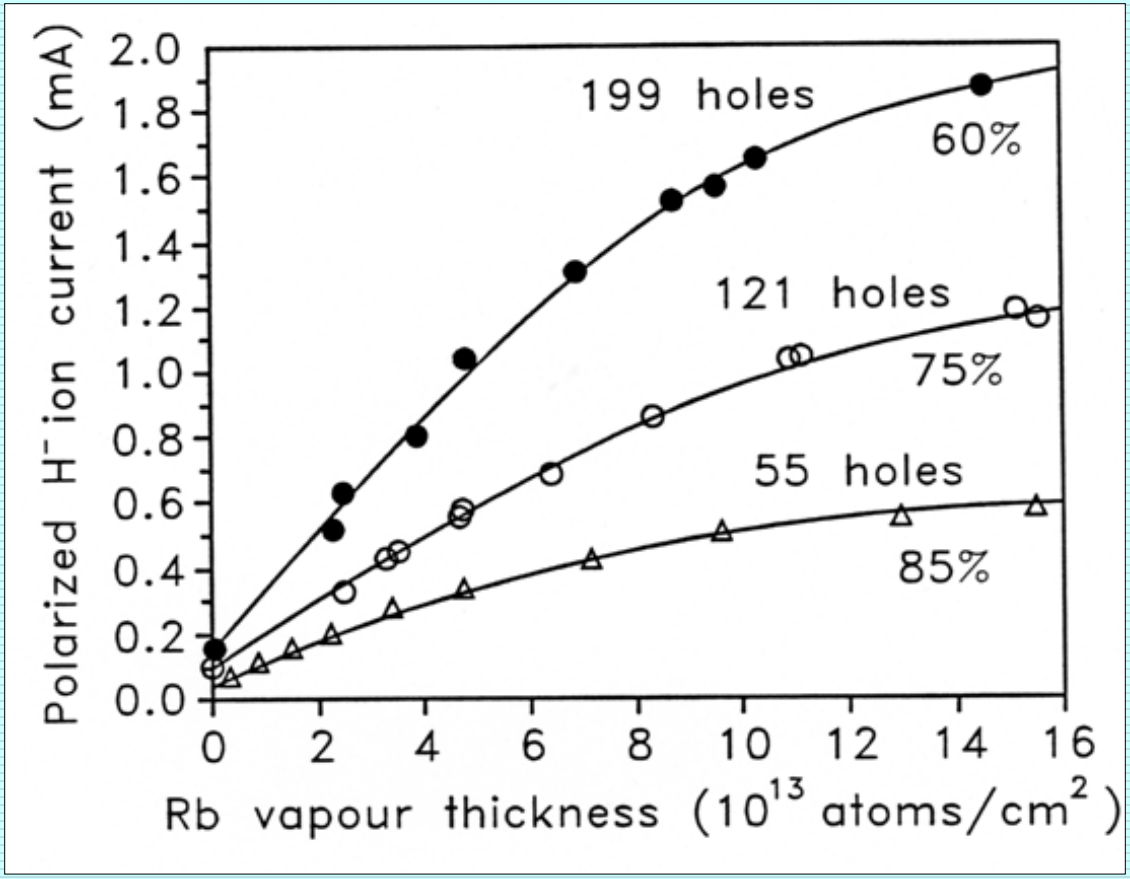
OPPIS- polarized H-ion source; SOL- 1,2 –spin-precession solenoids; IPM- beam profilometers; PPM- scanning polarimeters; TRIC-1,2- ionization chambers – beam current detectors.

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



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

Optically Pumped Polarized H^- Ion Source (OPPIS) at TRIUMF



Beam current and polarization vs. Rb-vapor thickness

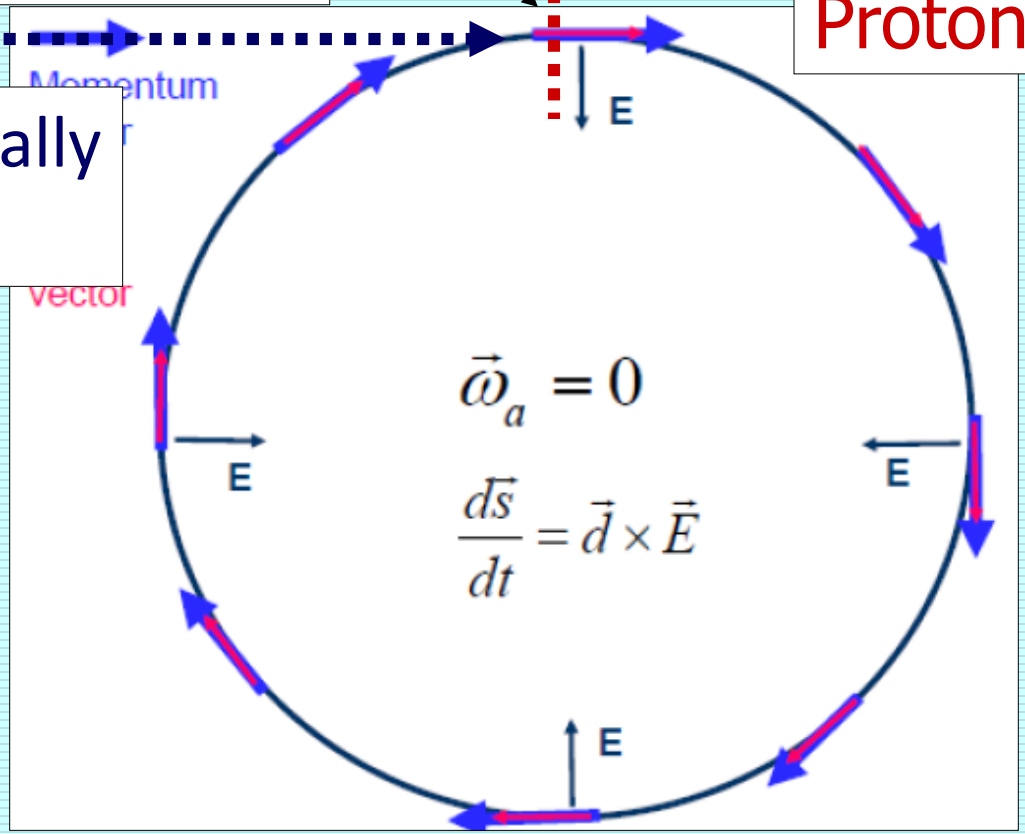
Strip-Injection of longitudinally polarized H^- ion beam into the p-EDM storage ring

Carbon stripping target

232.8 MeV H^- beam

Protons

Longitudinally polarized

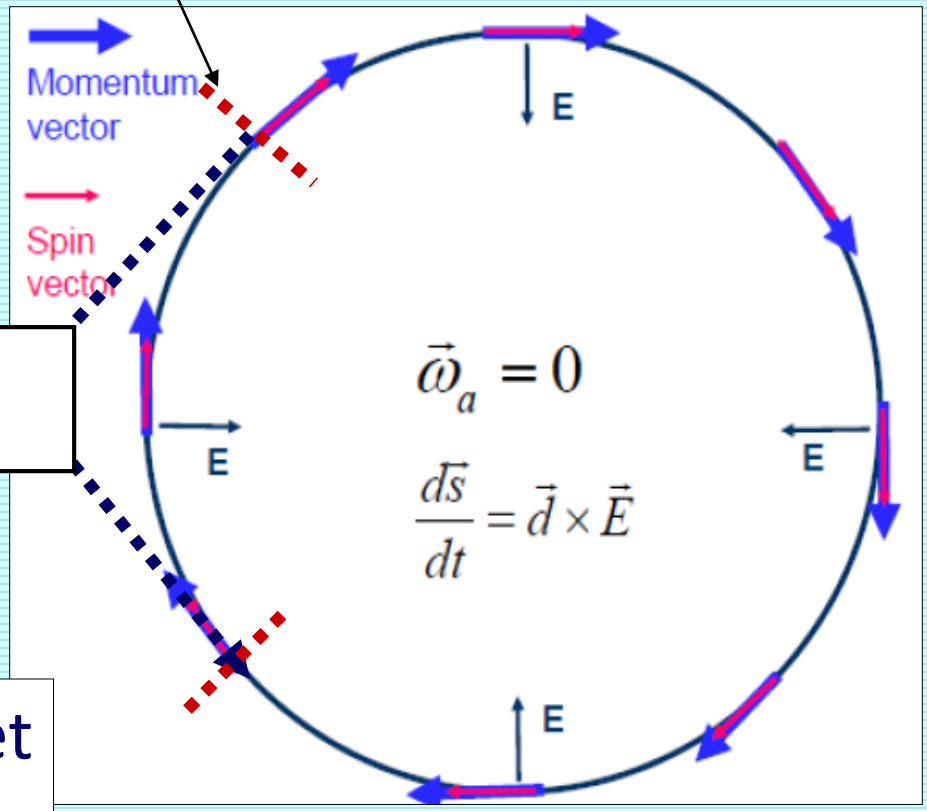


1.0 mA x 10 μs → 6 x 10^{15} x 10^{-5} =6 x10^{10} H^- ions/pulse

Strip-Injection of longitudinally polarized H^- ion beam

Carbon stripping target

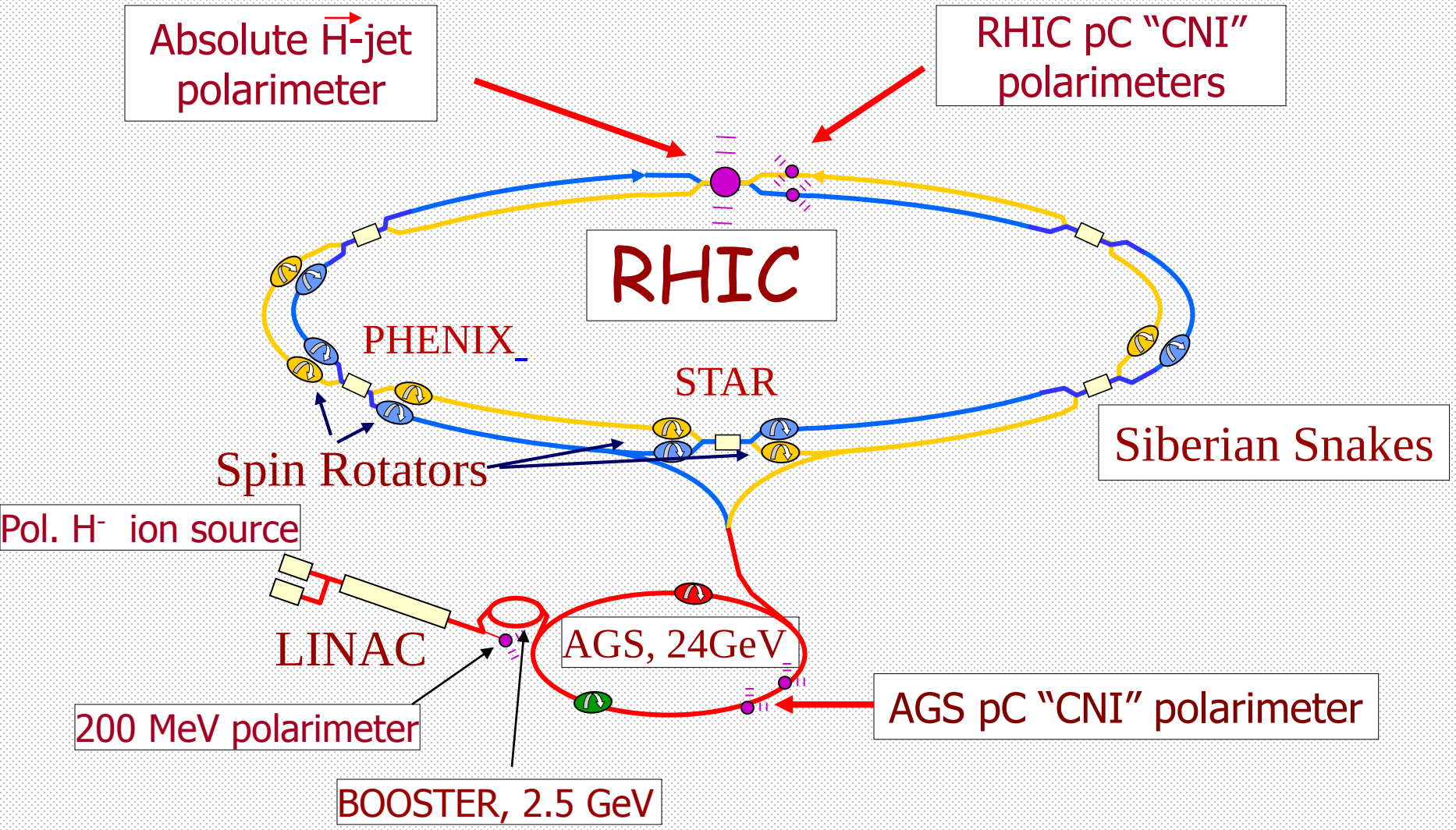
Longitudinally polarized
232.8 MeV **H^-** beam



47.5deg bending magnet
Flip the longitudinal pol.

Polarization facilities at RHIC

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



RHIC Polarized beam in Run 2013-15-17

OPPIS

1.0-2.0 mA H^- ion beam, 300-500 us pulse duration

LINAC

(8.0-14.0) $\cdot 10^{11}$ polarized H^- /pulse at 200 MeV

Booster

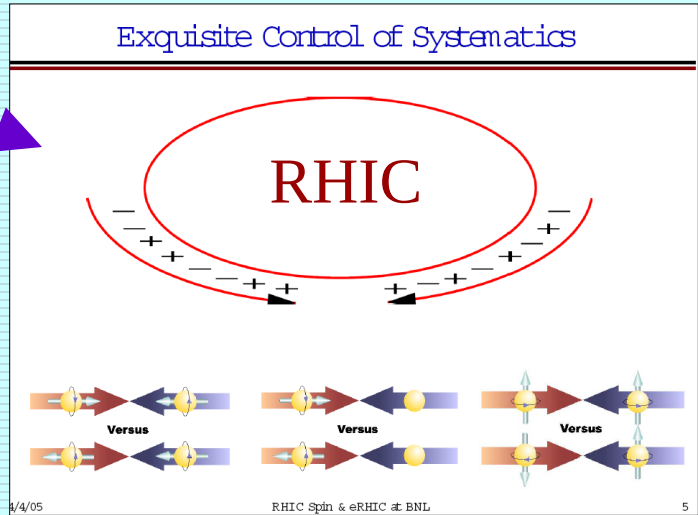
(3.0-3.5) $\cdot 10^{11}$ protons /pulse at 2.3 GeV

AGS

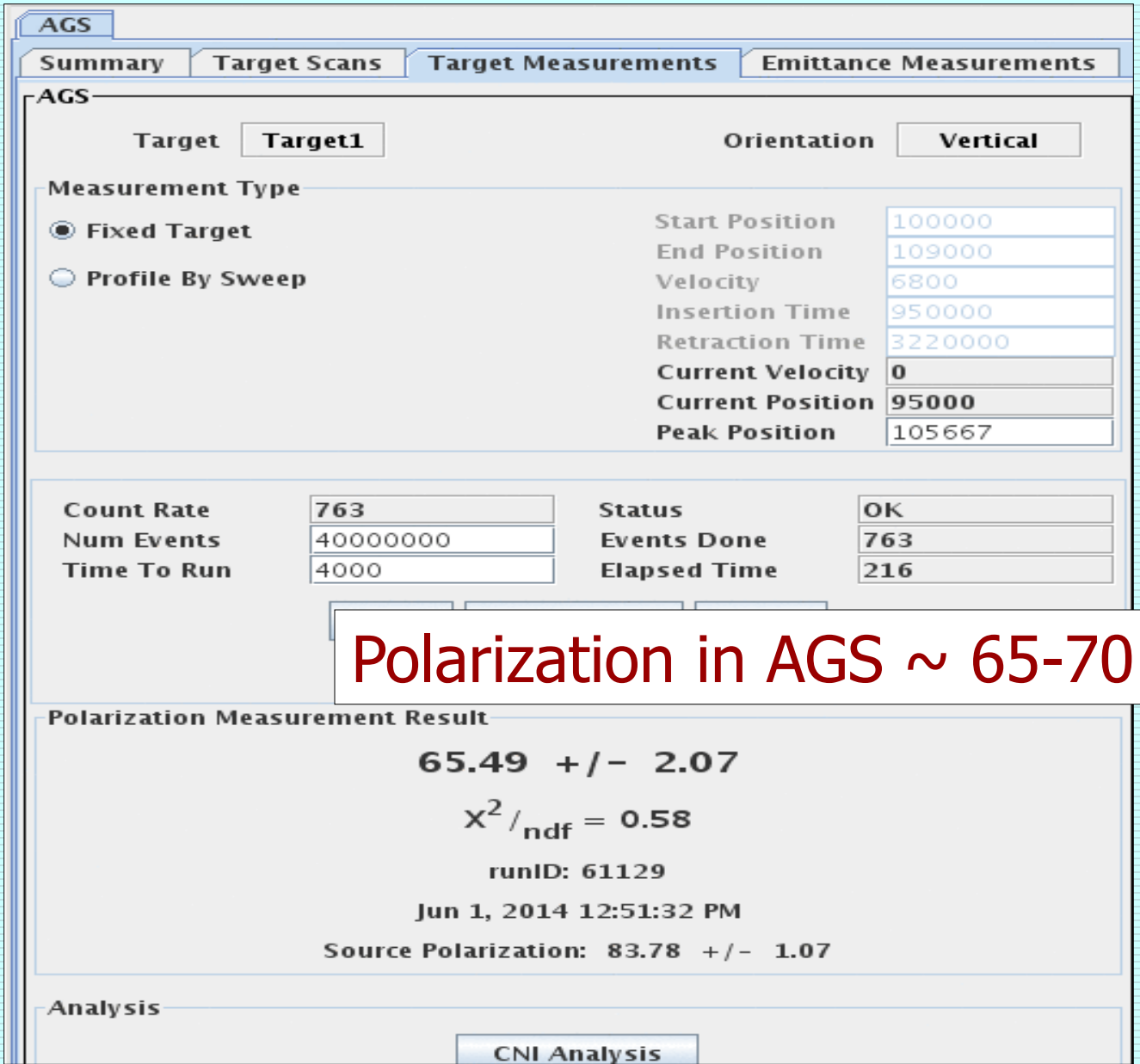
(2.5-3.0) $\cdot 10^{11}$ p/bunch

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

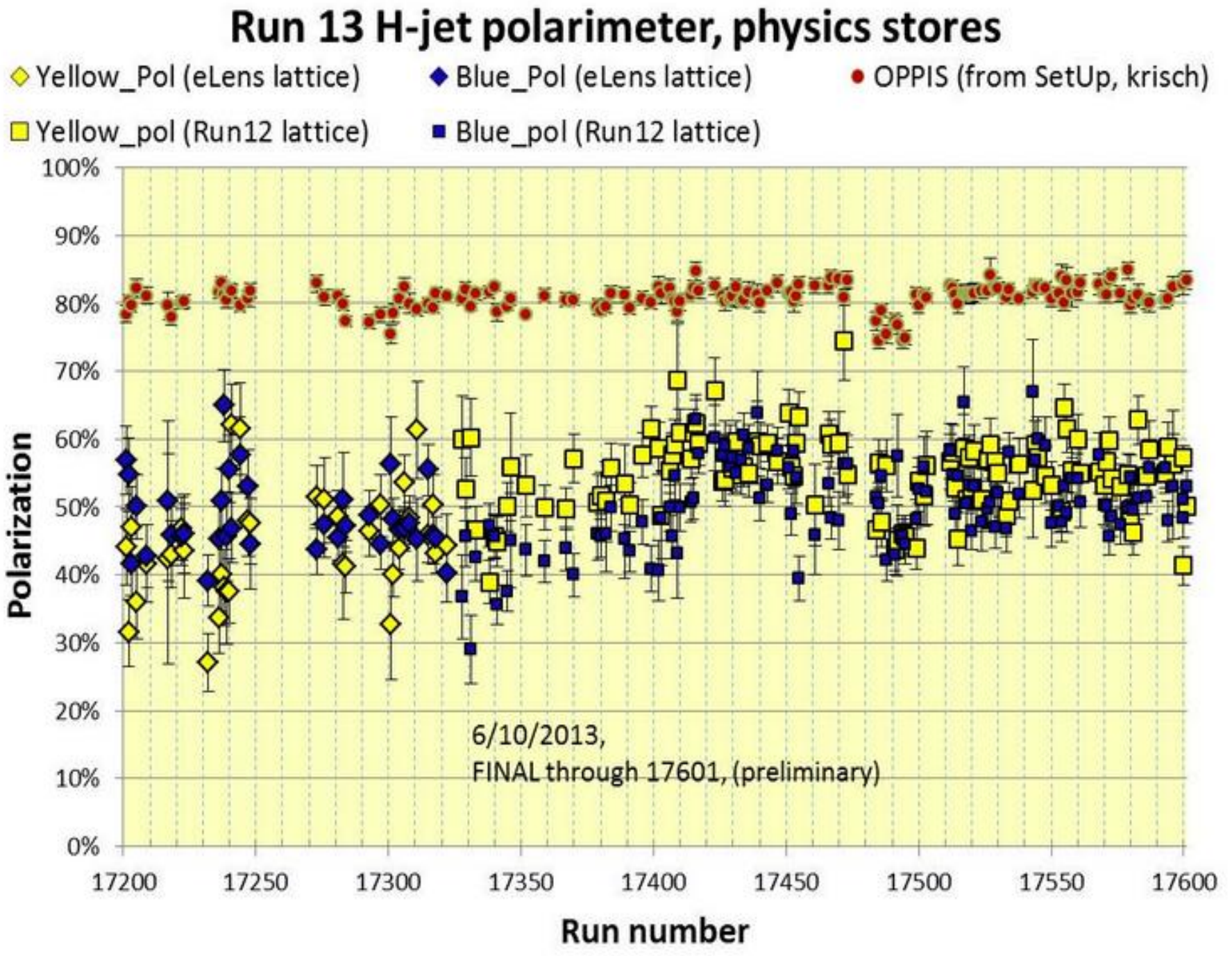
It is expected, that use of Electron Lens will allow increase of the bunch intensity to ~2.5$\cdot 10^{11}$ p/bunch.



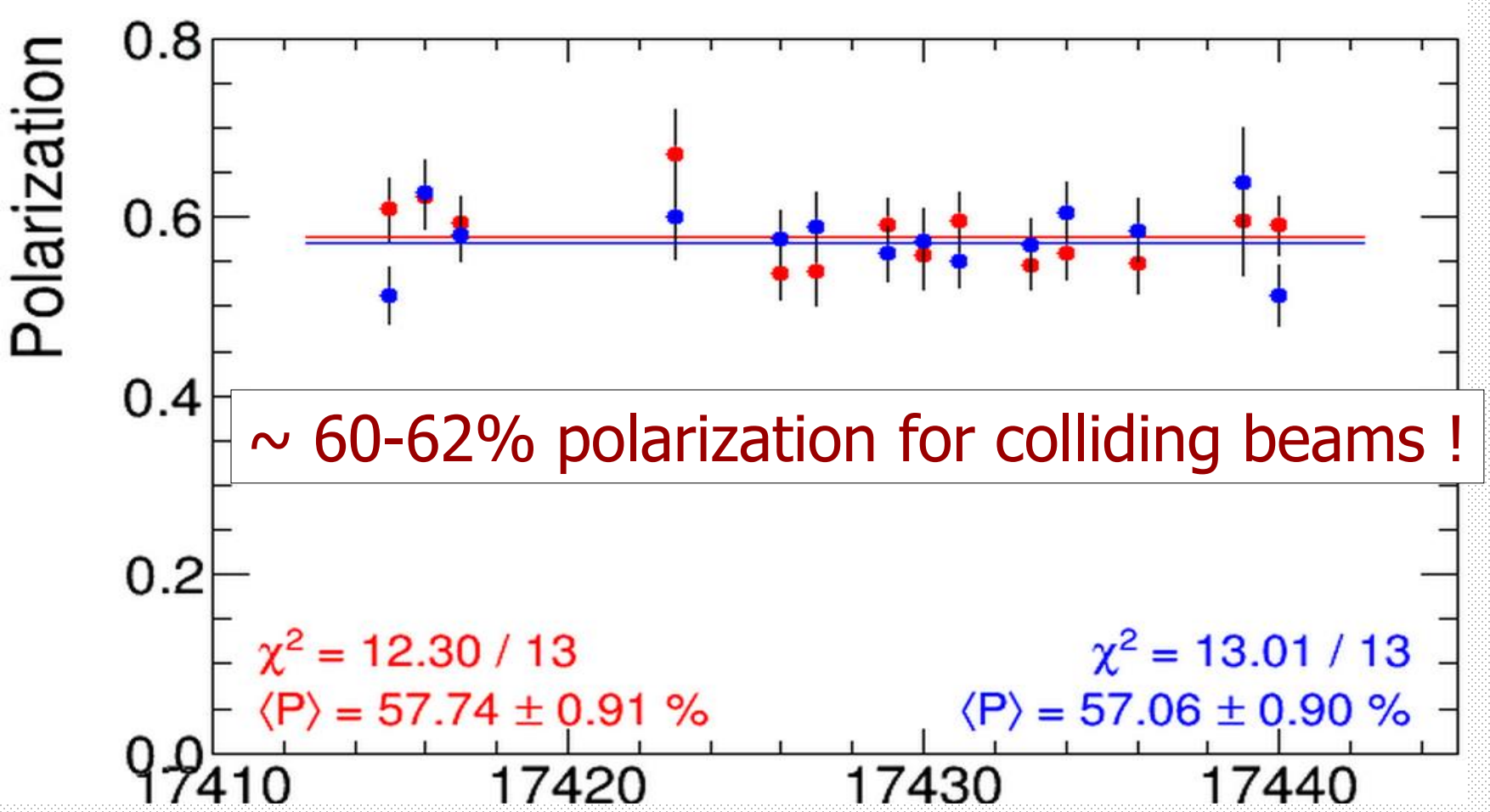
Rb-90deg, Booster input-$9.3 \cdot 10^{11}$, 200 Mev-83.8%



Polarization in AGS ~ 65-70 %

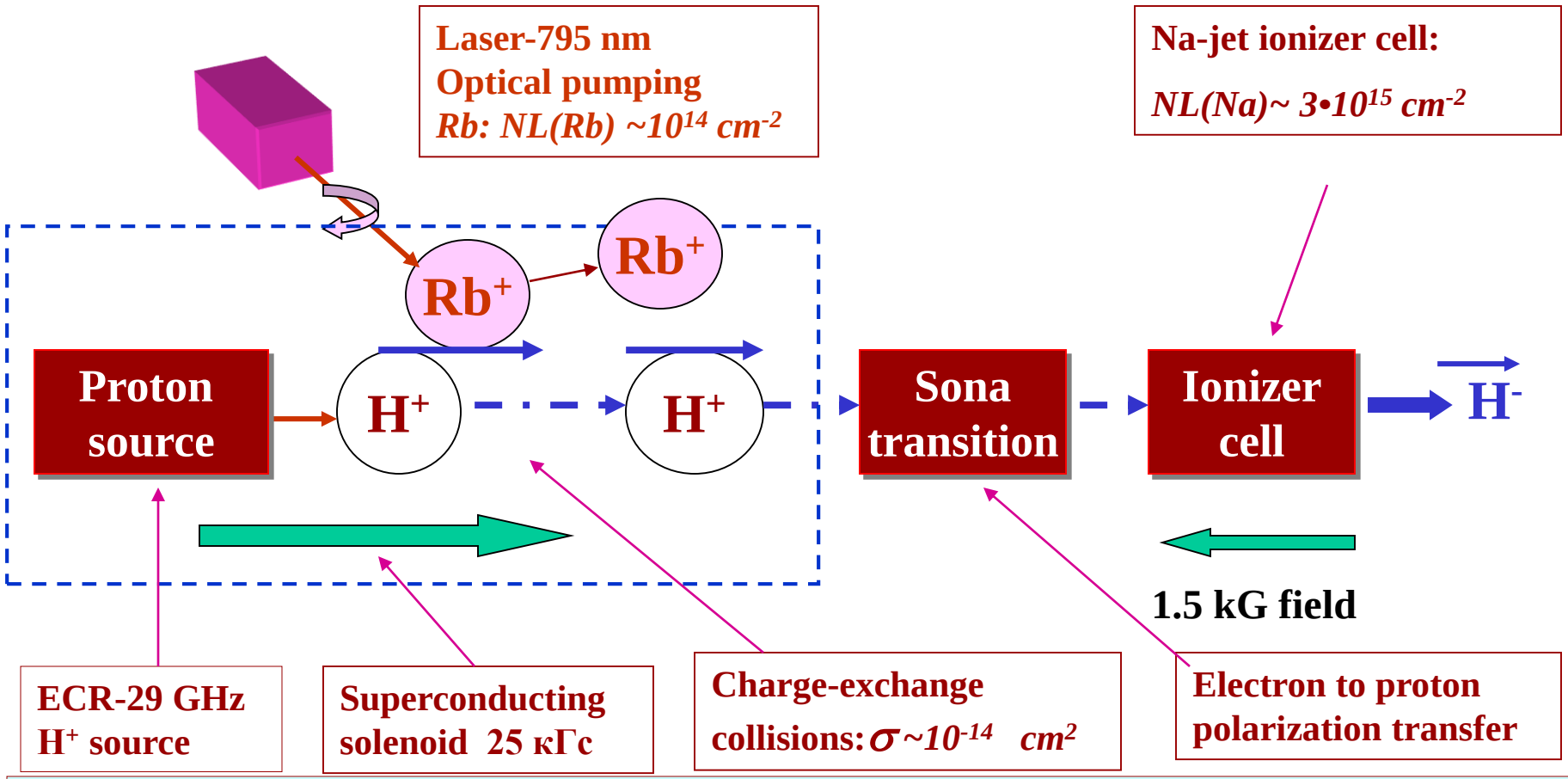

Run 13 H-jet polarimeter, physics stores
Yellow_Pol (eLens lattice)
Blue_Pol (eLens lattice)
OPPIS (from SetUp, krisch)
Yellow_pol (Run12 lattice)
Blue_pol (Run12 lattice)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Polarization
6/10/2013,
FINAL through 17601, (preliminary)
17200
17250
17300
17350
17400
17450
17500
17550
17600
Run number

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



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

SPIN -TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS.

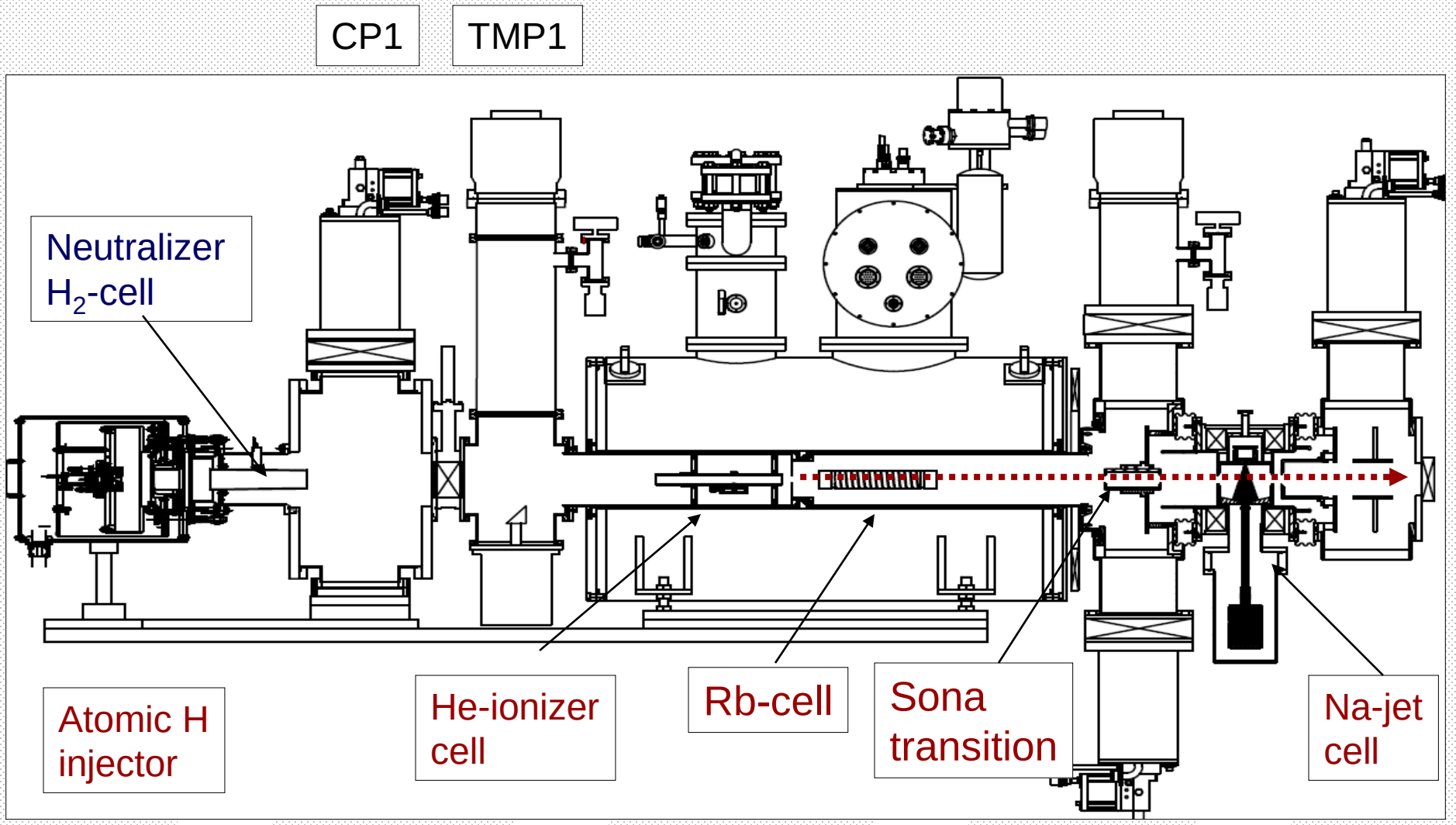


Laser beam is a powerfull primary source of angular momentum:

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

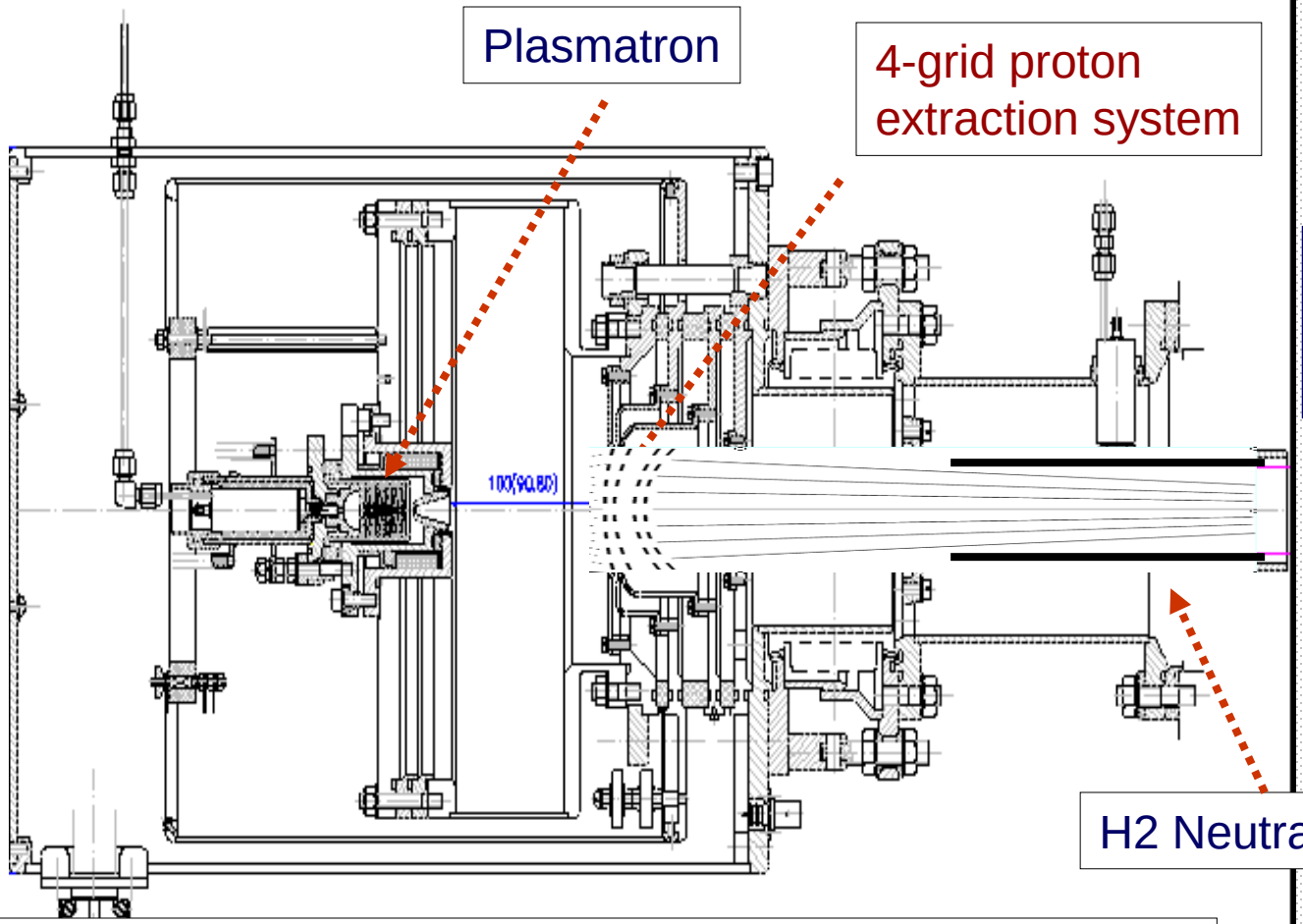
Feasibility of Multi-ampere polarized beams.

New OPPIS with atomic H^0 injector layout



H^+ —H2→ H^0 —He→ H^+ —Rb→ H^0 —Na→ H^-

"Fast Atomic Beam Source", BINP 2011



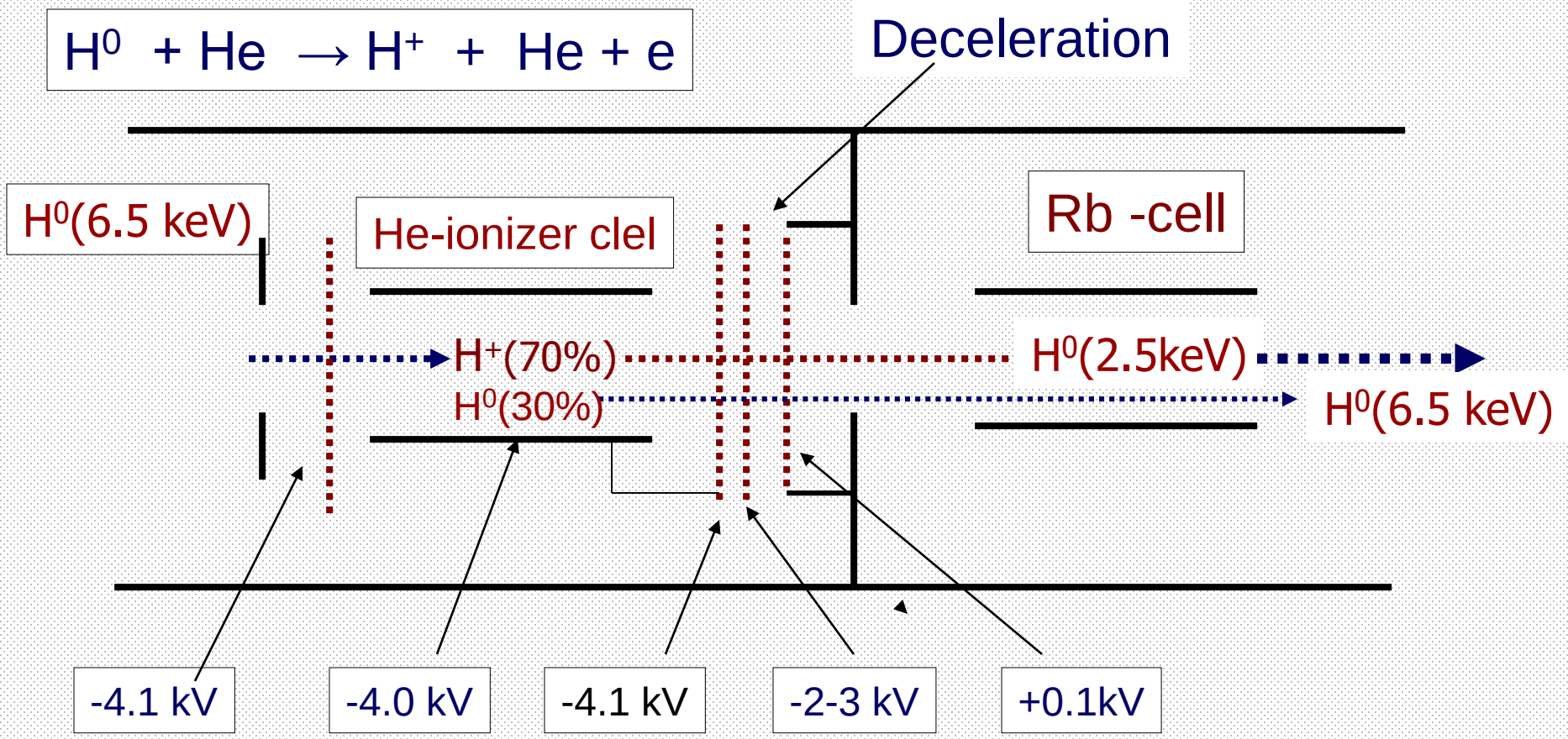
FABS produces 200-300 mA equivalent H0 beam intensity
Within the Na-jet ionizer acceptance.

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

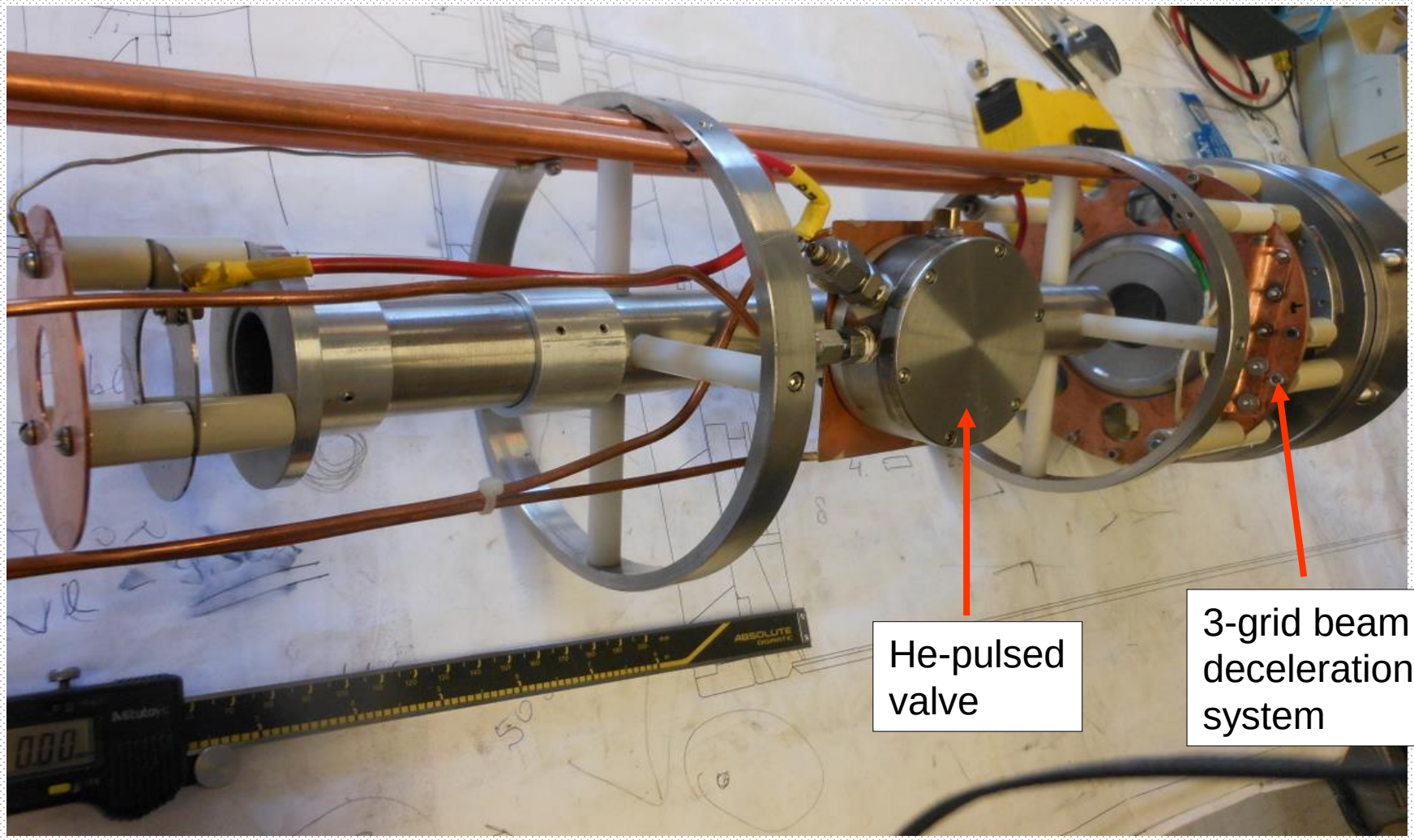
1820 holes ,5 cm in diameter

3-5 A of proton beam

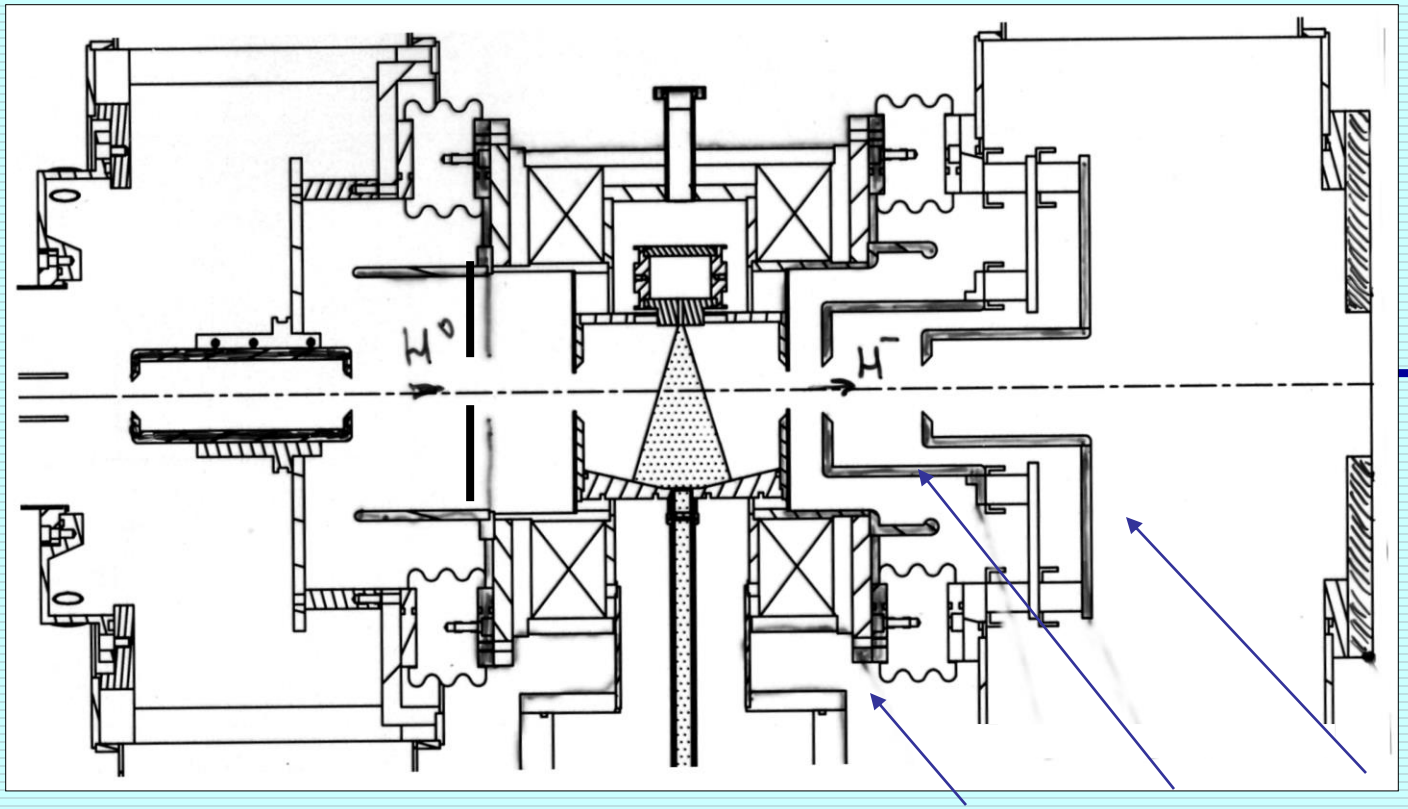
Residual un-polarized H^0 beam component suppression by the energy separation



He-ionizer cell and three-grid energy separation system



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



H^-

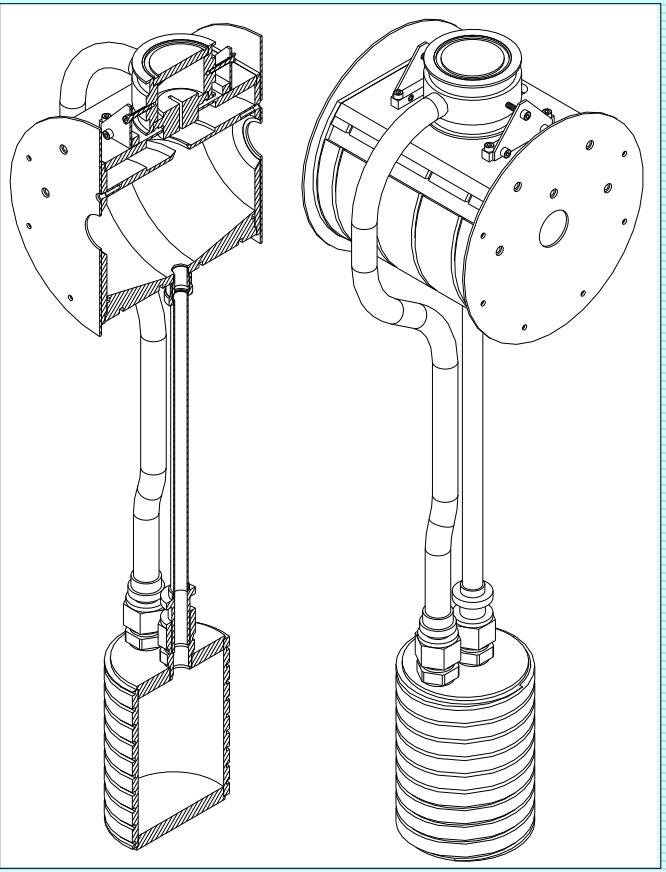
35 keV

-32 kV -28 keV -15 keV

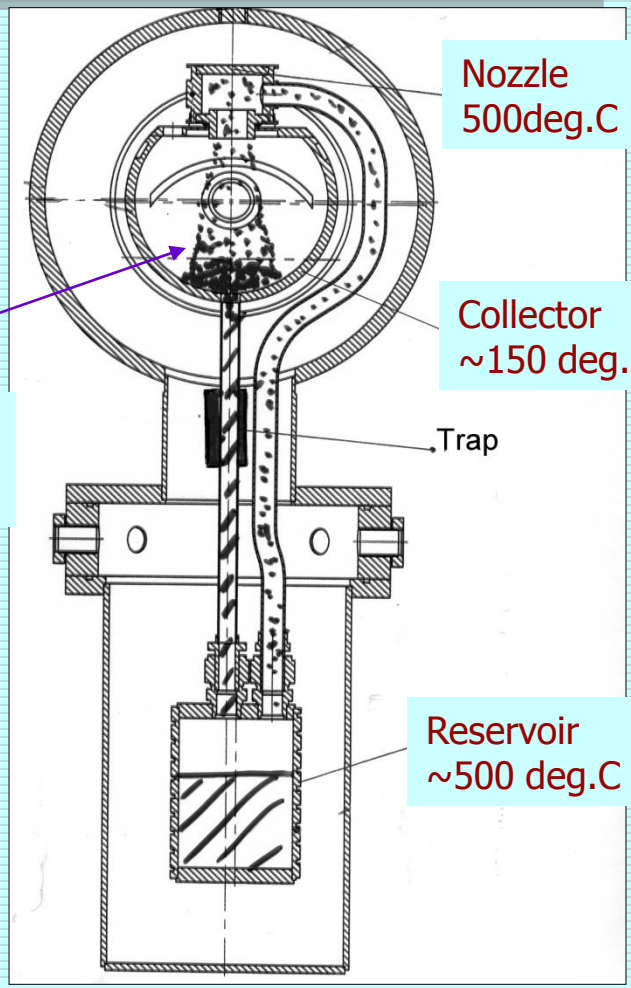
Na-jet cell is isolated and biased to – 32 keV. The H^- beam is accelerated in a two-stage acceleration system.

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 .

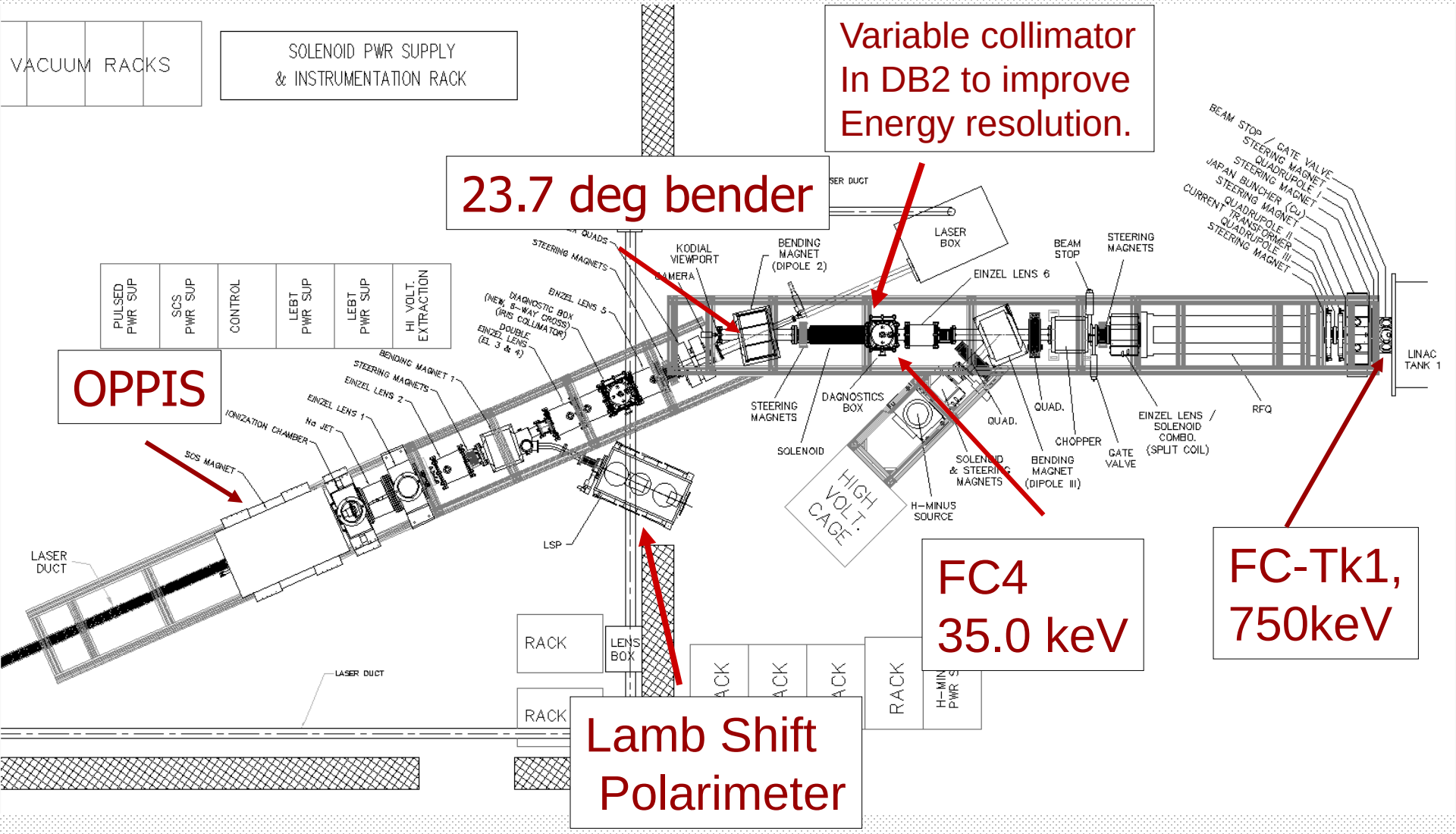


NL ~$2 \cdot 10^{15}$ atoms/cm^2
L ~ 2-3 cm



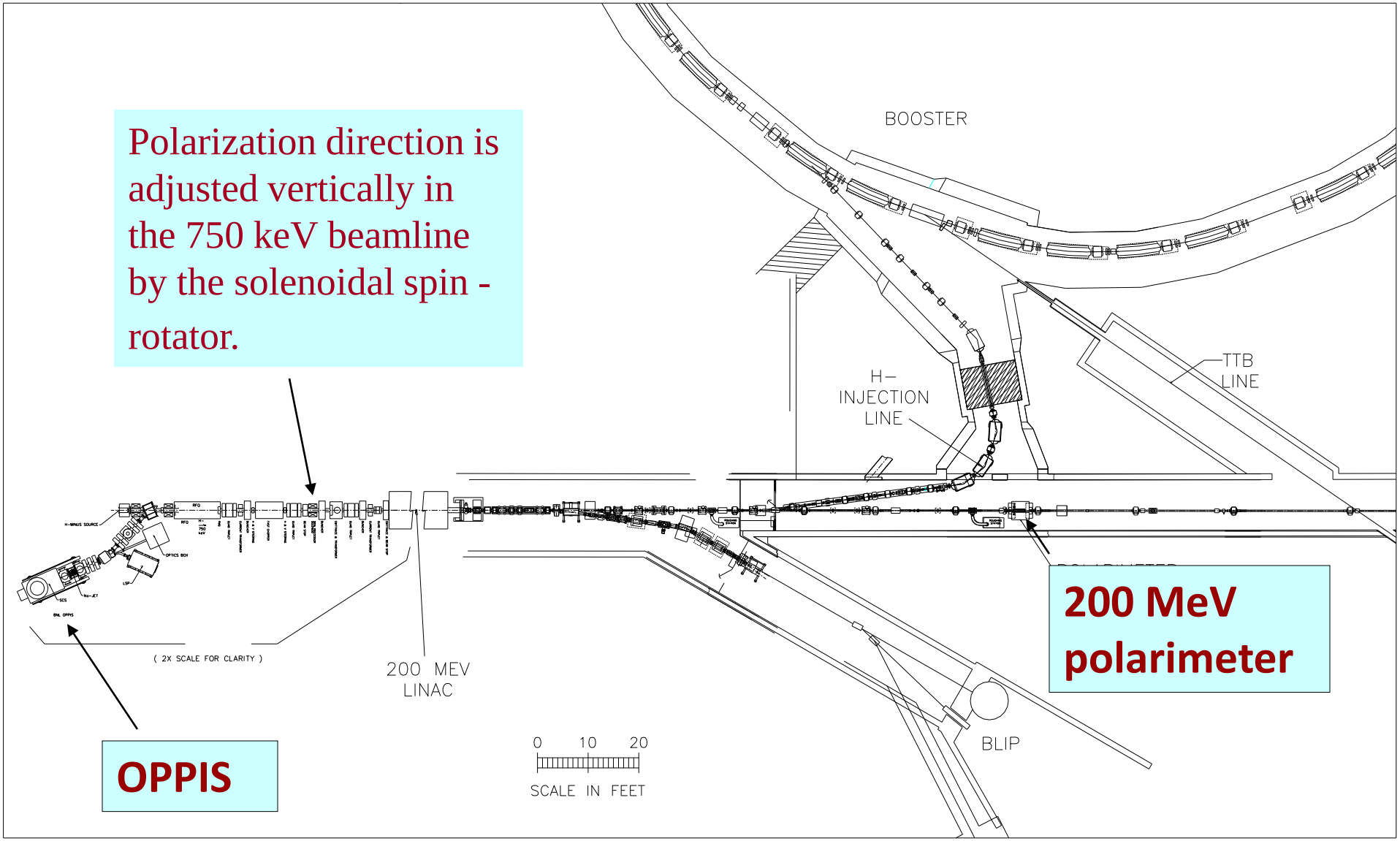
Reservoir– operational temperature. Tres. ~500 °C.
Nozzle – Tn ~500 °C.
Collector- Na-vapor condensation: Tcoll.~120°C
Trap- return line. T ~ 120 – 180 °C.

Low Energy Beam Transport line.

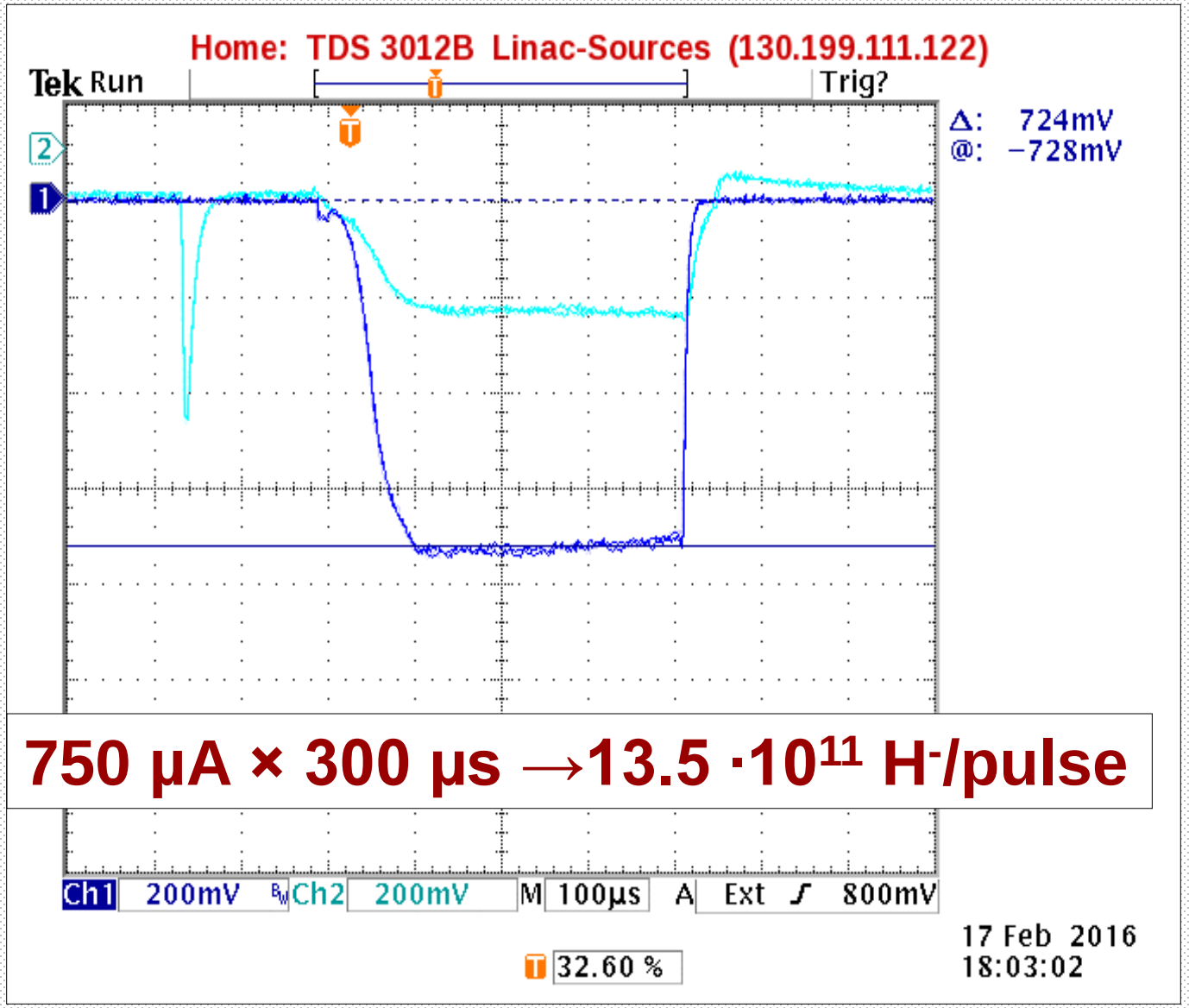


Polarized injector, 200 MeV Linac and HEBT

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



Febr. 17, 2016. 750 uA polarized current out of the Linac



750 µA × 300 µs →13.5 ·10^{11} H$^-$/pulse

Proton-Carbon Elastic Scattering at 200 MeV.

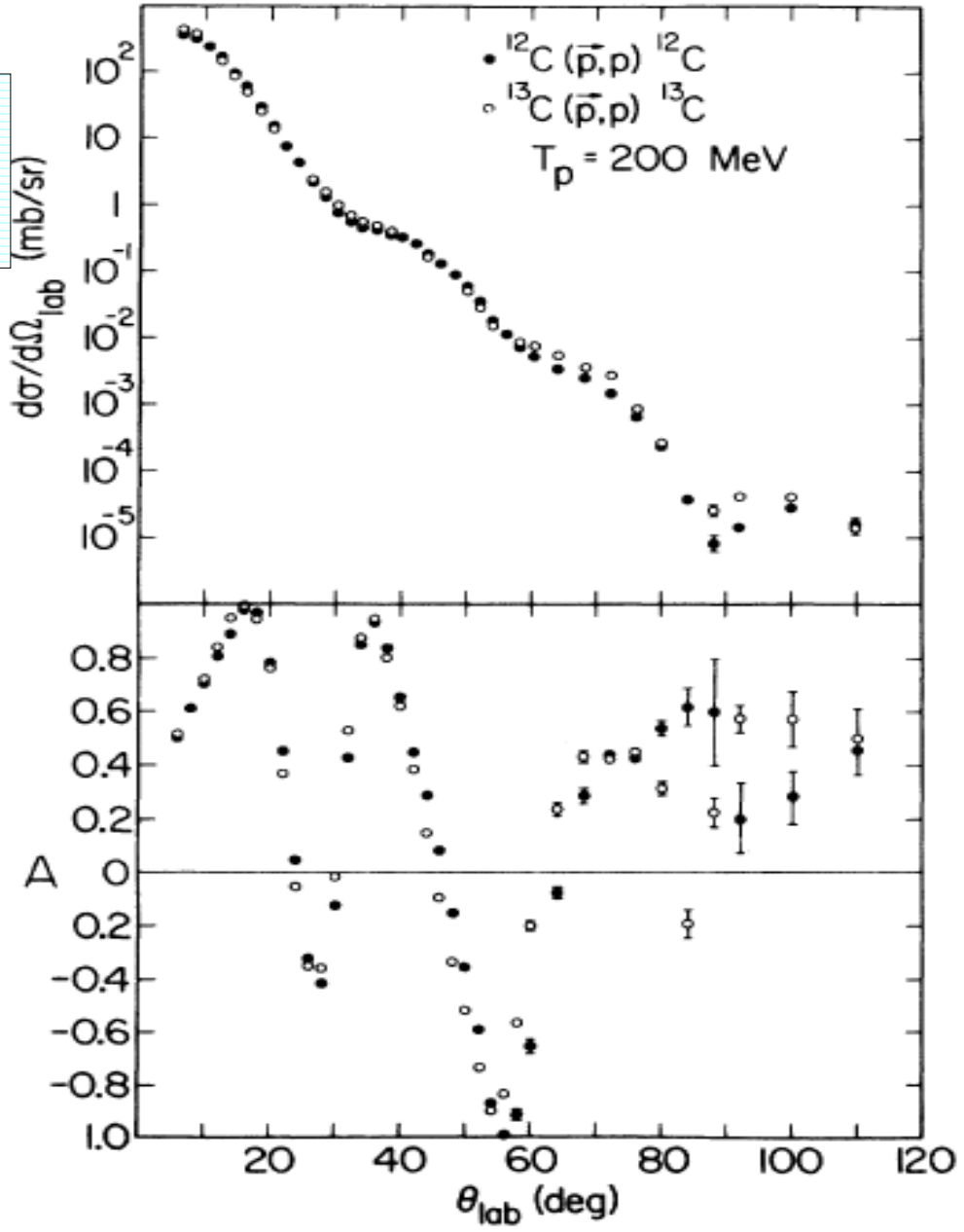
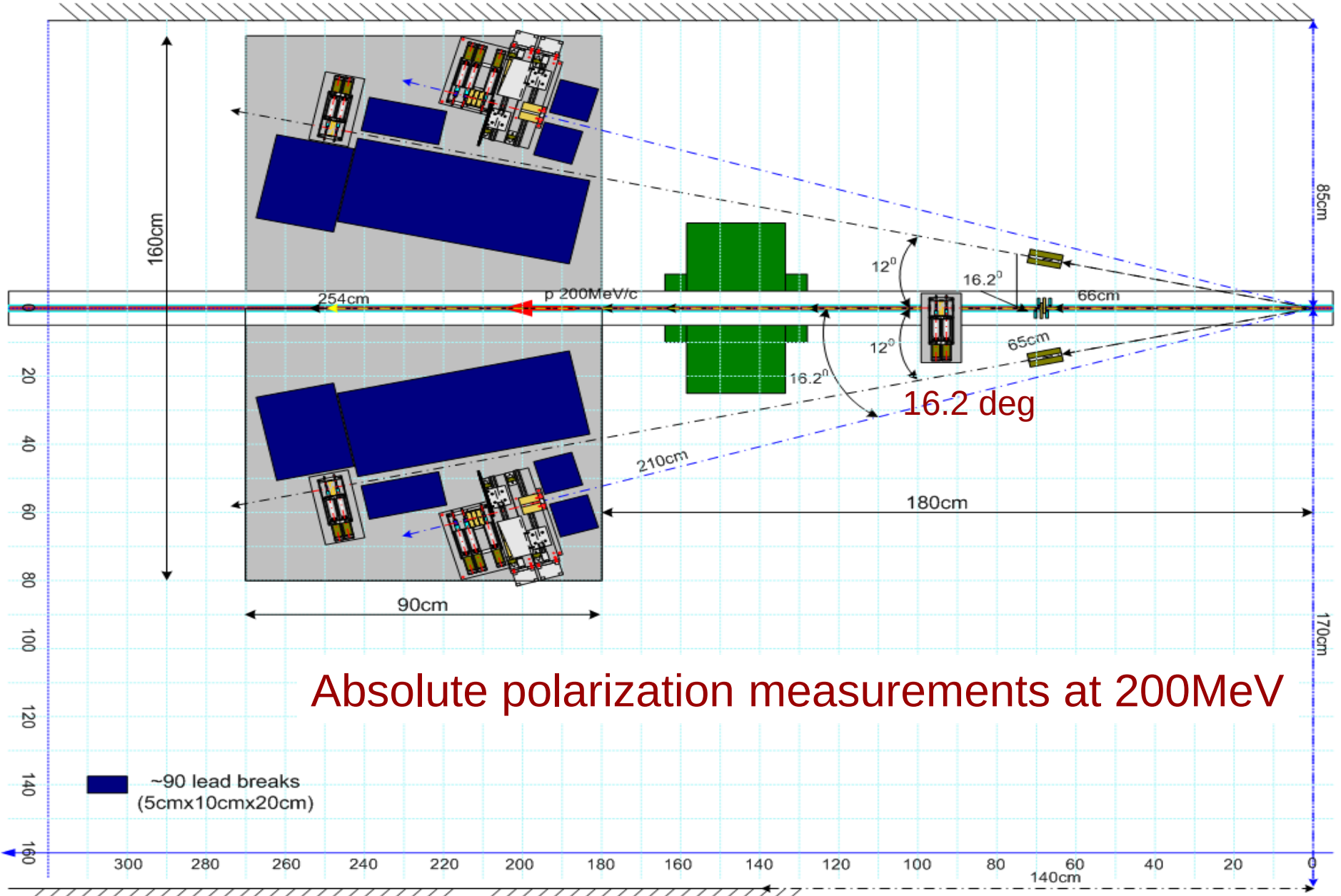
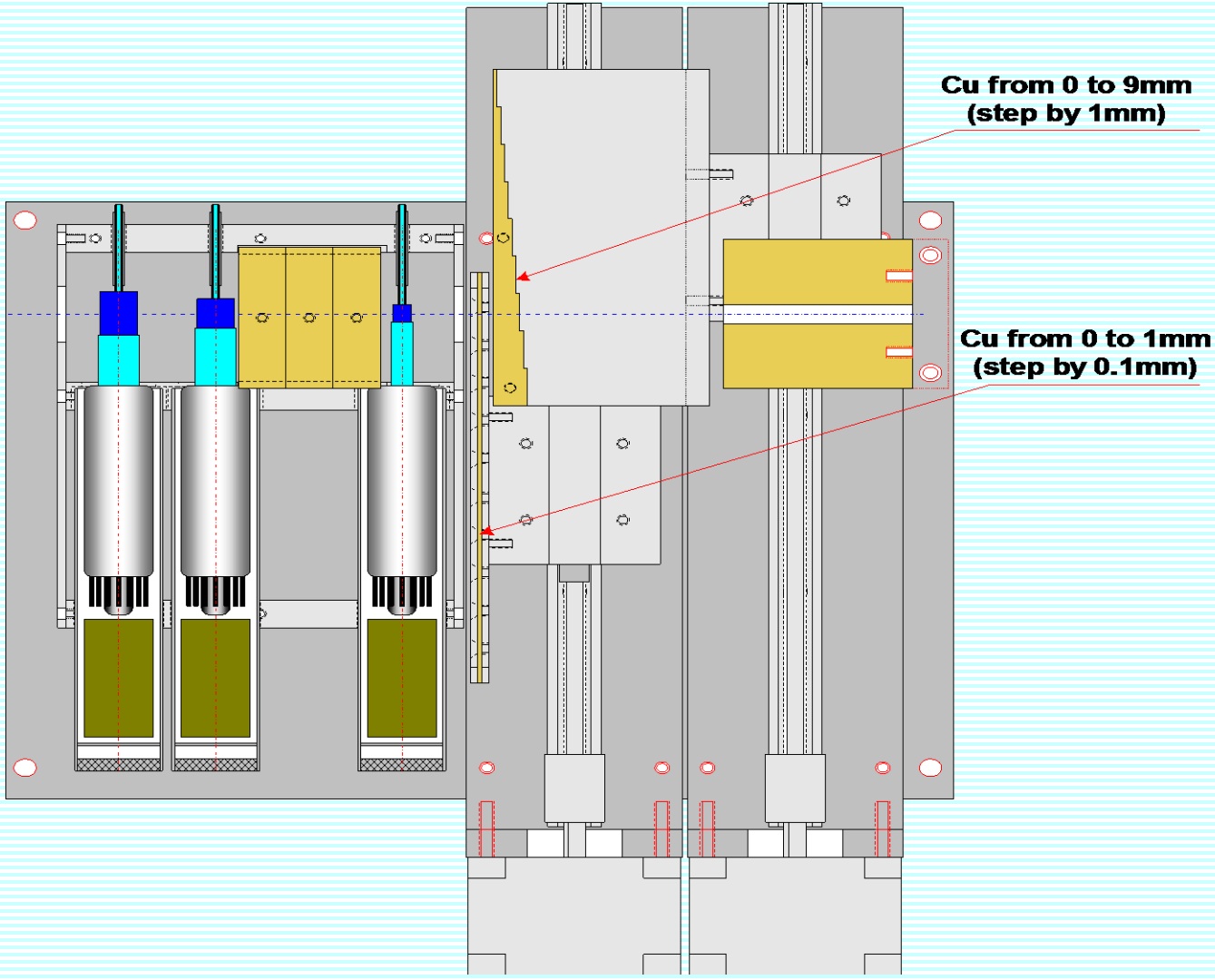


FIG. 1. Laboratory differential cross sections and analyzing powers, as a function of laboratory scattering angle, measured for 200 MeV polarized protons elastically scattered from ^{12}C and ^{13}C.

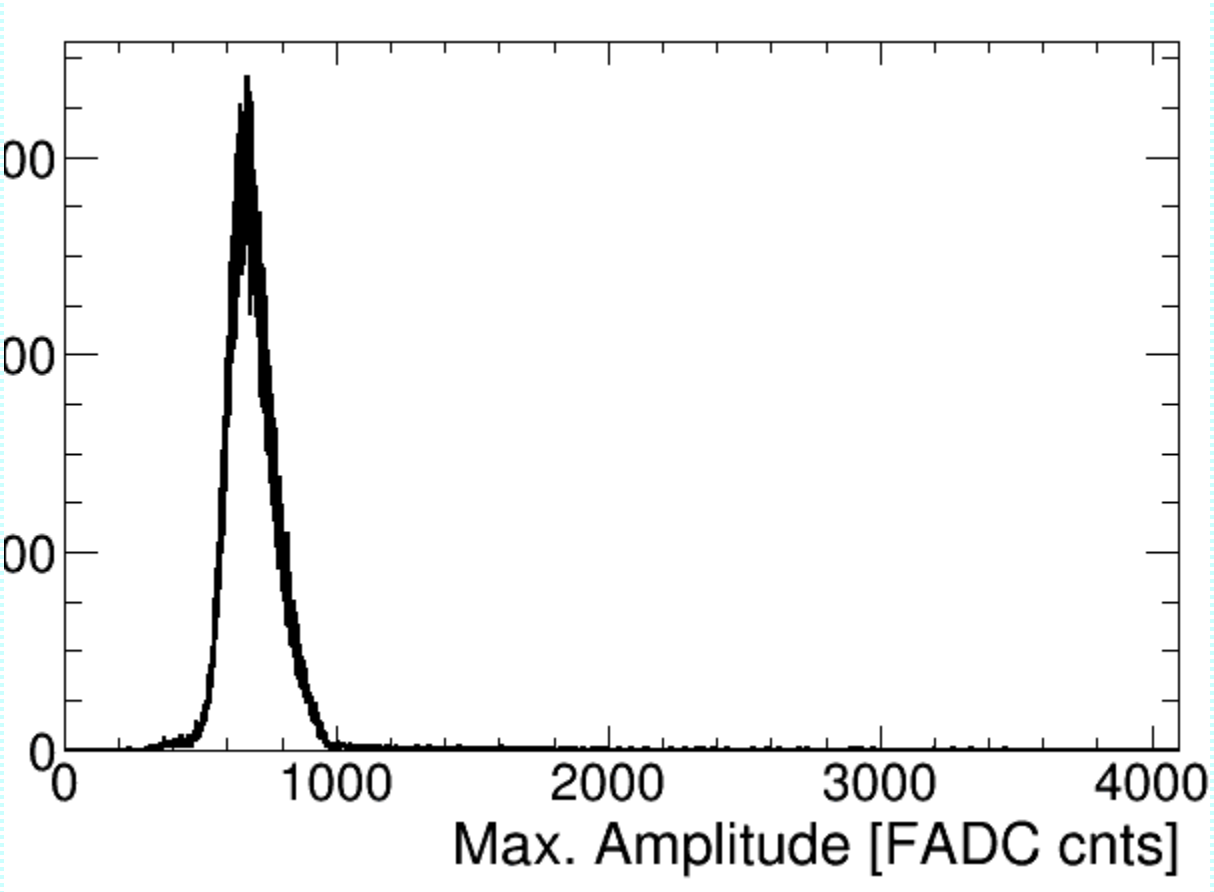
Layout of the 200 MeV proton polarimeter, (2010)



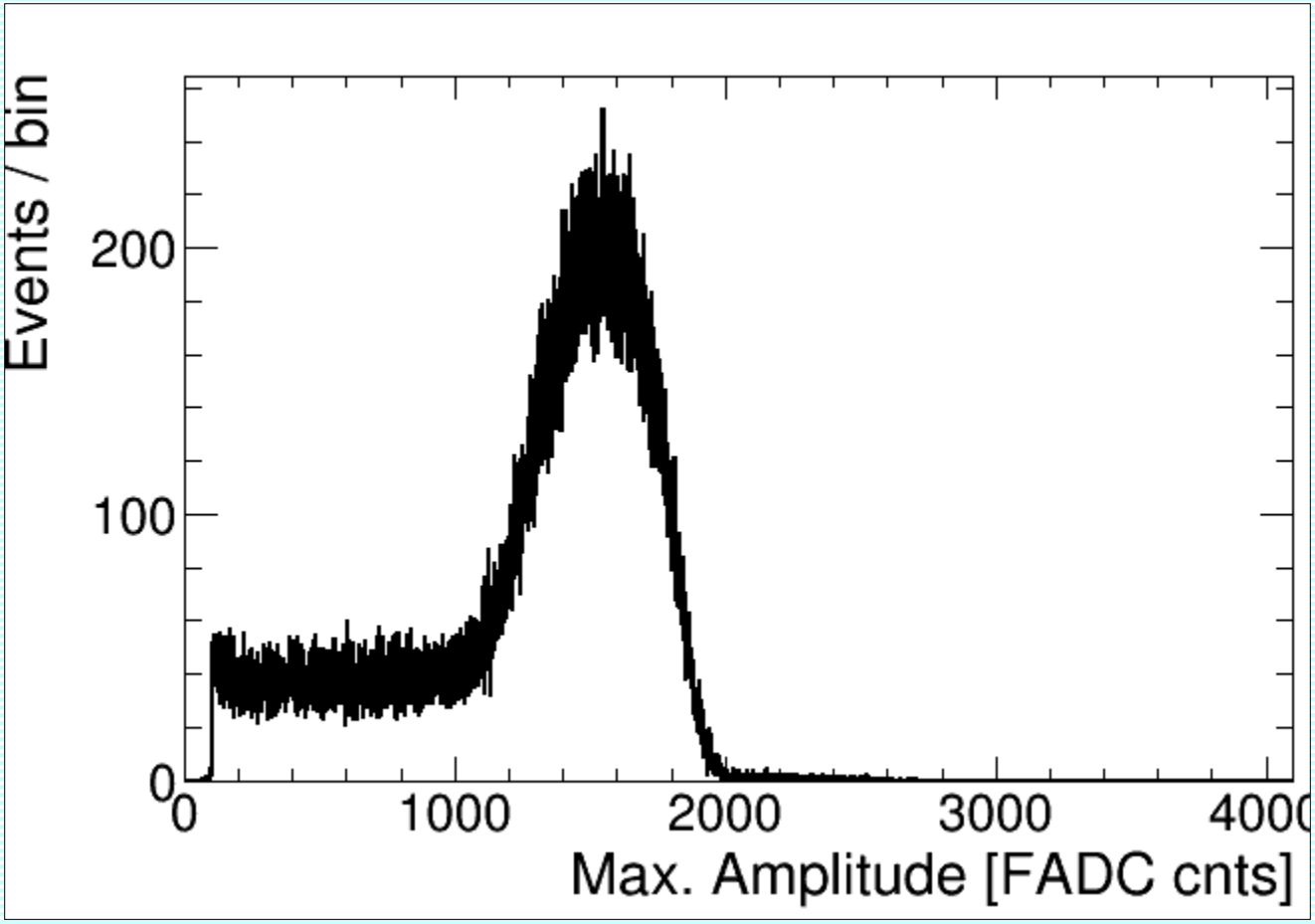
Detector and variable absorber setup for 200 MeV proton beam.



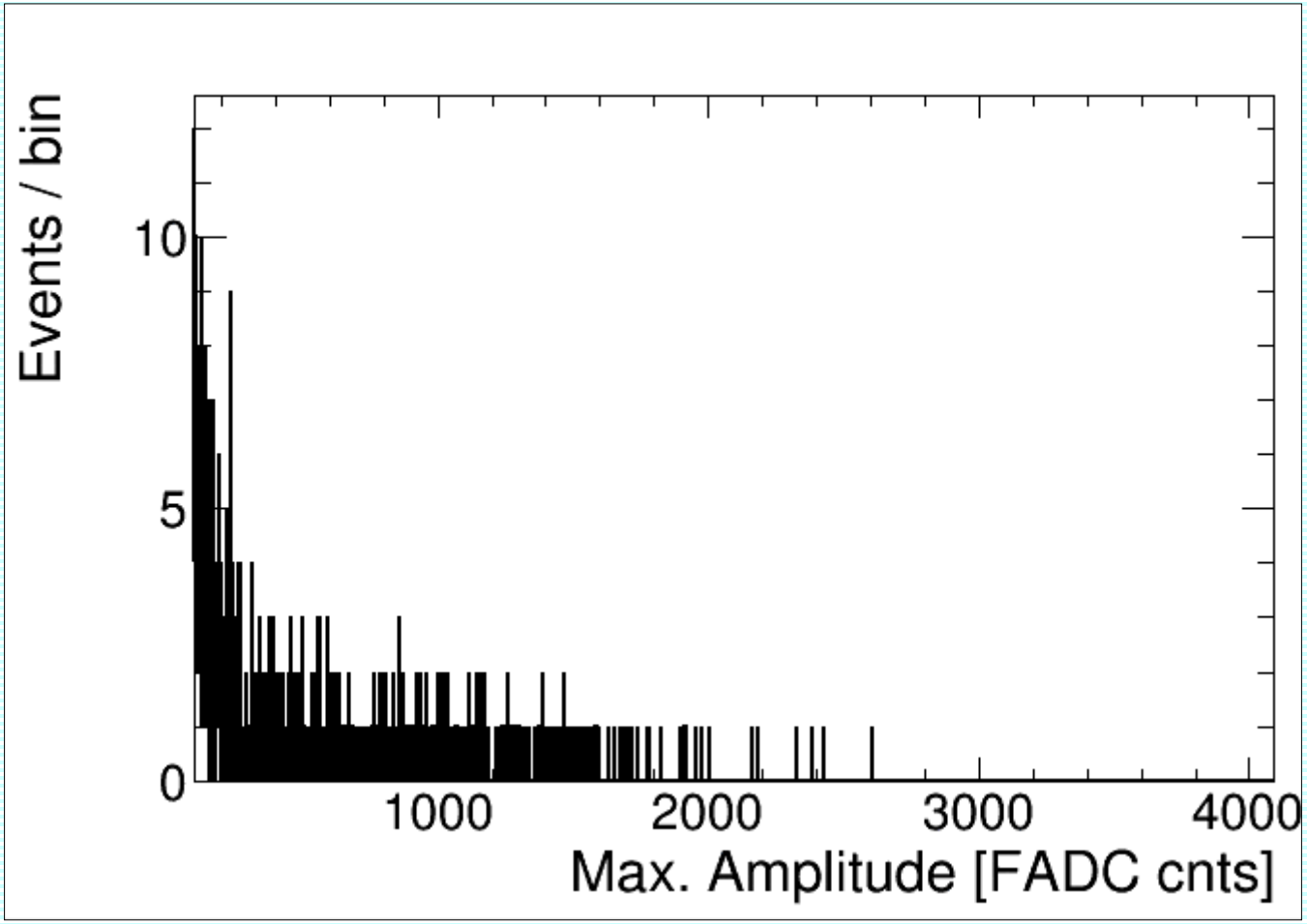
Signal amplitude distribution in the first detector



Signal amplitude distribution in the 2-nd detector



Signal amplitude distribution in the 3-rd detector



84.5% polarization was measured using WFD.

		Points	Polarization	Left Polar.	Right Polar.	Left Up	Right Up	Left Down	Right Down
12°	All	6	0.8563 ± 0.0209	0.8558 ± 0.0281	0.8568 ± 0.0309	49.3 ± 4.3	170.3 ± 14.4	160.8 ± 13.1	52.1 ± 5.2
	4 Sigma Cut	6	0.8563 ± 0.0209	0.8558 ± 0.0281	0.8568 ± 0.0309	49.3 ± 4.3	170.3 ± 14.4	160.8 ± 13.1	52.1 ± 5.2
	3 Sigma Cut	6	0.8563 ± 0.0209	0.8558 ± 0.0281	0.8568 ± 0.0309	49.3 ± 4.3	170.3 ± 14.4	160.8 ± 13.1	52.1 ± 5.2
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	1 Sigma Cut	6	0.8563 ± 0.0209	0.8558 ± 0.0281	0.8568 ± 0.0309	49.3 ± 4.3	170.3 ± 14.4	160.8 ± 13.1	52.1 ± 5.2

		Points	Polarization	Left Polar.	Right Polar.	Left Up	Right Up	Left Down	Right Down
16°	All	6	0.8517 ± 0.0181	0.8529 ± 0.0169	0.8505 ± 0.0321	0.55 ± 0.14	7.32 ± 0.57	6.51 ± 0.79	0.63 ± 0.33
	4 Sigma Cut	6	0.8517 ± 0.0181	0.8529 ± 0.0169	0.8505 ± 0.0321	0.55 ± 0.14	7.32 ± 0.57	6.51 ± 0.79	0.63 ± 0.33
	3 Sigma Cut	6	0.8517 ± 0.0181	0.8529 ± 0.0169	0.8505 ± 0.0321	0.55 ± 0.14	7.32 ± 0.57	6.51 ± 0.79	0.63 ± 0.33
	2 Sigma Cut	6	0.8517 ± 0.0181	0.8529 ± 0.0169	0.8505 ± 0.0321	0.55 ± 0.14	7.32 ± 0.57	6.51 ± 0.79	0.63 ± 0.33
	1 Sigma Cut	6	0.8517 ± 0.0181	0.8529 ± 0.0169	0.8505 ± 0.0321	0.55 ± 0.14	7.32 ± 0.57	6.51 ± 0.79	0.63 ± 0.33

CONTROL

STATUS

DATA

Pulse	12														
106															
107															
108															
109															
110															
111															
112															
113		183		41		10		1		729	0	1335			
114	36		153		0		7		776		1335	0	1.0166	1.0101	0.0568
115		135		44											
116	53		171		0										
117		143		38											
118	46		179		2										
119		156		51		5		0		755	0	1336			
120	44		157		0		8		771		1335	0	0.8634	1.0101	0.0191
121		159		45		5		0		736	0	1335			

Polarization at 200 MeV -85.2%

SETUP

12° Analyzing power	0.62	12° Min. count (LU, RD)	20	Moving average	stack
16° Analyzing power	0.99	12° Min. count (LD, RU)	99	Averaging interval	10
U/D Analyzing power	0.55			Energy ave. interval	10

ANALYSIS

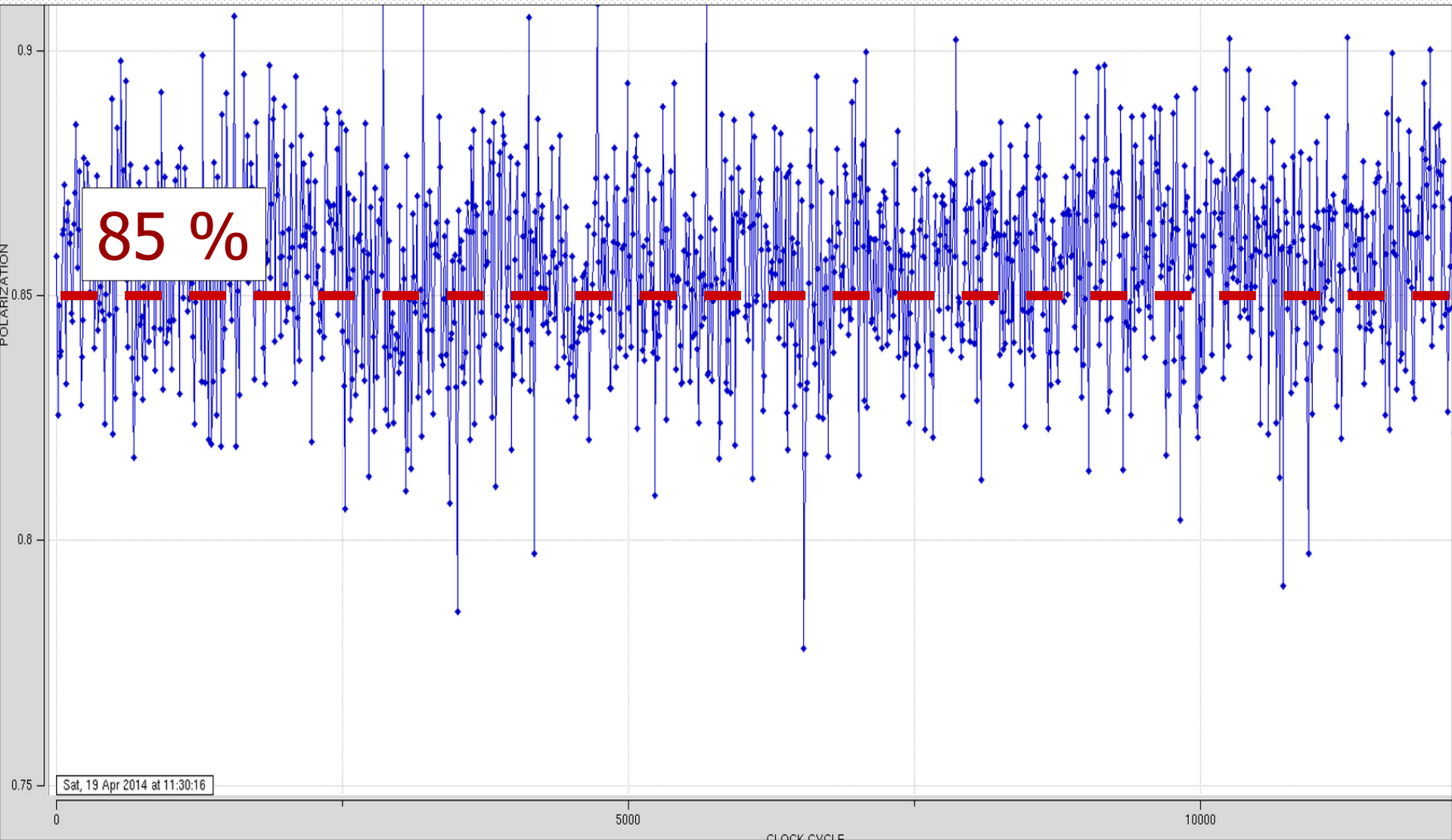
REFRESH	HISTOGRAMS	TIMECHARTS
ANALYZE	PULSE COUNTS	BEAM ENERGY

RESULTS

Comment

12° Left Arm events (U, D)		2966 - 7	9664 - 15		49.4 - 0.1	161.1 - 0.2		47.8 - 0.1	157.8 - 0.3
12° Right Arm events (U, D)	Totals	10229 - 12	3135 - 7	Averages	170.5 - 0.2	52.2 - 0.1	Moving ave.	159.4 - 0.4	49.9 - 0.2
12° POLARIZATION (P, dP)		0.8563	0.0085		0.8576	0.0092		0.8539	0.0213
16° Left Arm events (U, D)		35 - 0	406 - 3		0.58 - 0.00	6.77 - 0.05		0.60 - 0.00	6.40 - 0.20
16° Right Arm events (U, D)	Totals	445 - 1	38 - 0	Averages	7.42 - 0.02	0.63 - 0.00	Moving ave.	6.20 - 0.00	0.60 - 0.00
16° POLARIZATION (P, dP)		0.8498	0.0180					0.8318	0.0491

Polarization stability ~12 hrs, April 19



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.

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.

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 ~ $5 \cdot 10^{-3}$)

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

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

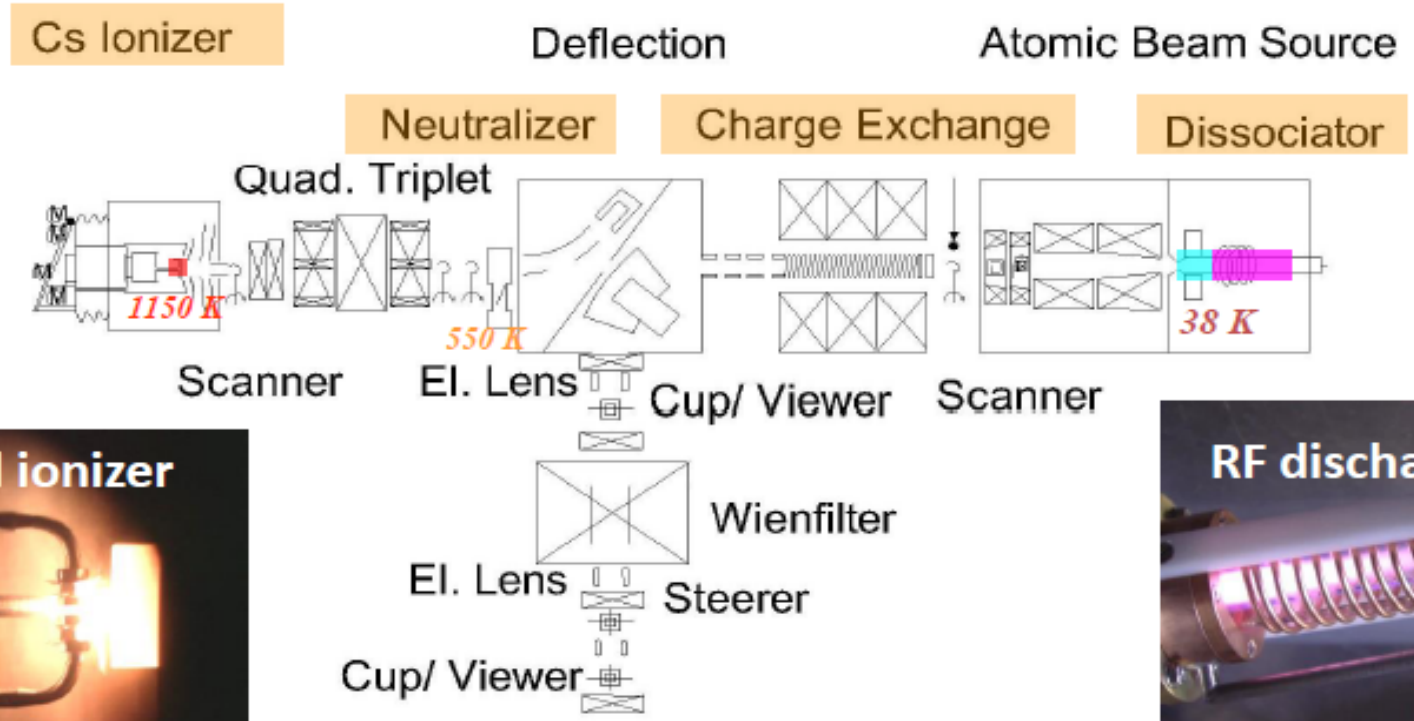
$$H^0\uparrow + D^- \Rightarrow H^-\uparrow + D^0$$

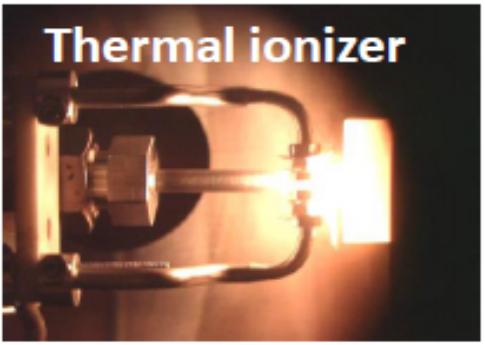
(conversion efficiency ~ 0,12)

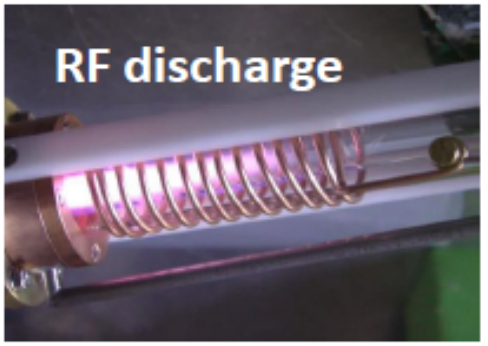
4 mA of pulsed $H^-\uparrow$ (Belov et. al., INR RAS)

COSY's Polarized Ion Source

R.Gebel







Charge exchange reaction

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

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

INR RAS source of polarized H^- ions

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

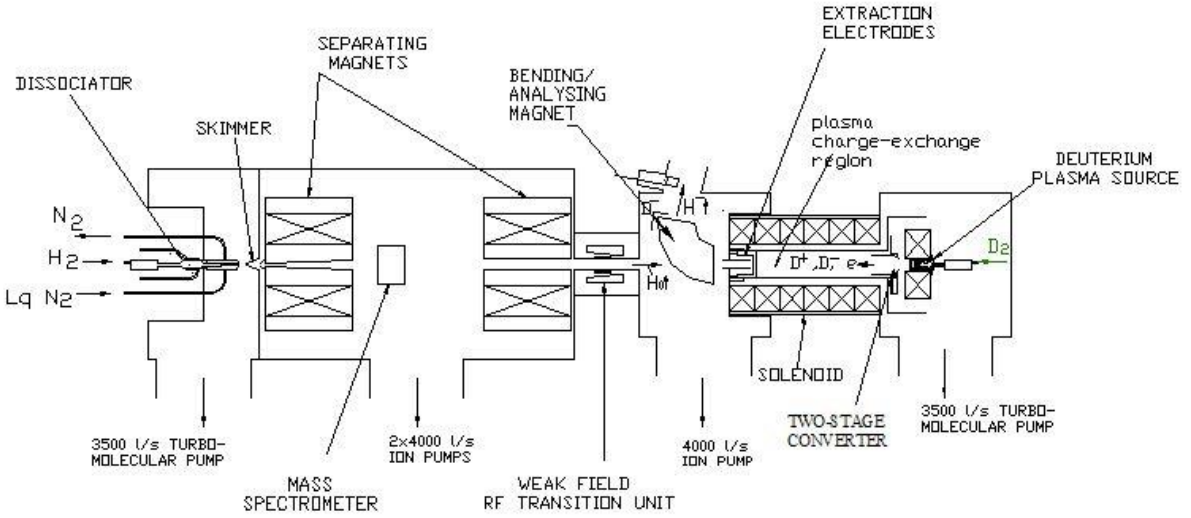
Peak H^- ion current - 4 mA
Polarization ~ 0.9

Unpolarized D^- ion current
60 mA (~20 mA/cm^2)

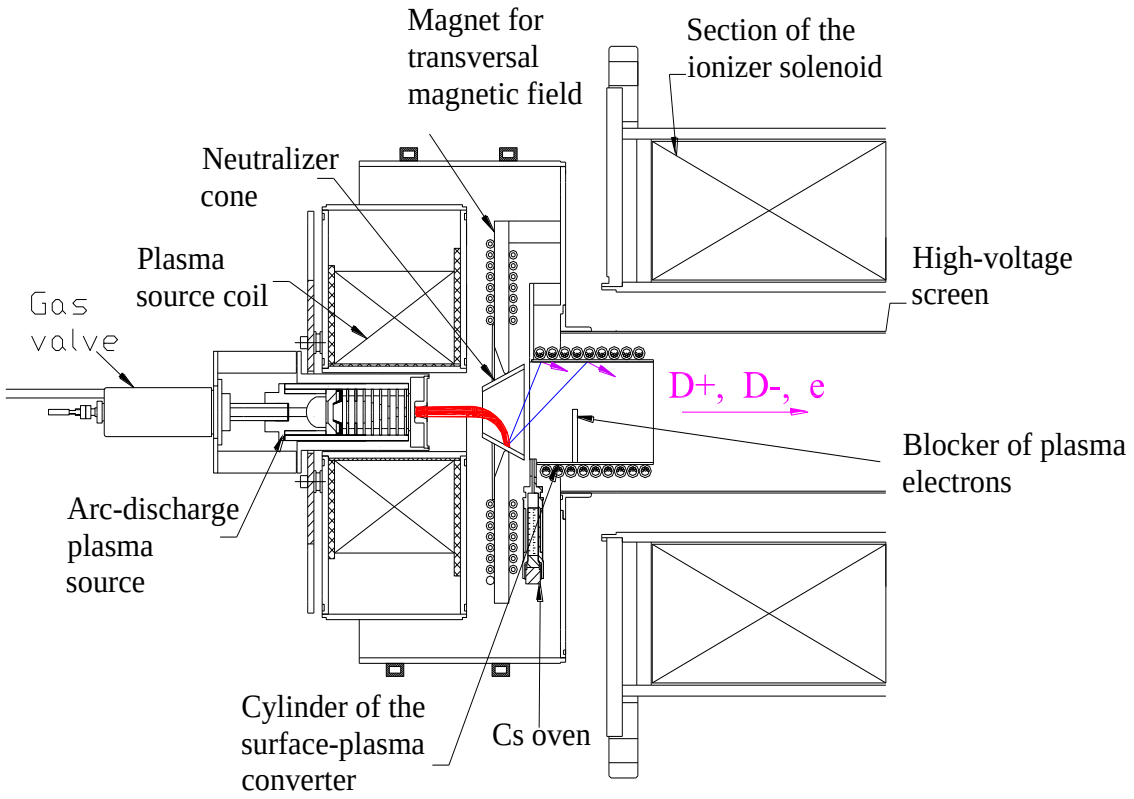
Pulse duration (FWHM) –
170 μs

Rep. Rate 5 Hz

(Belov et. al, 2007)



Plasma generator for resonant charge-exchange ionizer

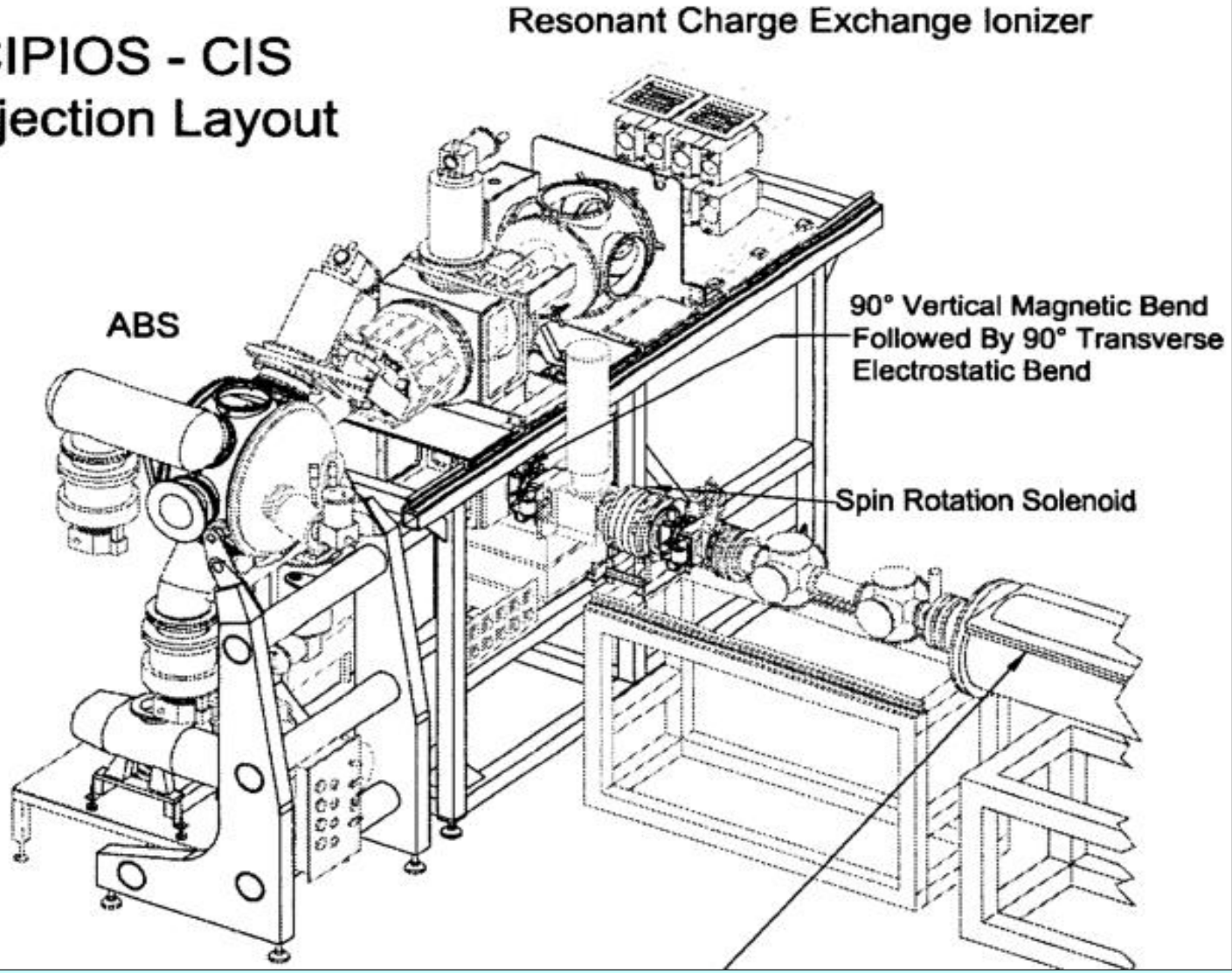


- In order to produce polarized negative hydrogen ions it was necessary to have deuterium plasma consisting mainly from D^+ and D^- ions because slow polarized H^- ions can be easily destroyed in collisions with plasma electrons.

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

CIPIOS polarized H^- ion source with INR plasma ionizer at IUCF

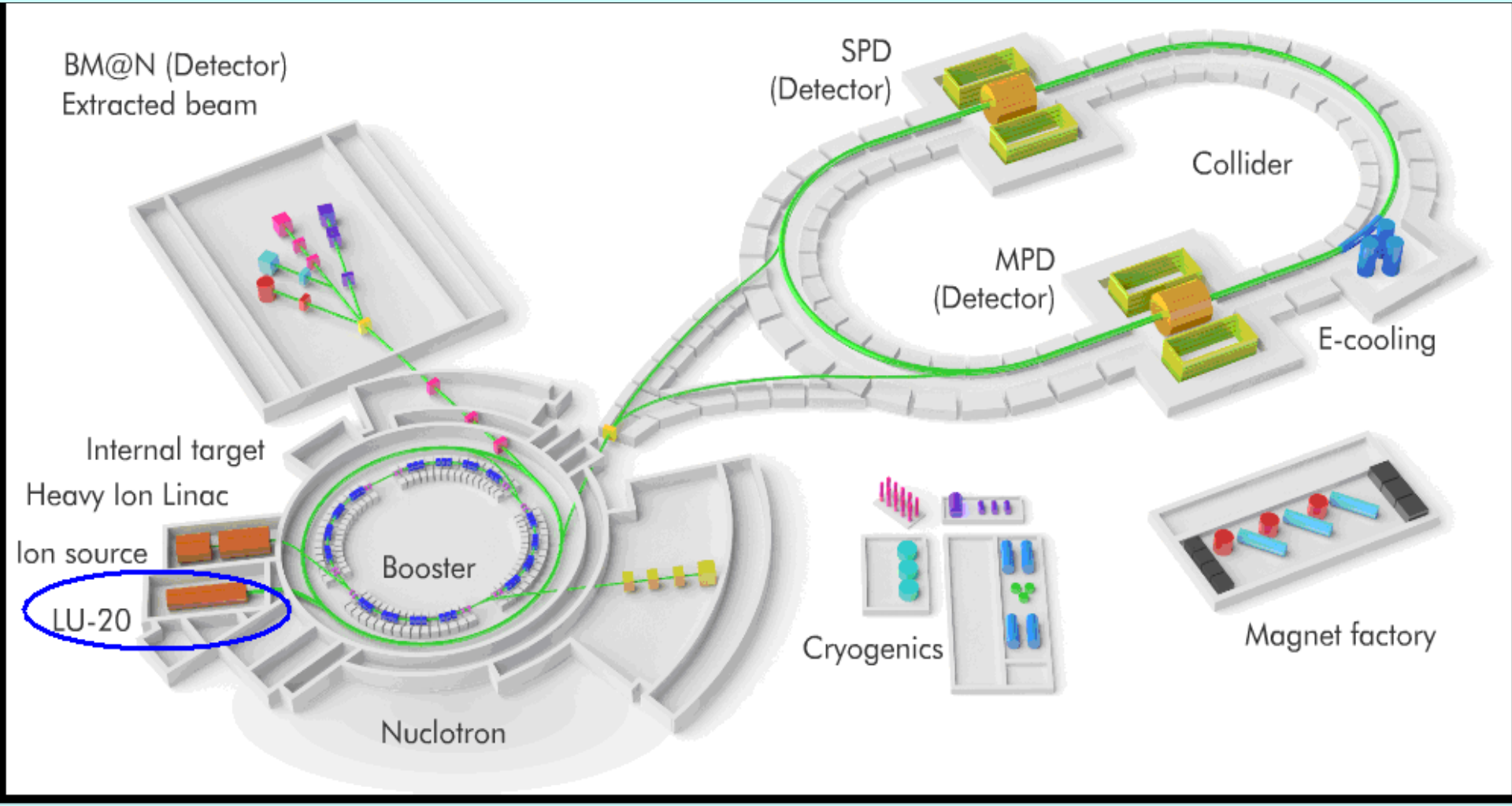
CIPIOS - CIS Injection Layout



Beam Properties

- Pulsed @ 1Hz to 4Hz
- 25 keV Beam Energy
- Polarized H^- or D^-
- Nominal polarization ≥80%
- ≈1.5 mA (peak) from source
- ≥25 mA (peak) unpolarized available

NICA- accelerator –collider complex at JINR, Dubna



The polarized ions source for NICA accelerator complex

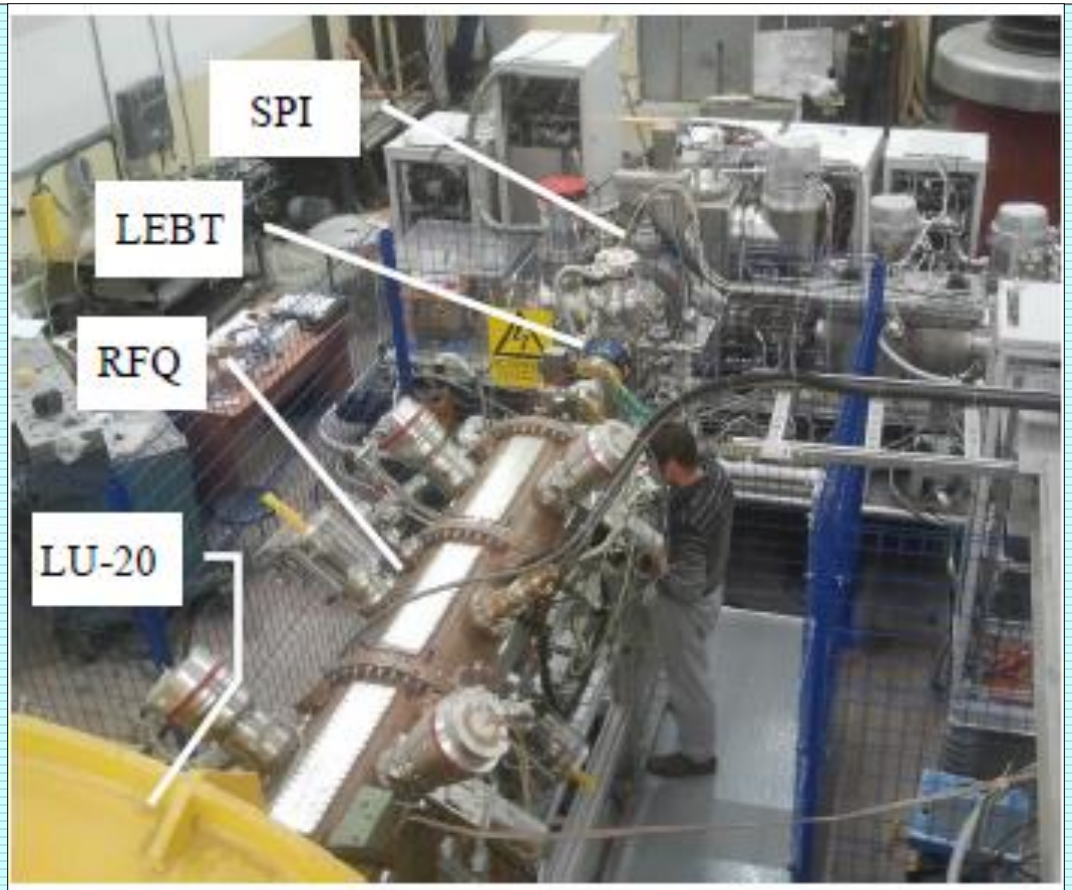
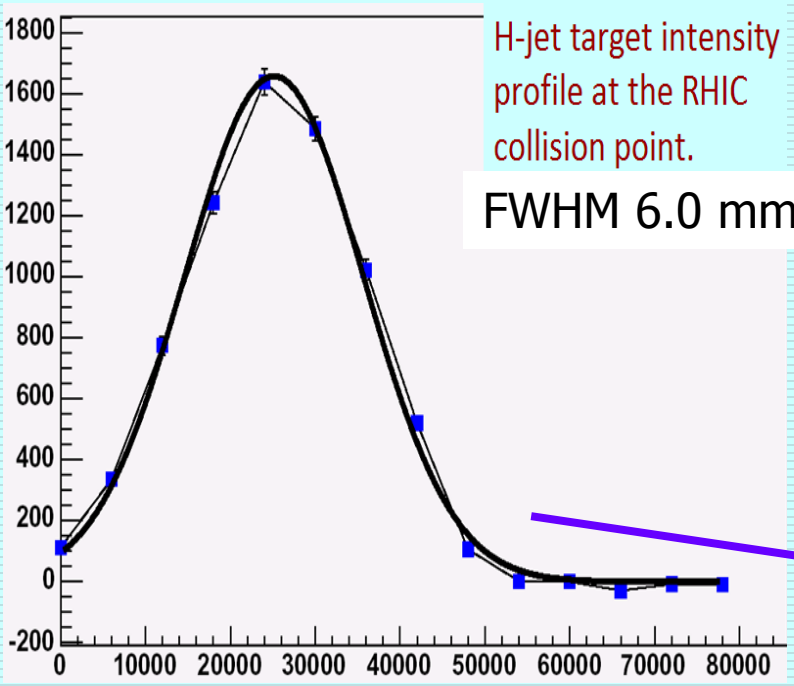


Figure 6: Source of Polarized Ions mounted on the HV terminal and RFQ connected to the LU-20

In October-November 2016 Run, D^+ beam current of 1.7-2.0 mA was produced and accelerated In Nuclotron. D polarization ~75-90% of maximum value.

H -jet polarimeter



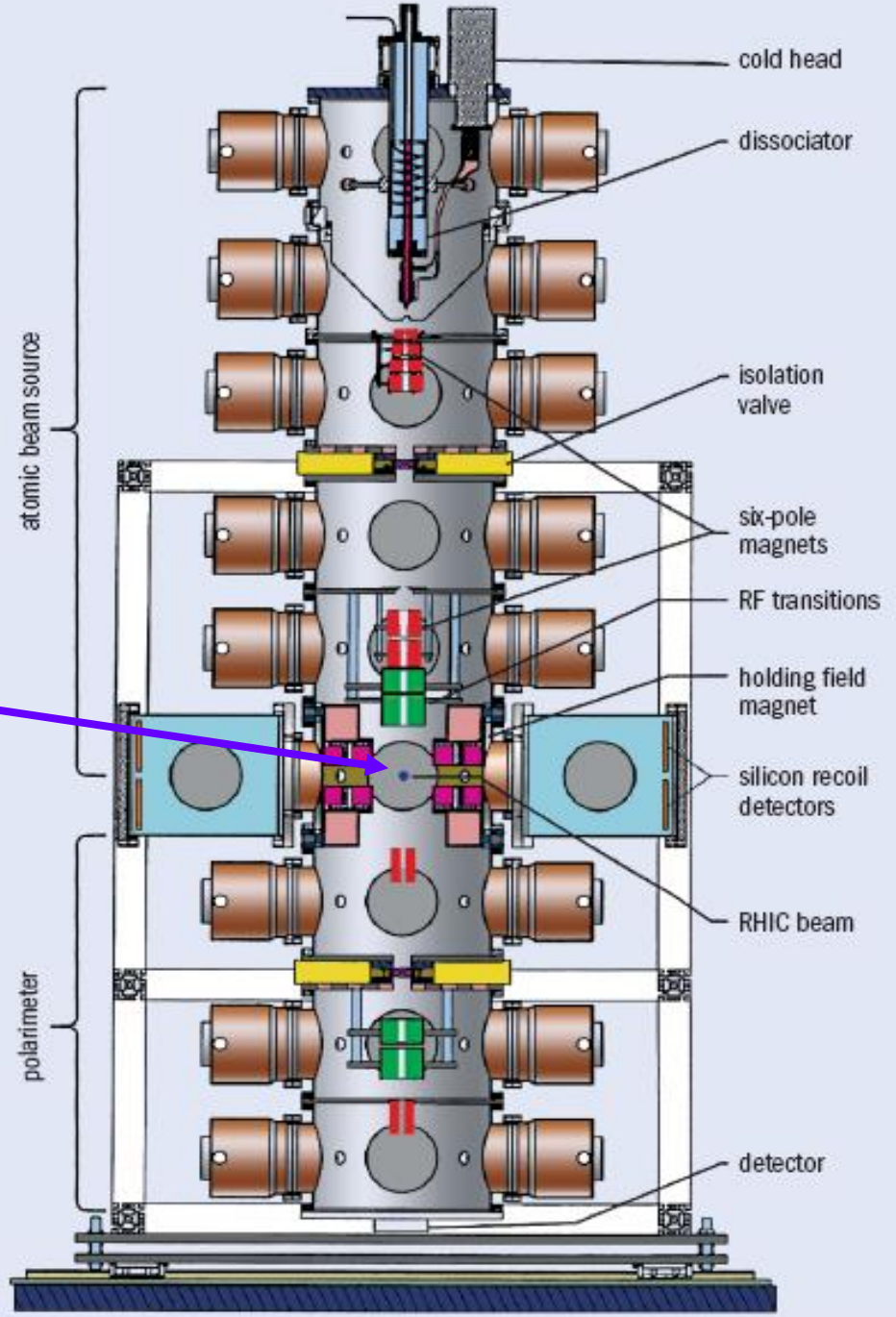
H-jet target intensity profile at the RHIC collision point.

FWHM 6.0 mm

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

H-jet target thickness at the collision point

~$1.2 \cdot 10^{12}$ atoms /cm^2

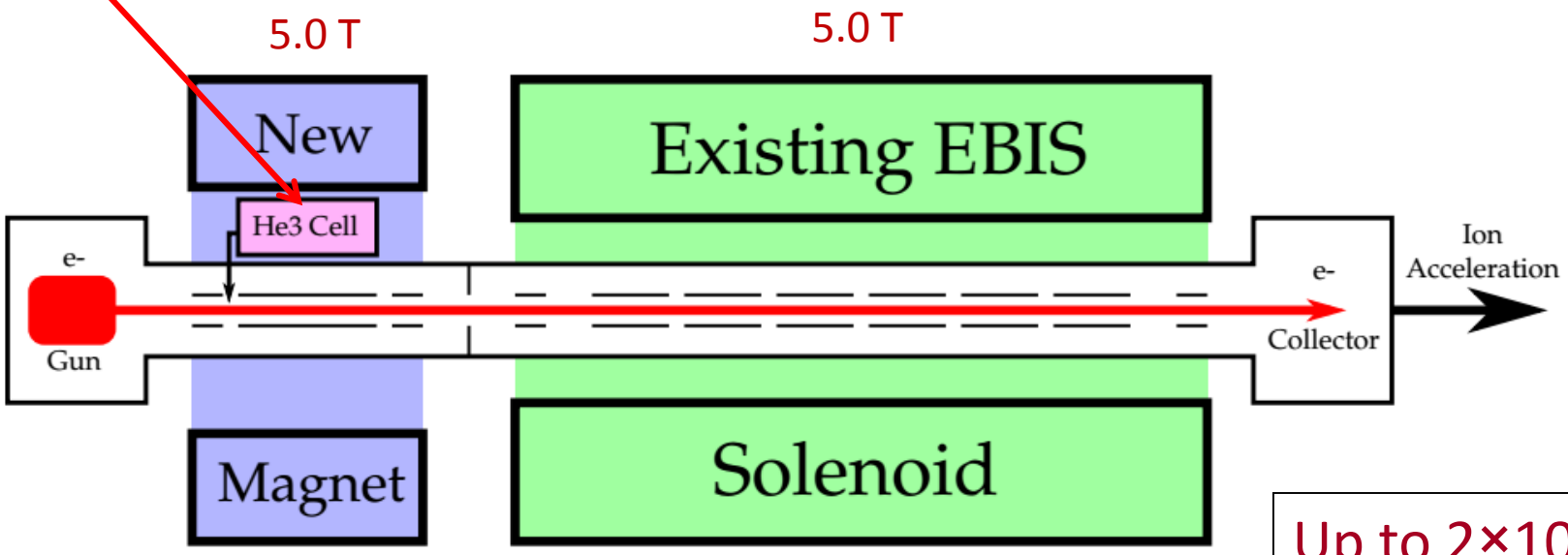


EBIS upgrade with new "injector" solenoid for polarized $^3He^{++}$ ion production.

BNL-MIT collaboration

Optical pumping in High magnetic field

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

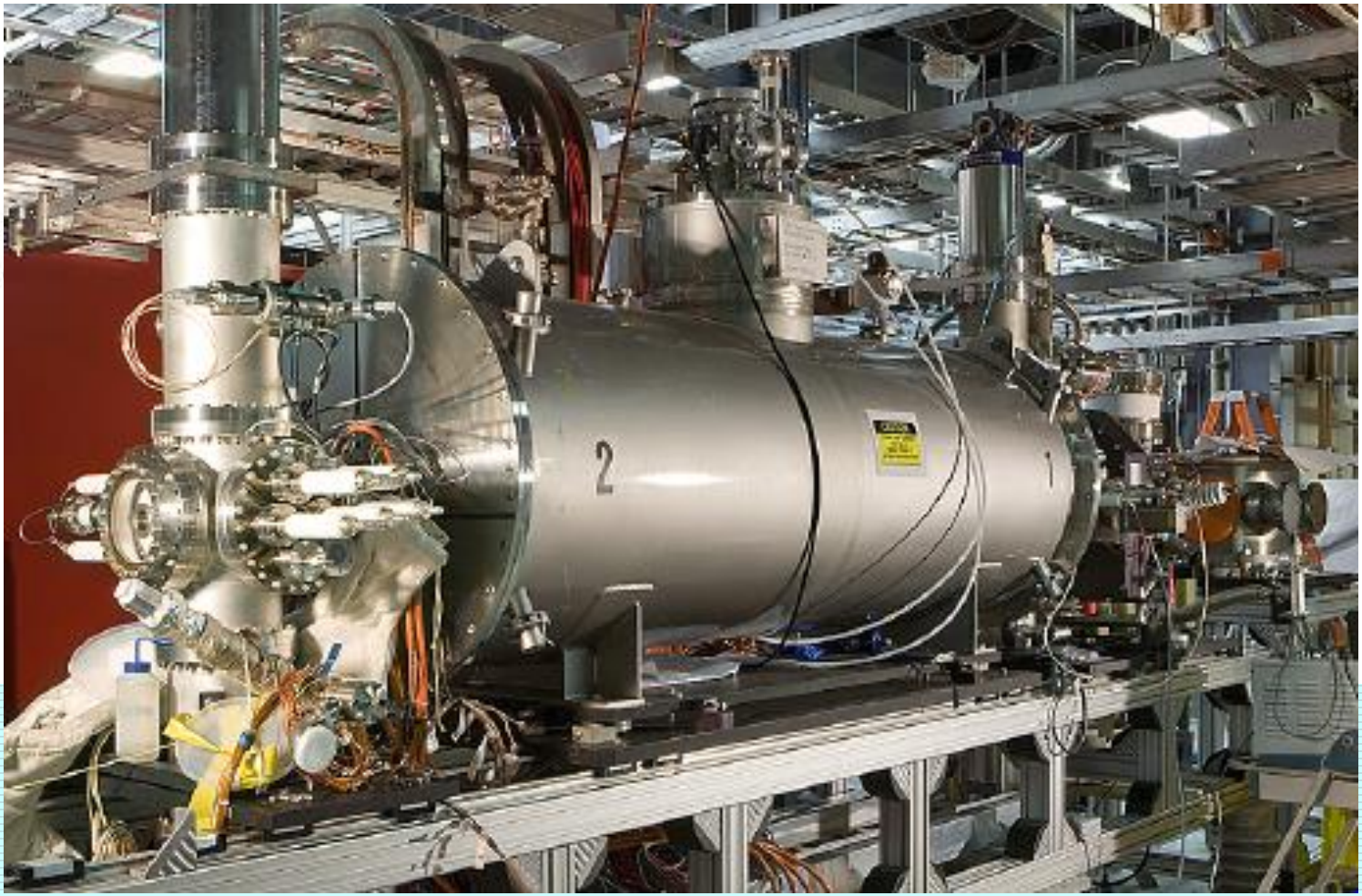


$^3He^+$ → Ionization to $^3He^{++}$ →

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

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



Summary

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

- Accelerated to energy 233 MeV polarized H^- ion beam is an ideal injector for Proton-EDM storage ring.

- In the future RHIC, eRHIC will require high-intensity $^3He^{++}$ ion beams. The high intensity $^3He^{++}$ ion source on the basis of new EBIS injector is under development at RHIC.