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U.S. Department of ENERGY

Polarized Proton Source

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EIC Polarized IOn Source (EPIOS), Stony Brook University, ***USA***

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EIC Accelerator Performance

Requirements for an Electron-Ion Collider are defined in the White Paper:

> "*In order to address the crucial scientific questions discussed in the previous sections, the EIC must provide:*
> • *A Highly polarized electron (~70%) and proton (~70%) beams;*
> • *Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium;*
> • *Variable e+p center-of-mass energies from 29−140 GeV;*
> • *High collision electron-nucleon luminosity $10^{33}-10^{34}$ cm^{-2} s^{-1};*
> • *The possibility to have more than one interaction region.*"

In accordance with the requirements of the "White Paper," it is necessary to improve both the polarization and the intensity of the polarized proton beam.

"White Paper on the Electron-Ion Collider in Preparation for the NSAC Long Range Plan EIC", p.5 User Group, January 2, 2023

Introduction

For 25 years, the polarized proton source based on OPPIS (Optically Pumped Polarized Ion Source) reliably delivered the high-intensity polarized proton beam for the RHIC spin physics program.
The OPPIS polarized source ECR-type (Electron Cyclotron Resonance) for RHIC was developed in collaboration BNL – KEK – TRIUMF – INR at 1998-2002.

The source has been upgraded several times and continuously improves polarization, intensity and emittance.

* Prior to Run-12, the ECR-type source was used to generate the primary proton beam.
* In 2012, the ECR-source was replaced by a high-brightness OPPIS source FABS-type (Fast Atomic Beam Source).
* Unlike the ECR-type source, the FABS-type source operates in pulsed mode and is located outside the SCS magnet.
* This new source has enabled improvements in beam parameters such as current density, emittance, and stability.

Polarization transfer technique (OPPIS)

Polarized light → Polarized electron → Polarized proton

Circular polarized laser beam (tunable wavelength ~795nm)

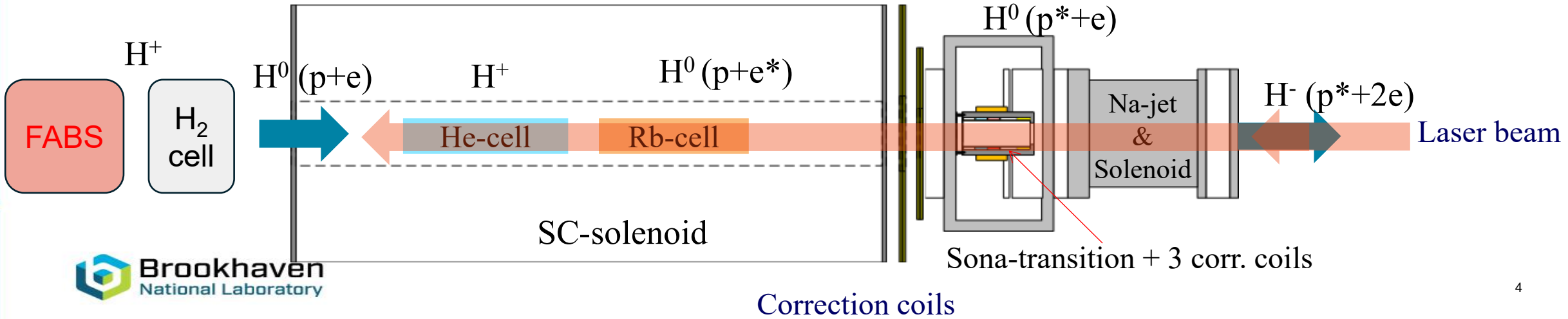
Ionization of hydrogen atom (ECR or FABS).

Polarization of the Rb-atom (Rb-cell)

Production of electron spins polarized hydrogen atoms by capturing an electron from Rb

Polarization transfer from the electron to proton by "Sona-transition" technique

The ionization of hydrogen atoms by capturing a second electron in Na-jet for acceleration (Na-cell)



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Polarization transfer technique milestones

- **1944- E. Zavoisky – Electron Paramagnetic Resonance.**
- **1966- Nobel prize A. Kastler, Optical Pumping Polarization Technique.**
- 1969 – M. Kaminskiy – experiment. Deutrons + magnetized nickel crystal.
- 1972 – B. Ad'yasevich – experiment. Protons on polarized by 6-pole hydrogen.
- 1978 – G.Witteveen –experiment. Protons +polarized by 6-pole magnet Na-vapor.
- 1978 – E.Shamovskiy, Y.Shatunov – proposal. Protons + Cs (6-pole). For the first time, the necessity of high field in neutralization region was pointed out.
- 1979 – L.W.Anderson – proposal. Optical pumping of Na-vapor by commercially available lasers. High field in the Na-cell to prevent depolarization.
- 1981- A.Zelenski -proposal to avoid emittance grows, by using atomic H-injector and He- ionizer cell placed in the same strong magnetic field as optically- pumped Na-vapor cell. Optical pumping of the high –thickness Na-cell by pulsed dye laser.
- 1981 – Y.Mori, W.Cornelius - proposal to use ECR-proton source in the high field to avoid beam emittance growth.
- 1983 – Y.Mori – experiment. The first operational OPPIS with the ECR primary proton source (40 uA, P=50%).
- 1984-1885 – A.Zelenski –exp. Pulsed OPPIS – H^- current 0.1 mA. H^+ - 1.0 mA. H^- current 0.4mA. H^+ - 4.0 mA, P =65%.
- 1986 – L.W.Anderson, D.Swenson- spin-exchange polarization (proposal).
- 1986 –1990 - A.Zelenski – exp. Spin-exchange polarization in Na and Rb vapors.
- 1992-1999 - A dc OPPIS development for "Parity" experiment at TRIUMF. Spin- correlated current modulations 10 –5 level, energy modulations <5 meV. The "Parity" experiment completed.
- 1995- A.Zelenski –exp. DC OPPIS – H^- current 1.0 mA. P=75%.
- 1996 - Y.Mori – exp. Polarized D^- production in the OPPIS with dual optical pumping. Pz –70%, current 300 uA.
- 1999 – A.Zelenski-Polarized H^- current of a 10.0 mA achieved in the pulsed OPPIS. P = 40% (limited by available solenoidal field strength)
- 1999 - OPPIS development for RHIC was completed at TRIUMF. Final tests with TRIUMF superconducting solenoid. H^- current 1.6 mA, P = 85%.
- 2000 - The first OPPIS operation at RHIC.
- 2002 –2003 – RHIC OPPIS operation. 0.5 mA at 200 MeV. P = 80%.

Polarization transfer technique

Lamb-shift sources

Concerning a Possible Method for the Polarization of a Proton Beam

E. K. ZAVOISKII

(Submitted to JETP editor December 14,1956)

J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 408 (February,1957)

Polarization transfer by capture of polarized electrons in magnetized ferromagnetic foil

A Source of Polarized Nuclei for Accelerators

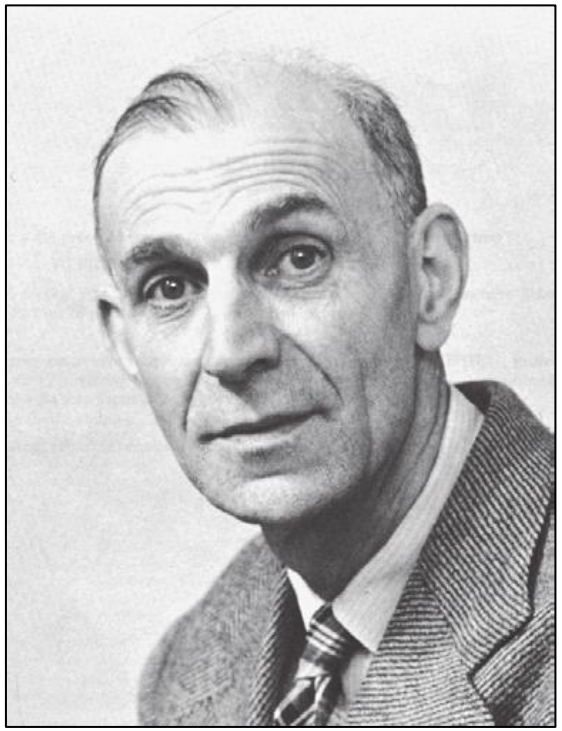
E. K. ZAVOISKII

(Submitted to JETP editor December 14, 1956)

J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 731-735 (April, 1957)

The Nobel Prize in Physics 1966 was awarded to Alfred Kastler.

Prize motivation: "for the discovery and development of optical methods for studying Hertzian resonances in atoms."



Polarization transfer technique

Workshop on high–energy spin physics (IHEP, Protvino, Sep. 1983)

Yaroslav Derbenev
"Siberian snakes"

Anatoli Zelenski
A new polarization technique.
Equal intensity for polarized and unpolarized proton beams.

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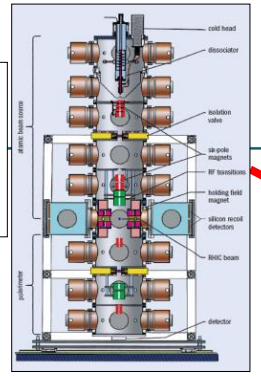
Polarization facilities at RHIC

The world's only polarized proton collider: 60% proton polarization , $L_{max}=1.6\times10^{32}$ $s^{-1}cm^{-2}$; $50<\sqrt{s}<510$ GeV

Absolute H-jet polarimeter



RHIC pC "CNI" polarimeters

Siberian Snakes

RHIC

PHENIX

STAR

Siberian Snakes

H- polarize source OPPIS

Spin Rotators

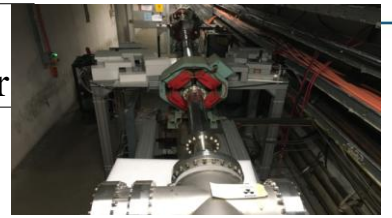
BOOSTER 2.5 GeV

LINAC

AGS 24 GeV

AGS pC "CNI" polarimeter

200 MeV polarimeter



Strong and Partial Siberian Snakes

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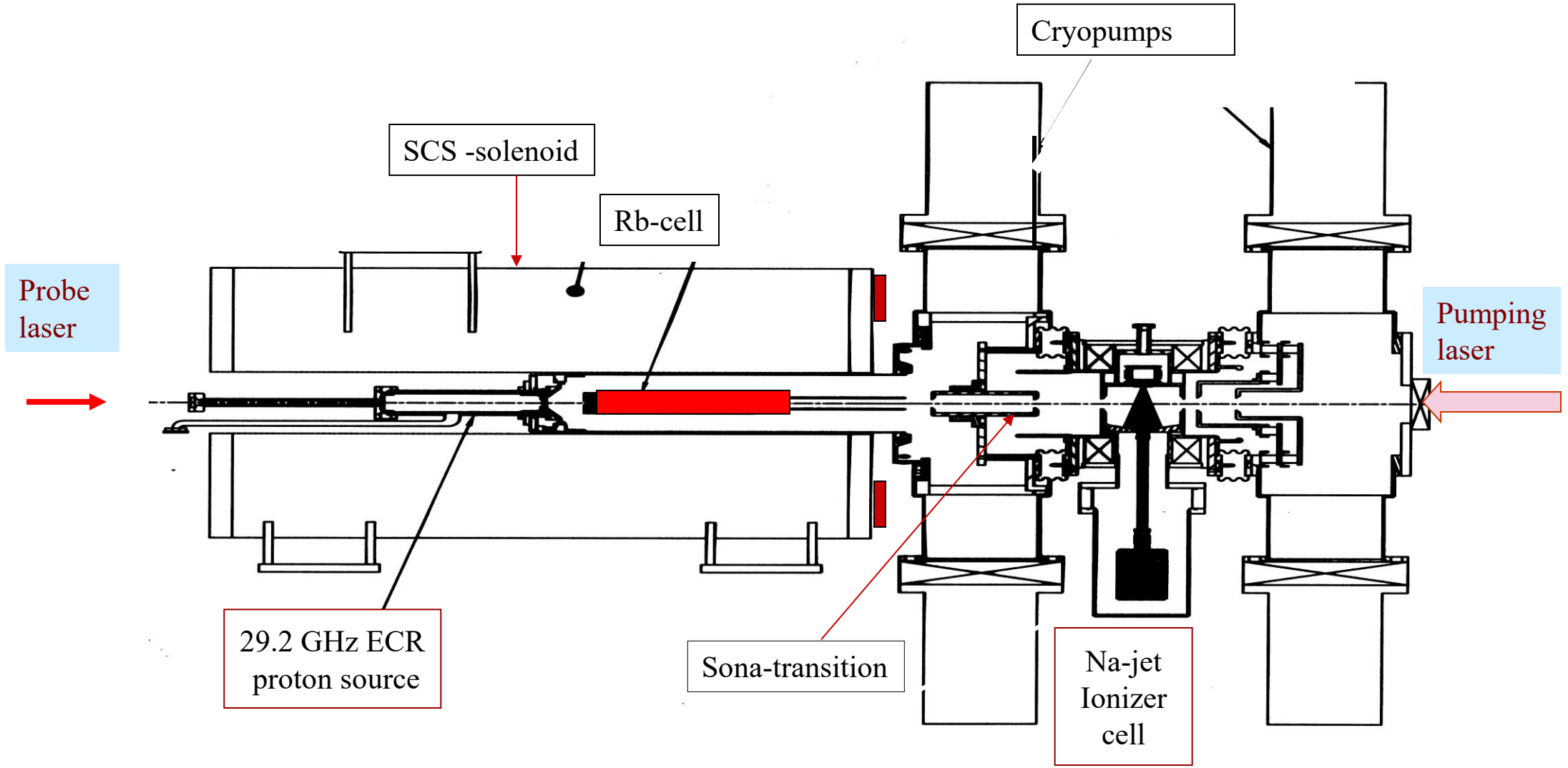
Schematic layout of OPPIS polarized source ECR- type



Operational OPPIS polarized source ECR- type

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

29.2 GHz, 1.2 kW dc extended Interaction oscillator tube

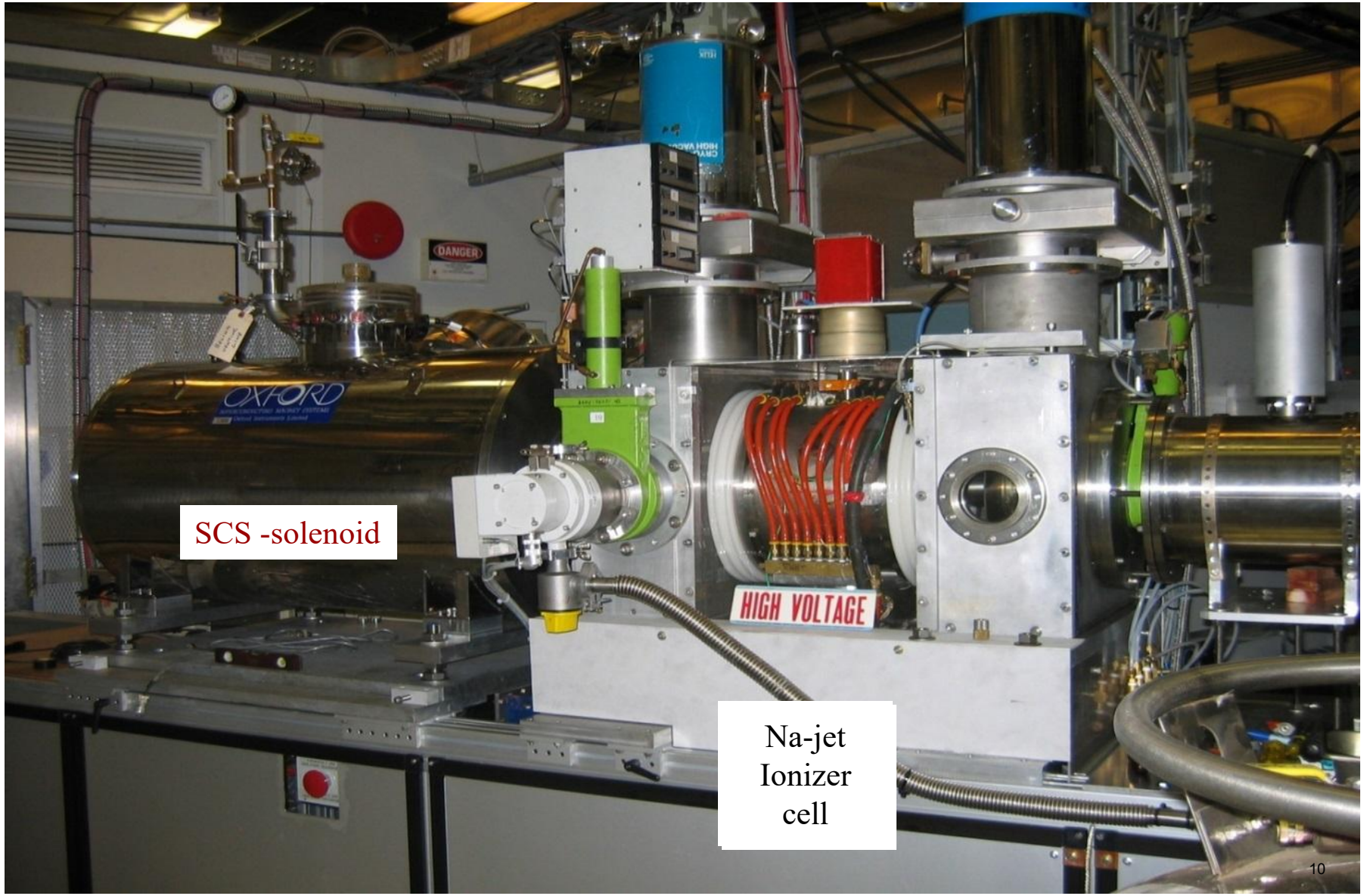
OPPIS produces reliably 0.5-1.0mA polarized H^- ion current.

Polarization at 200MeV: P = 80%.

Beam intensity (ion/pulse):

Source - 10^{12} H^-/pulse

Linac - $5 \cdot 10^{11}$ H^-/pulse



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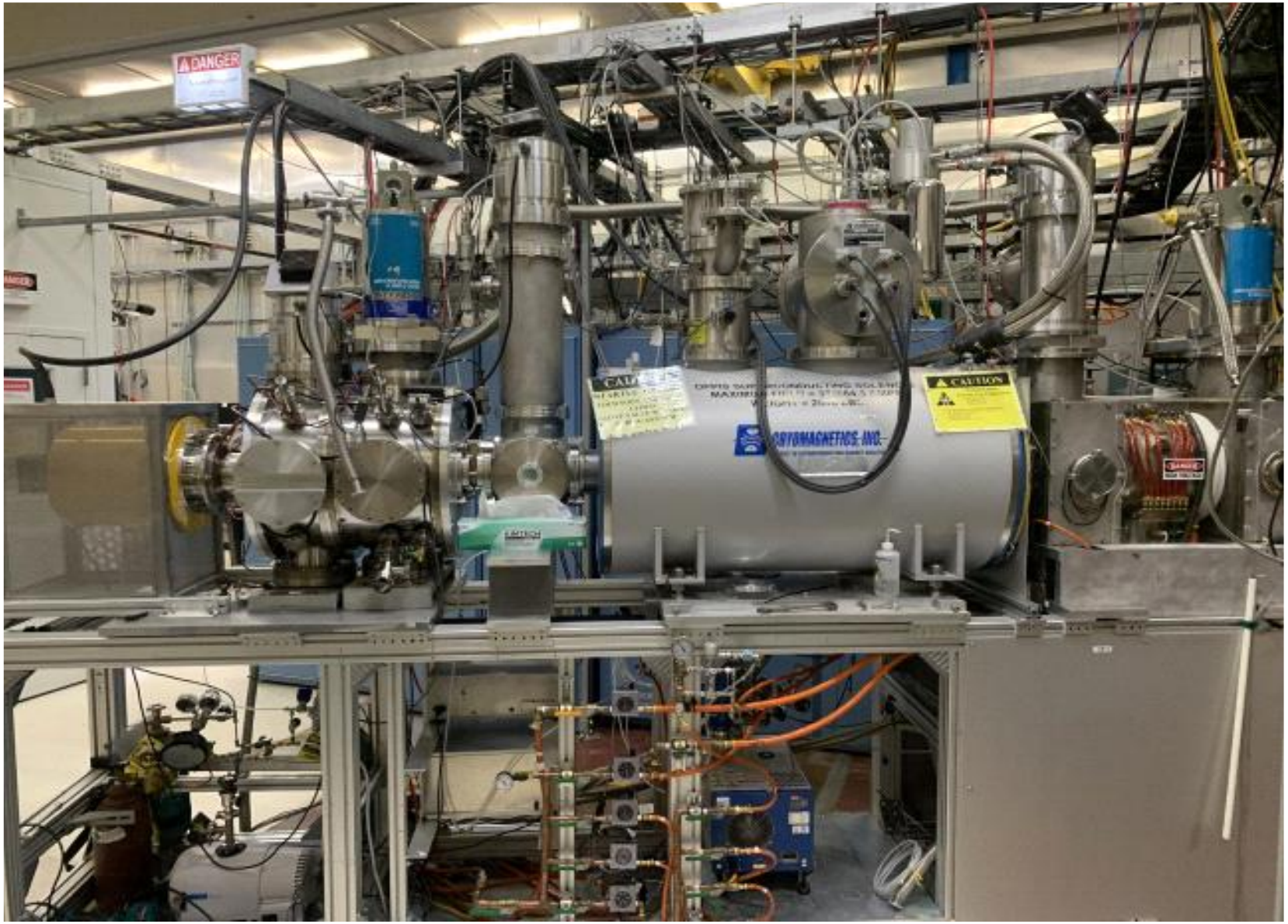
2013 OPPIS upgrade with FABS source

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 .



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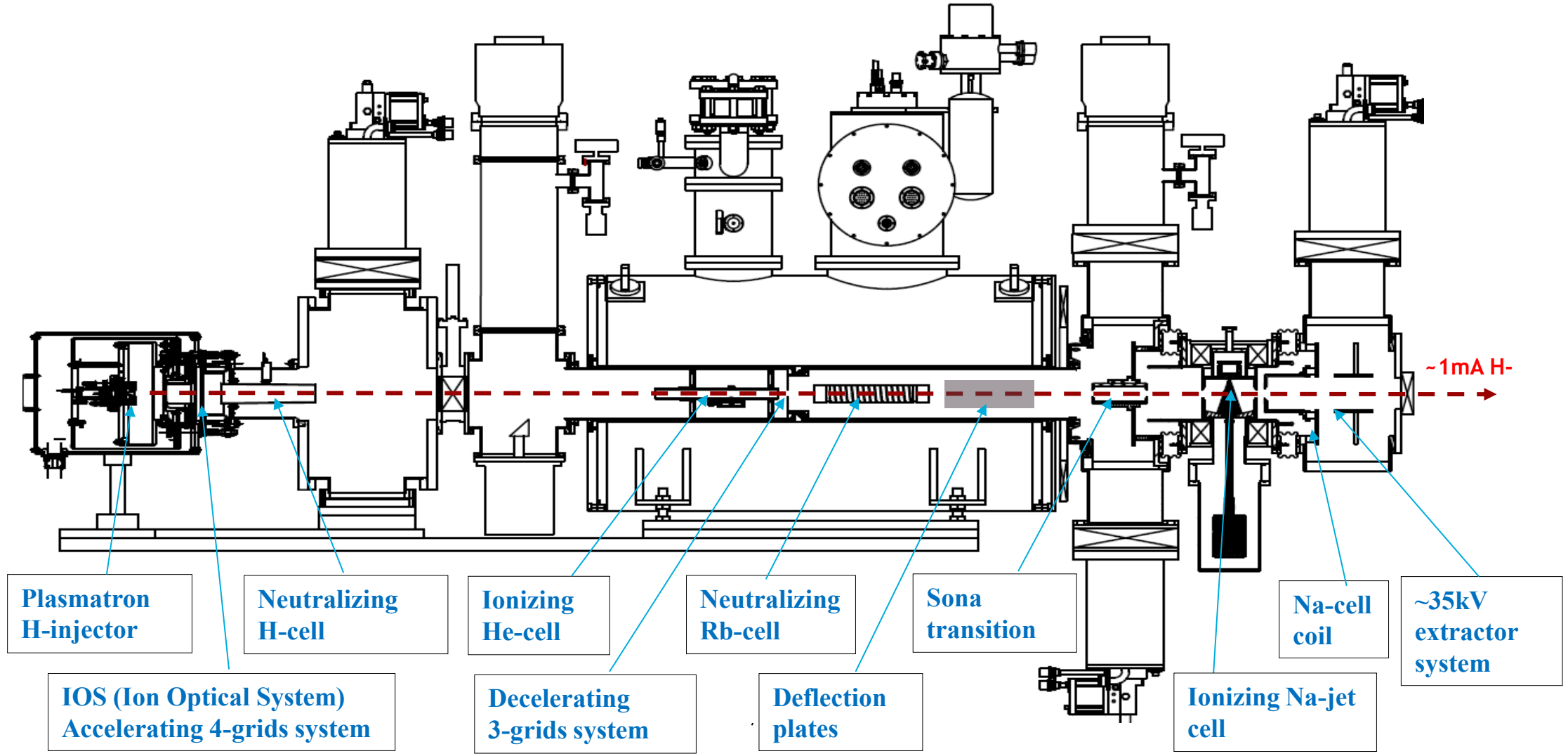
2013 OPPIS upgrade with FABS source



$H^+ \xrightarrow{H_2} H^0 \xrightarrow{He} H^+ \xrightarrow{Rb} H^0 \xrightarrow{Na} H^- \longrightarrow$

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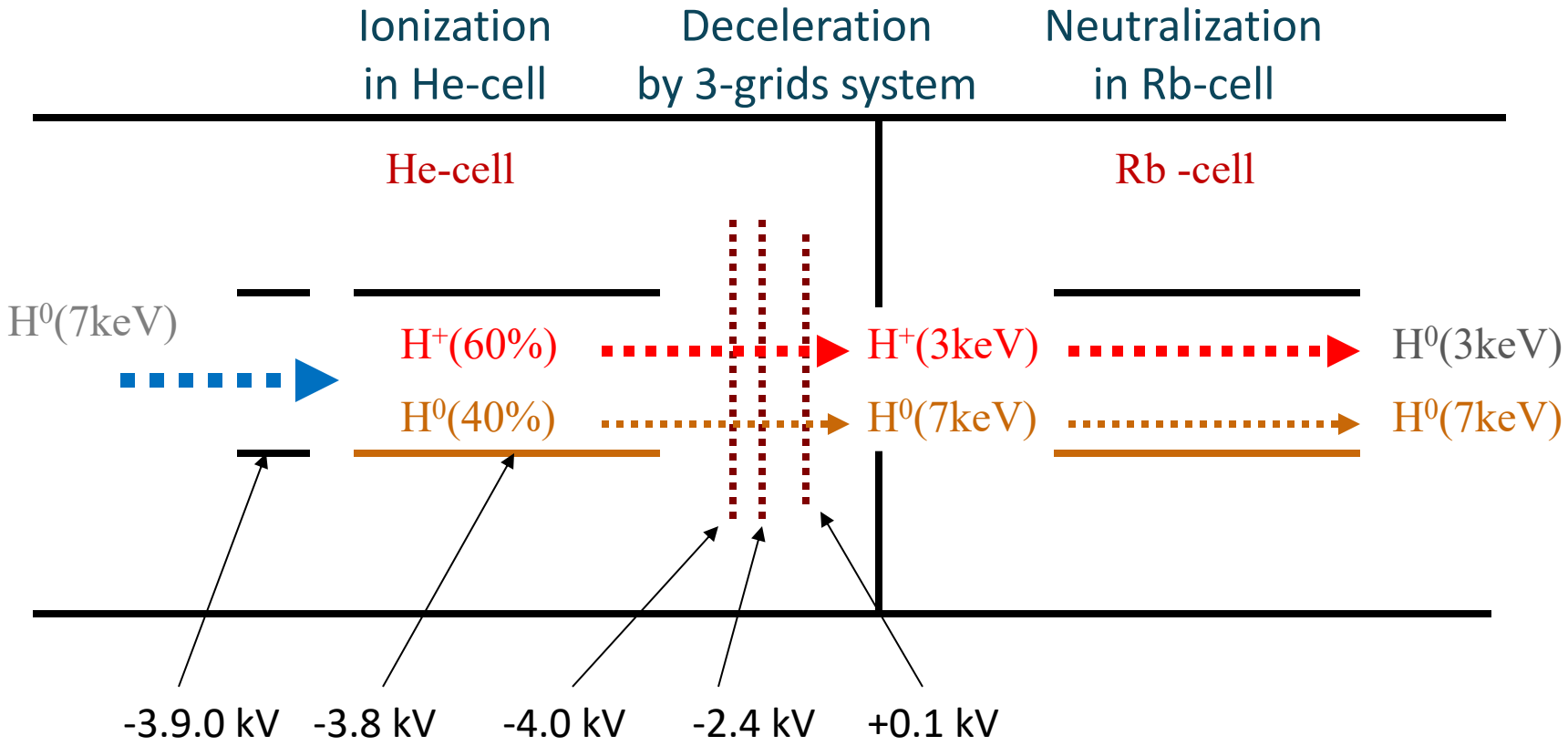
Energy separation a residual un-polarized H^0 component

Only a portion of the beam is ionized in the He-cell (~60%) and can be further polarized.

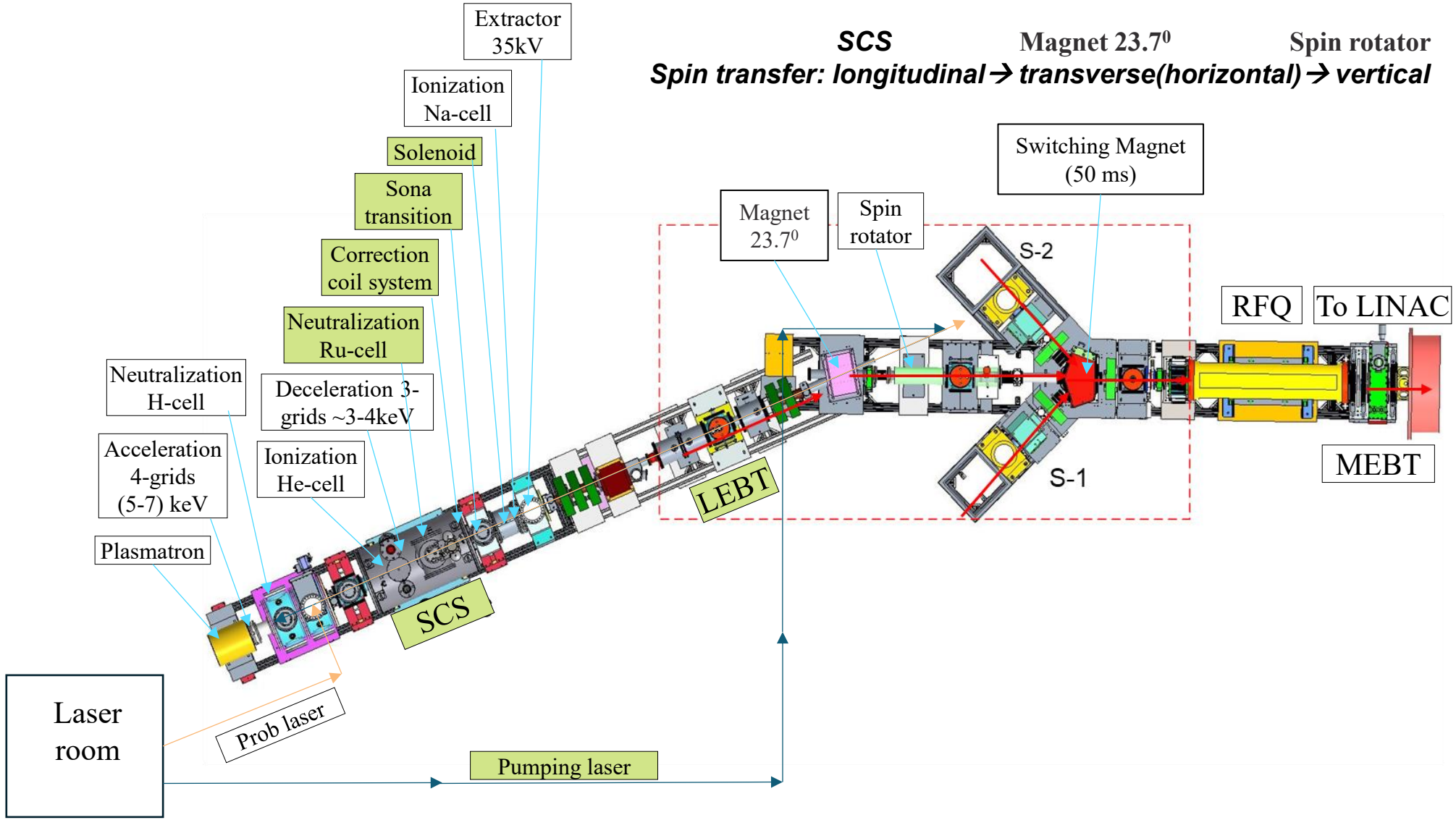
$H^0 + He \rightarrow H^+ + He + e^-$

$H^+ + Rb^* \rightarrow H^0 + Rb^+$

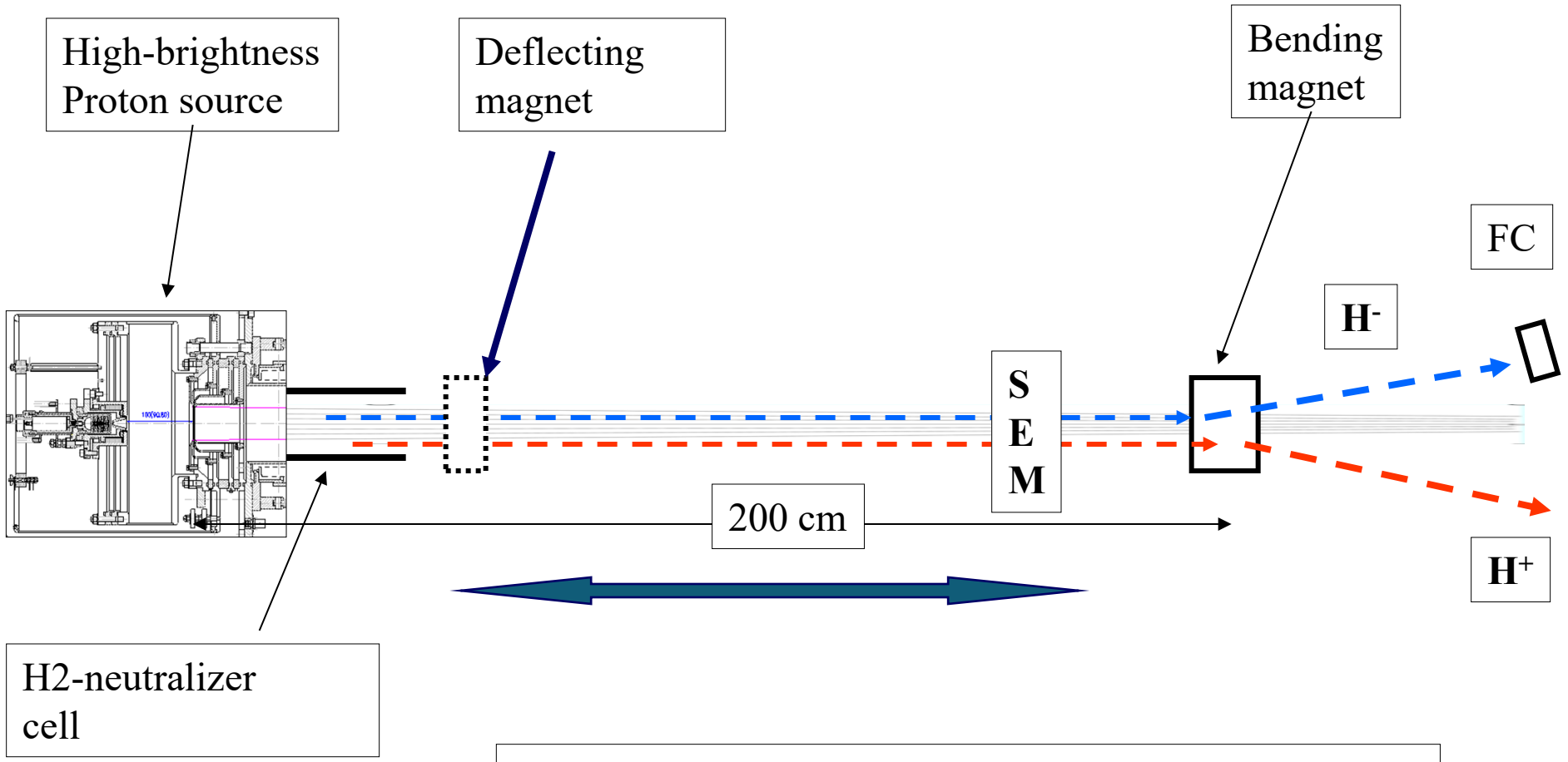


The polarized part of the beam separates from the un-polarized by the bending magnet, LEBT (quadrupoles and steering magnets) and collimators. Energy separation ratio H^-(4keV)/H^-(7keV)is better by 25-30 times.

Optically Polarized proton source (OPPIS)



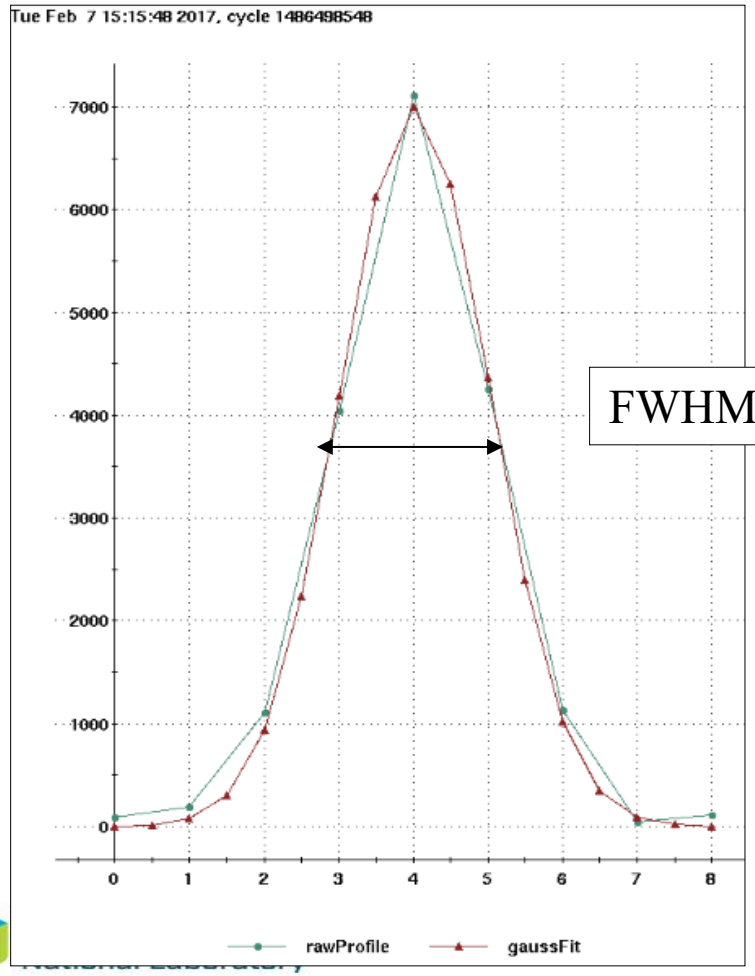
Atomic beam profile measurements on test bench



Atomic beam intensity profile vs. distance from the source

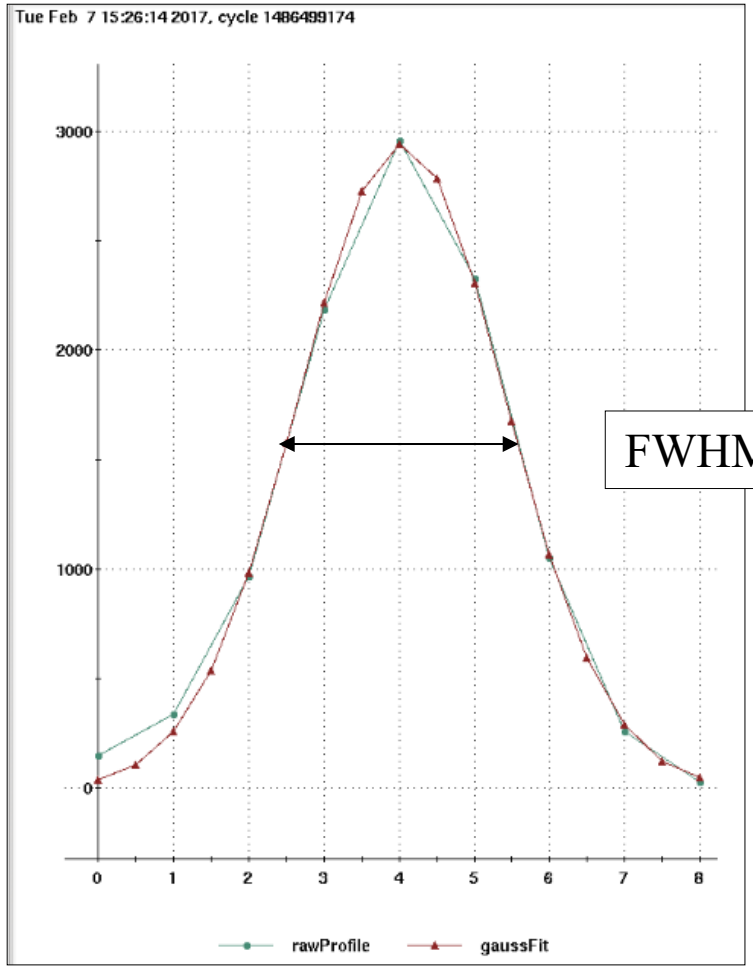
The measurement was performed using a movable (range: 45–200 cm) 9-channel secondary emission monitor (SEM).

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



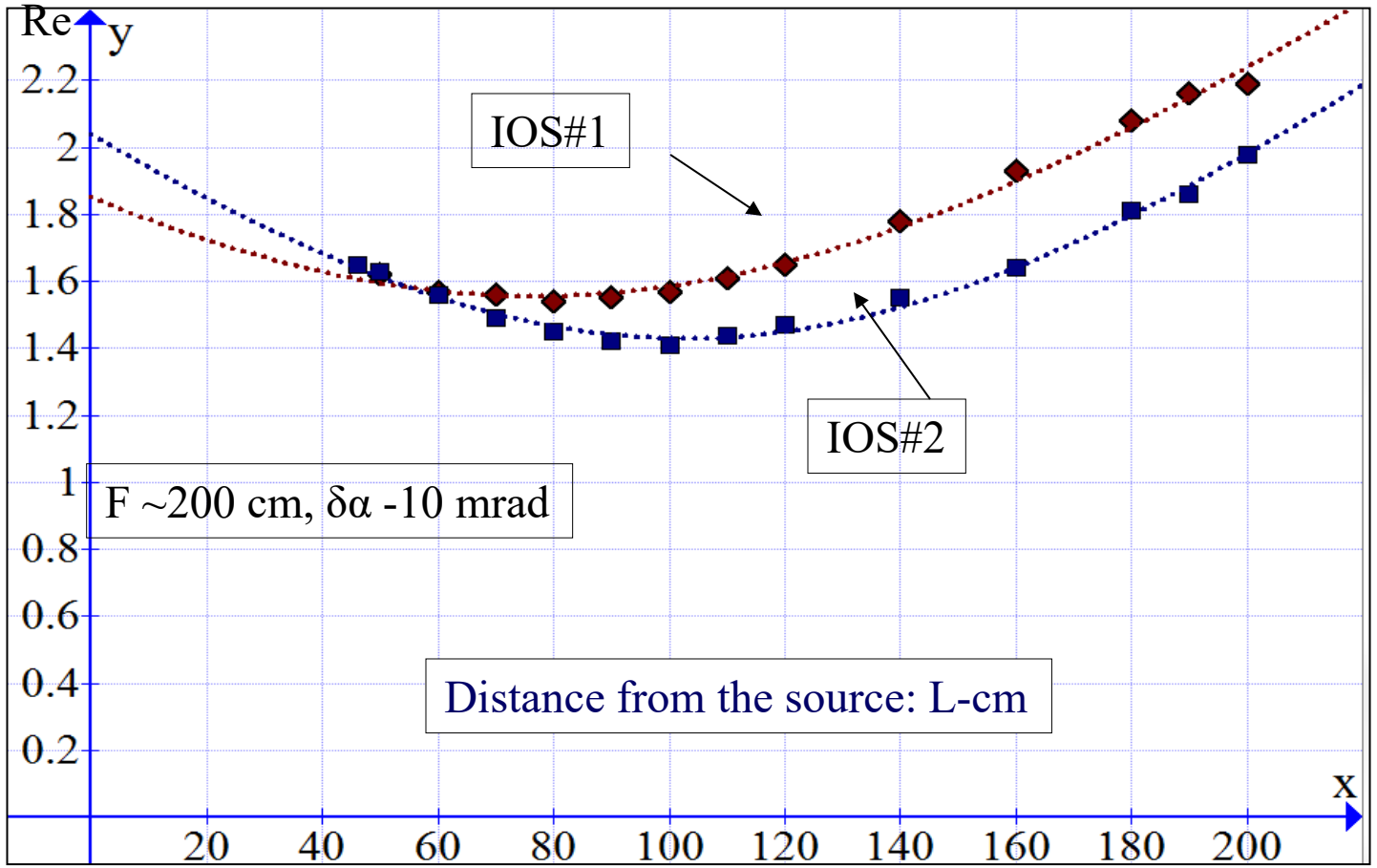
FWHM-3.25 cm

Atomic beam intensity profile vs. distance from the source

The measurement was performed using a movable (range: 45–200 cm) 9-channel secondary emission monitor (SEM).

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

Total equivalent H beam intensity 2.5A



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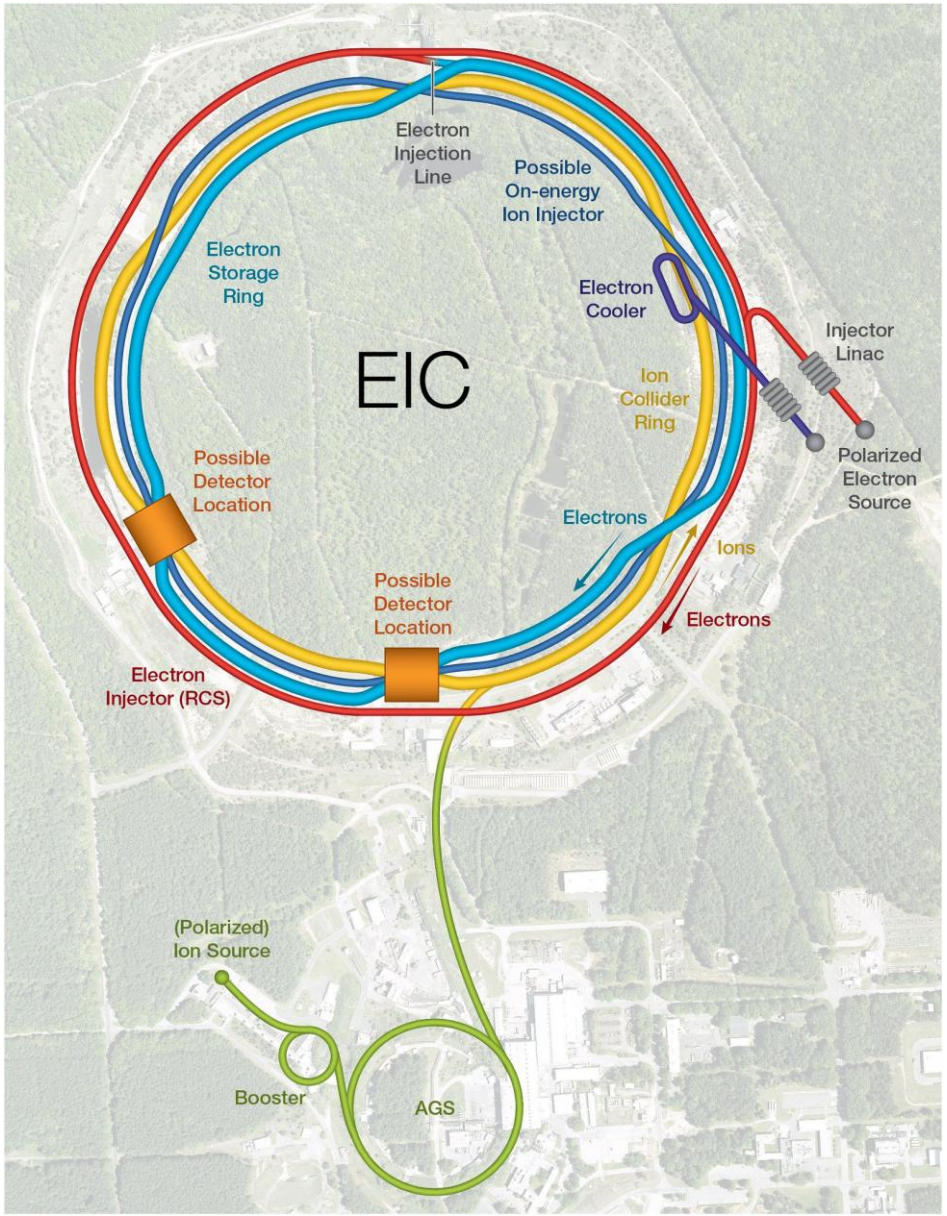
A Smashing Success: Relativistic Heavy Ion Collider Wraps up Final Collisions

February 6, 2026



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Performance of source at RHIC Run-26 (Dec 9, 2025 - Feb 6, 2026)

Average current : ~ 420 μA
pulse width : ~ 300 μsec
average polarization : ~ 82%
at 200 MeV after the Linac.

At present AGS and RHIC beam intensity acceptances are limited by about $1 \cdot 10^{11}$ p/bunch. The intensity excess was used to reduce transversal and longitudinal beam emittances by a strong dynamical collimation in the Booster.

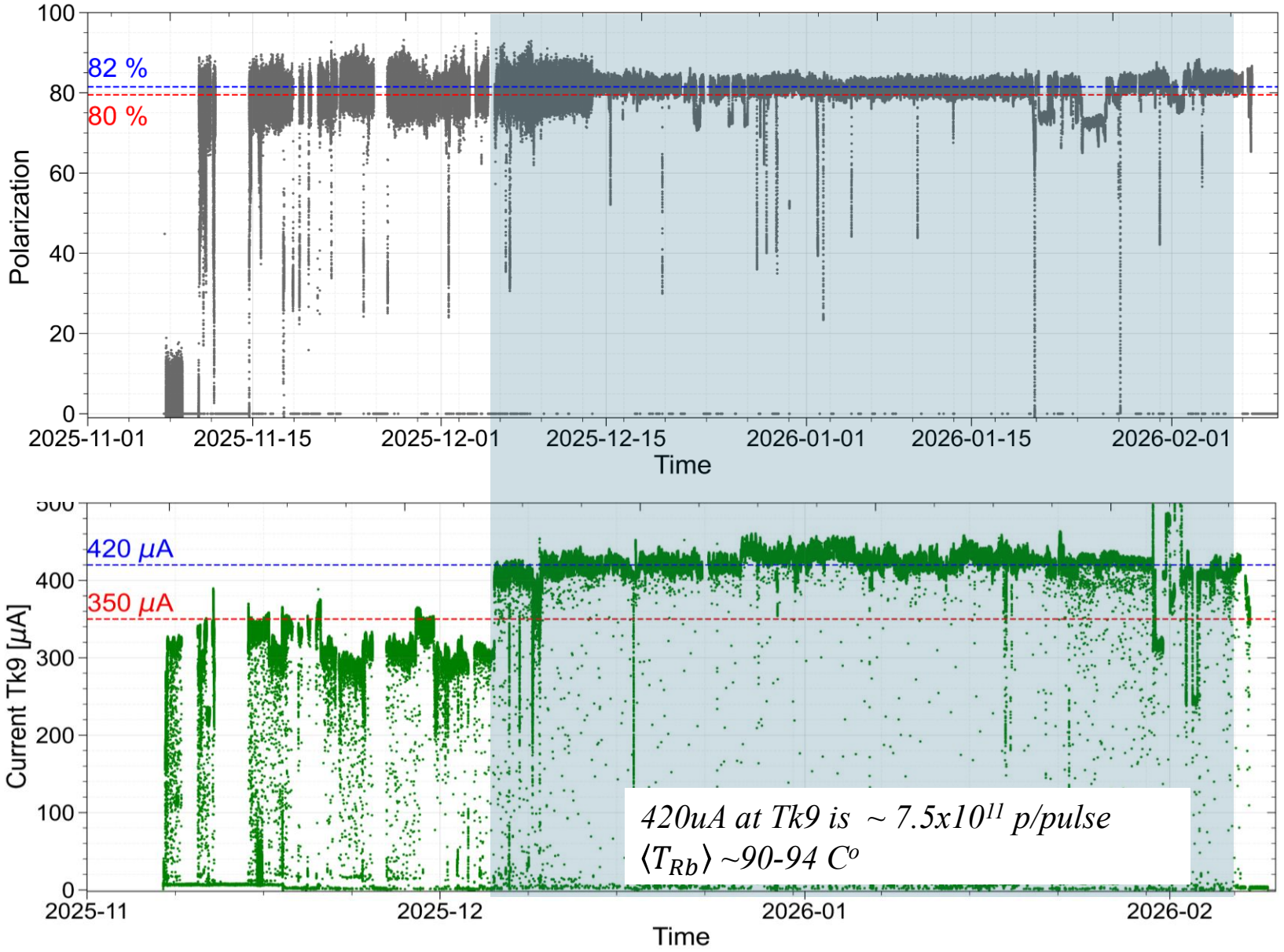
High beam polarization is crucial for reducing statistical uncertainties in polarized experiments. The statistic error of the double spin asymmetry is:

$$\sigma_{stat} \sim 1/p\text{^}2.$$

Increasing the source polarization from 80% to 85% is equivalent to more then 25% more data-taking time.

Beam intensity and polarization must be equal at spin-reversal and from pulse to pulse.

$\Delta I/I < 10^{-3}$ and $\Delta P/P < 1\%$ were measured in the RHIC OPPIS at Run-24.



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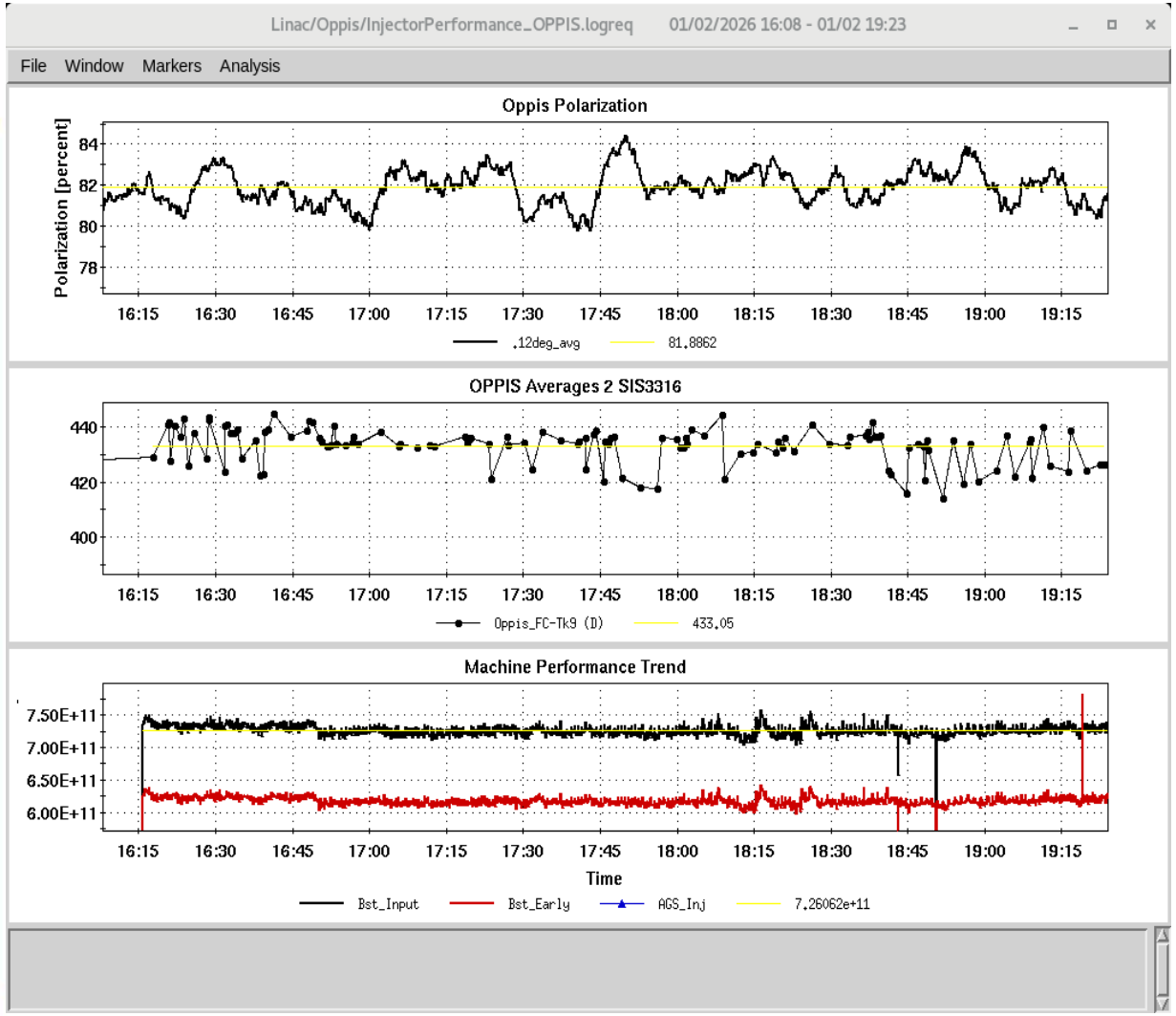
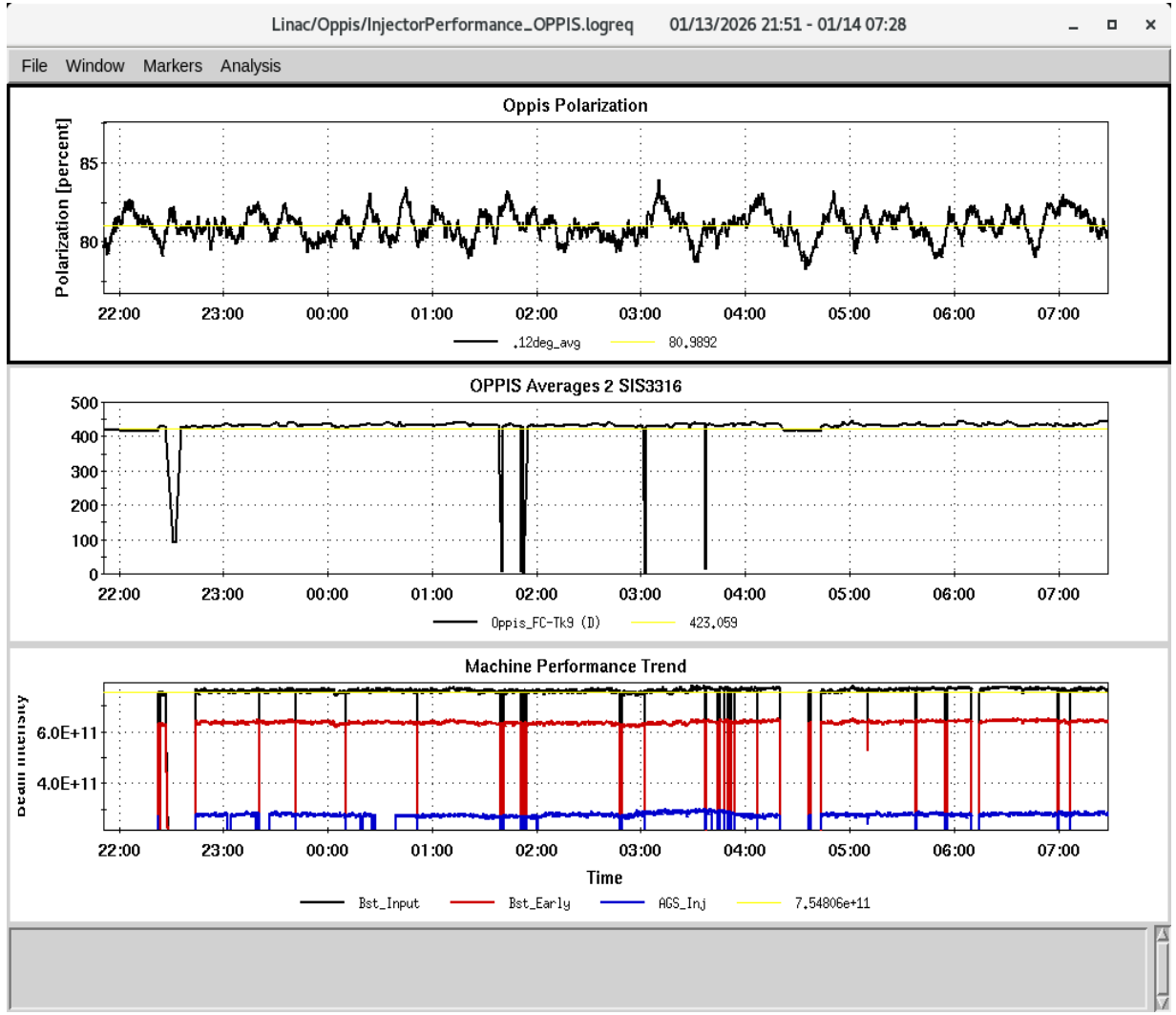
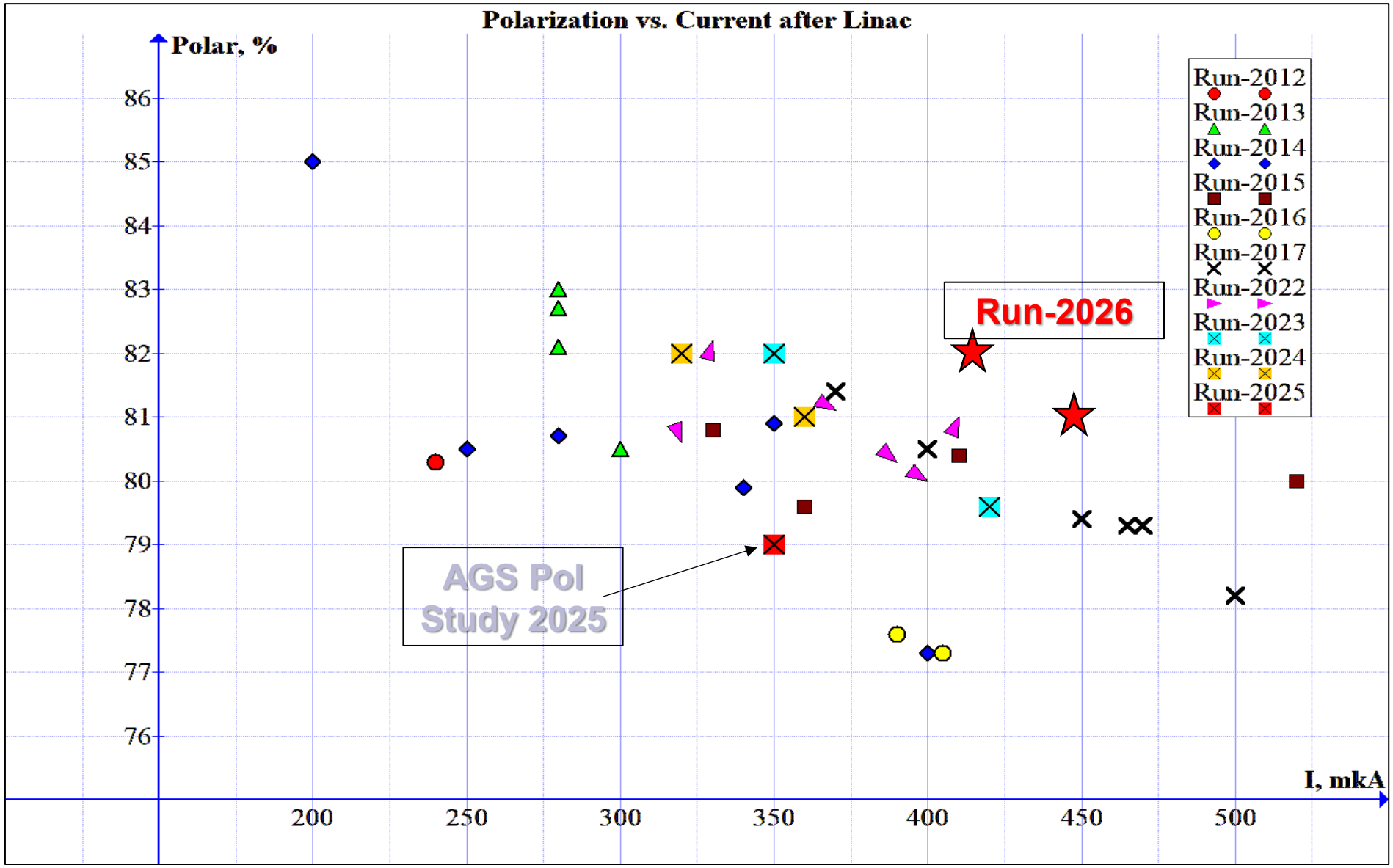
Performance of source at RHIC RUN (Dec 9, 2025 - Feb 6, 2026)





Beam performance at 2012-2026



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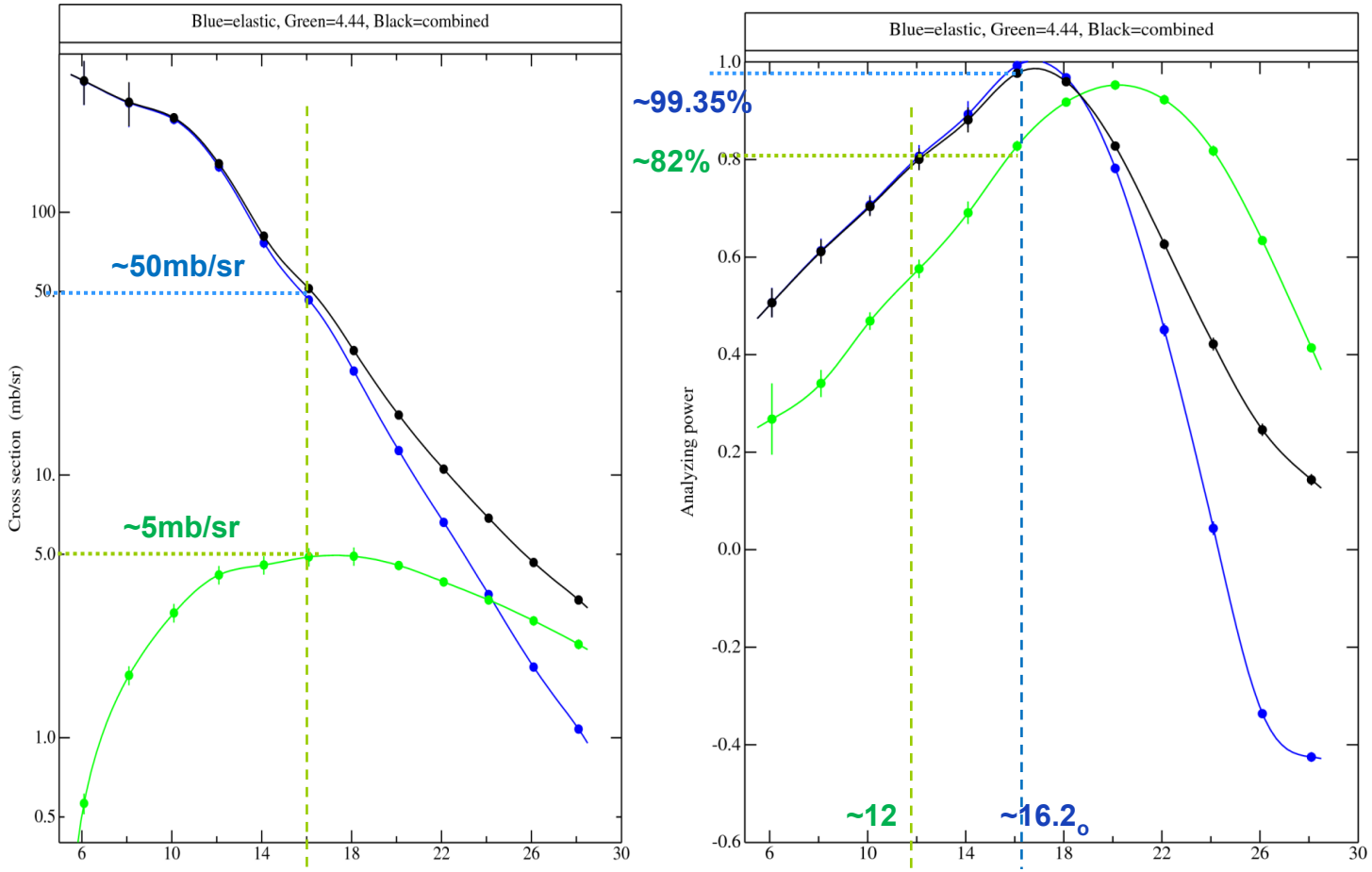
Precision, Absolute Proton Beam Polarimeter at 200MeV

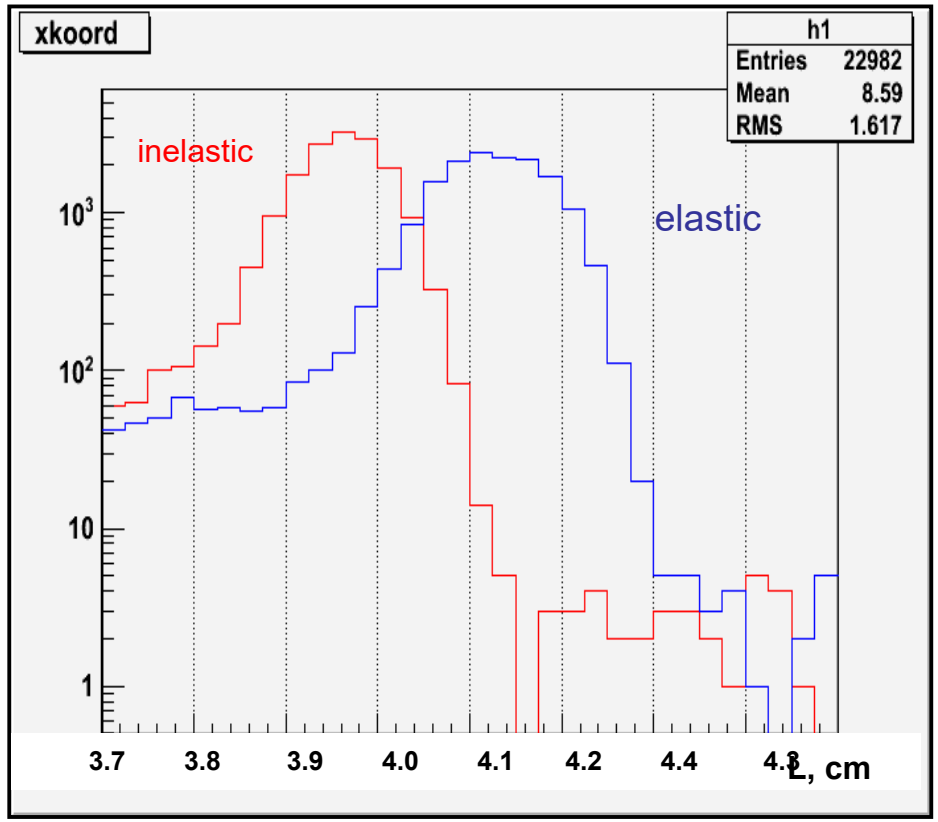
Cross section and analyzing power for elastic pC scattering at 200 MeV

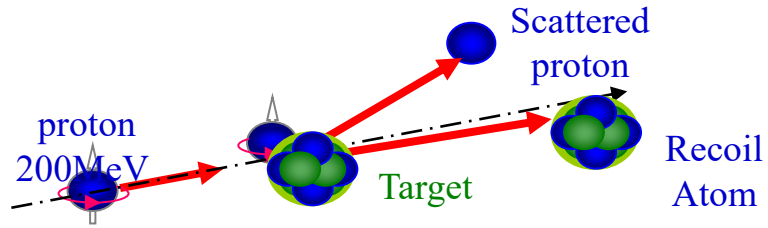


Measurements of the cross section and analyzing power for proton scattering from ^{12}C at 200 MeV. The blue curves correspond to the ground state protons of carbon. The green curve corresponds the protons from the first excited state (-4.44MeV). The black curve represents the sum of the two data sets.

GEANT calculation of pC polarimeter for 200MeV proton beam

N, particles stopped in the slice of Cu-absorber





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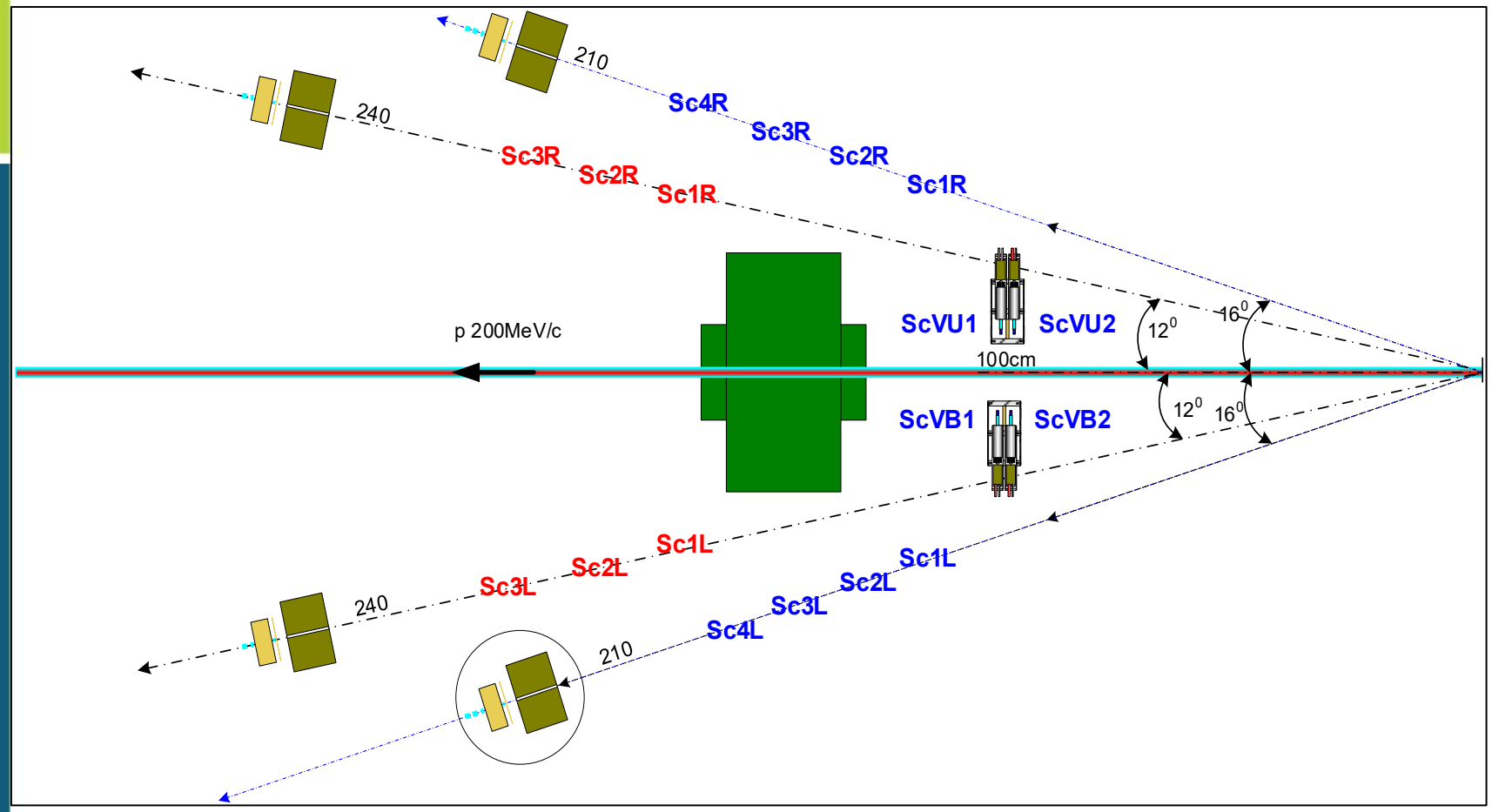
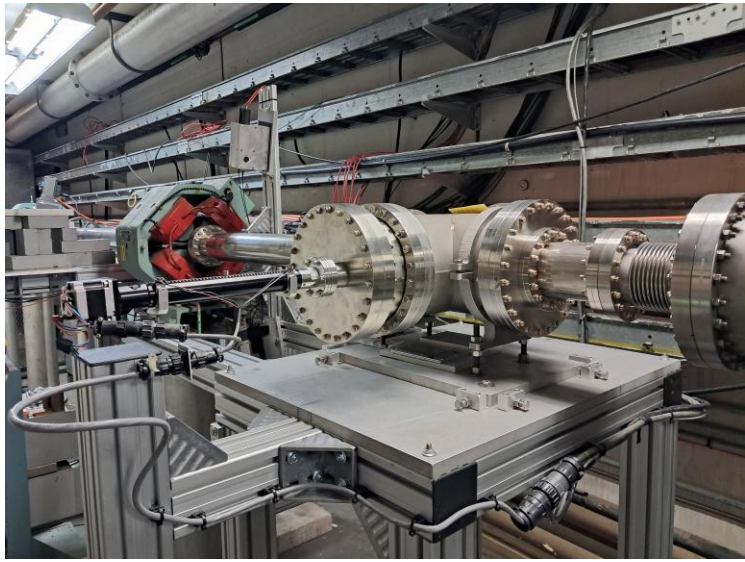
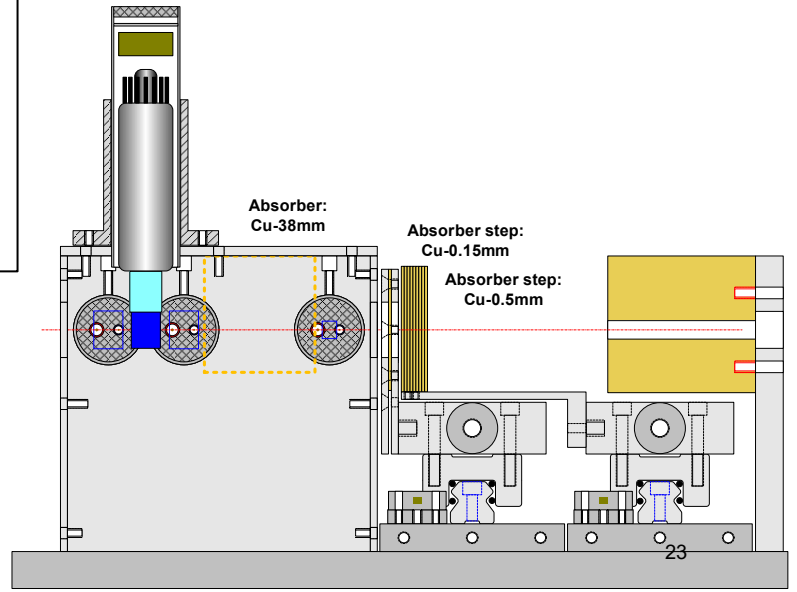
Precision, Absolute Proton Beam Polarimeter at 200MeV







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The 200MeV polarimeter

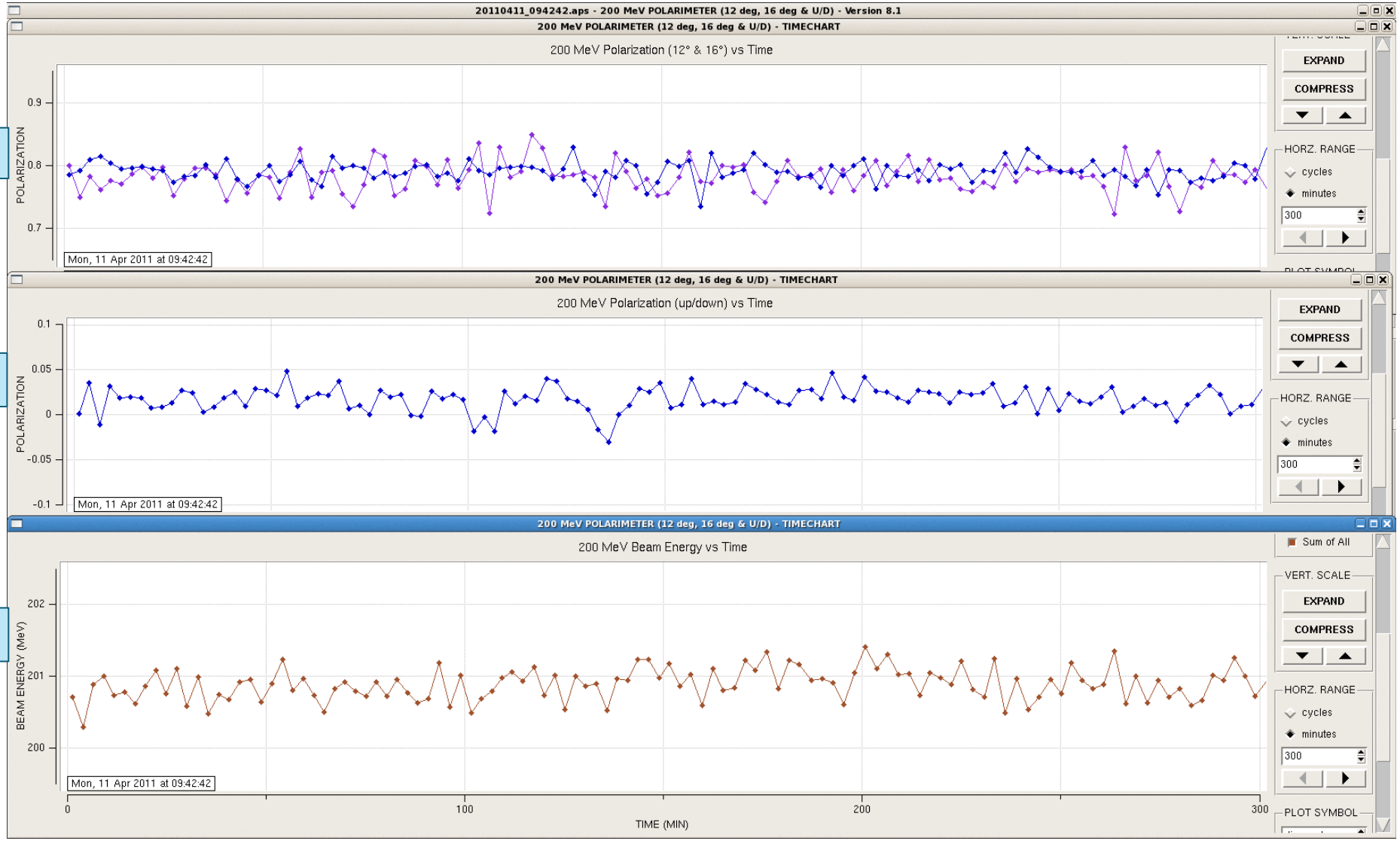
The 200MeV polarimeter simultaneous measured vertical and horizontal polarization and an energy of a beam.

Vertical and Horizontal polarization and Energy of a beam time chart

12 deg and 16 deg polarimeter

Vertical polarimeter

16 deg polarimeter



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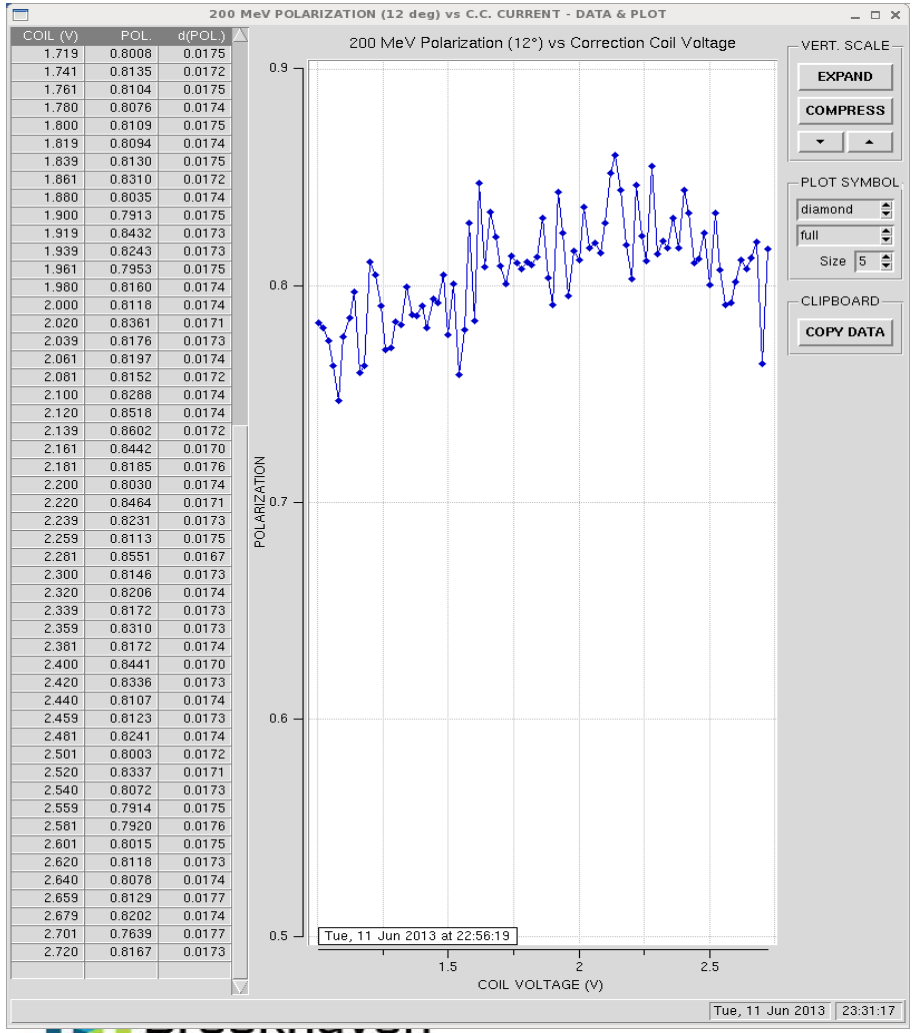
Depolarization factors by the shape of magnetic field

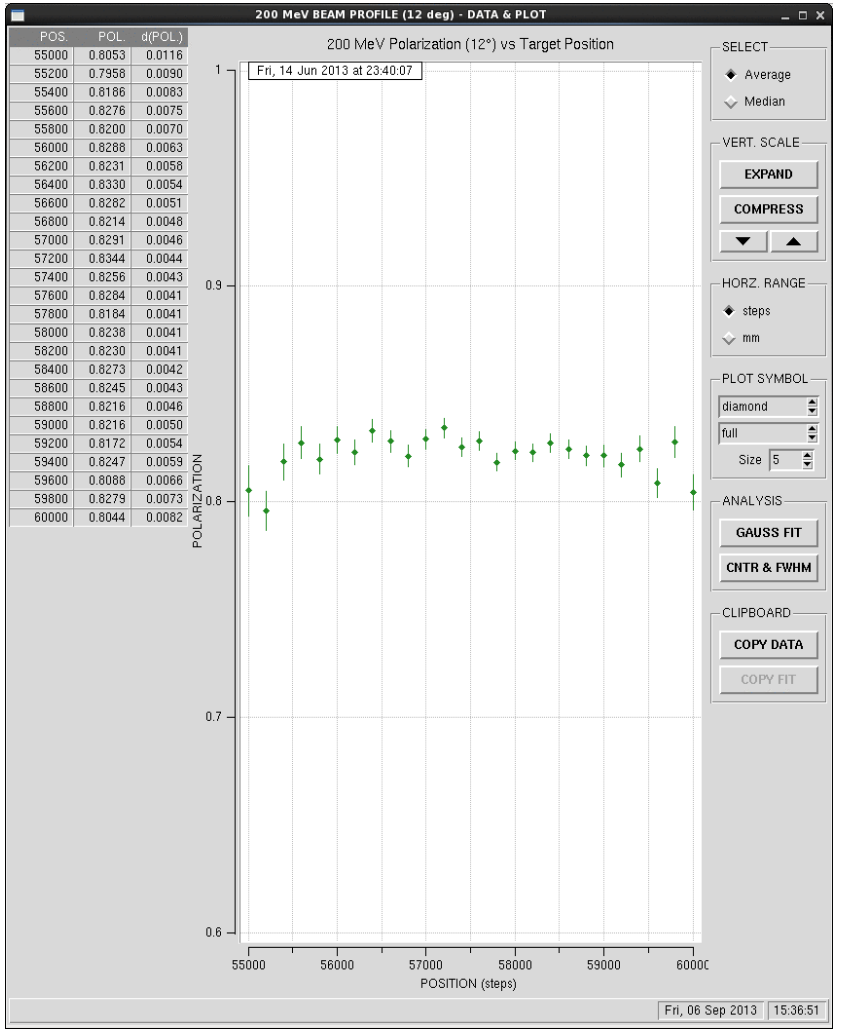
For maximum polarization there must be an accurate selection of settings for all correction coils. Any change in the magnetic field of coils, SCS or ionizer as well as their position requires a new setting.

Polarization vs. LCC current



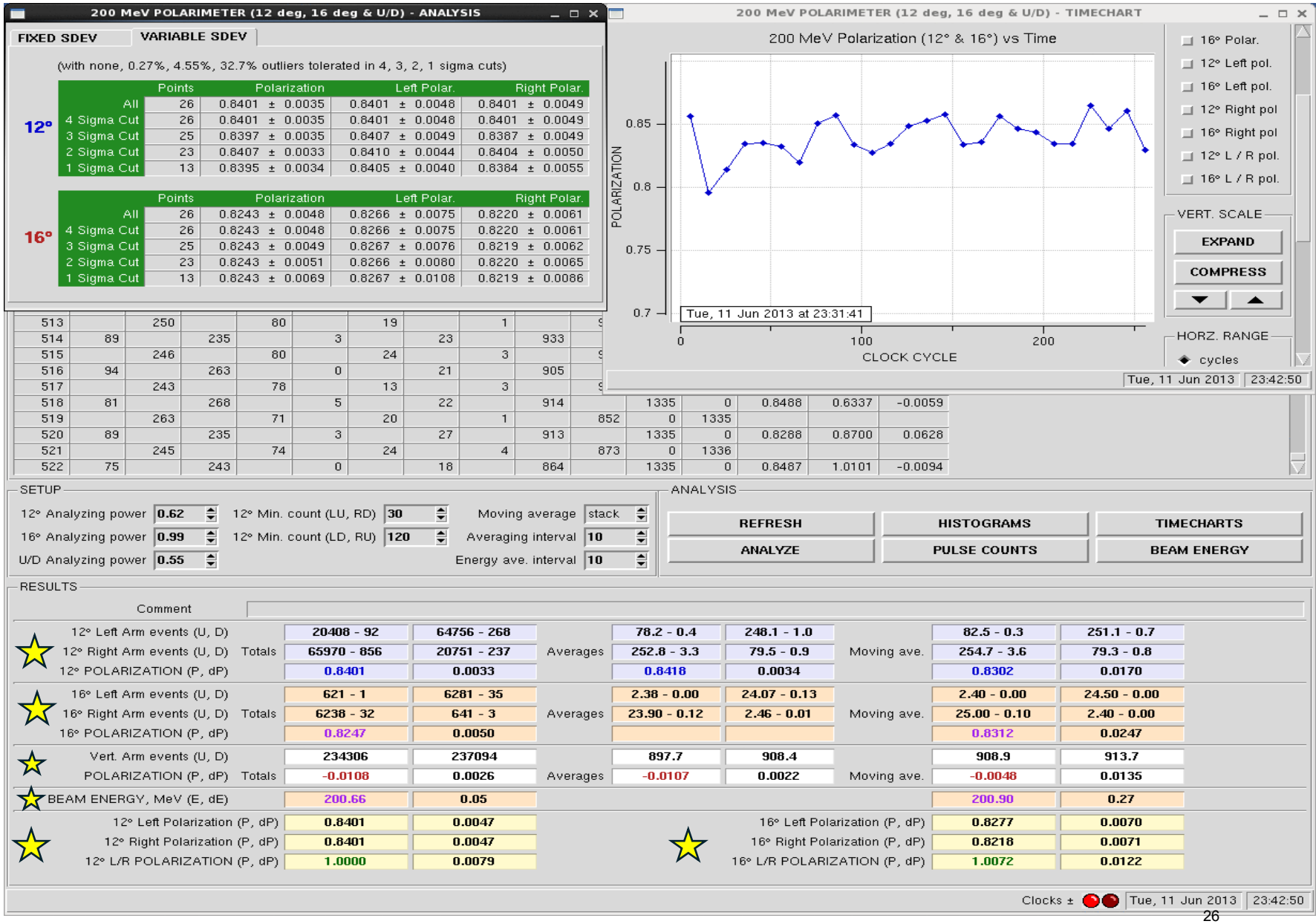
COIL (V)	POL.	d(POL.)
1.719	0.8008	0.0175
1.741	0.8135	0.0172
1.761	0.8104	0.0175
1.780	0.8076	0.0174
1.800	0.8109	0.0175
1.819	0.8094	0.0174
1.839	0.8130	0.0175
1.861	0.8310	0.0172
1.880	0.8035	0.0174
1.900	0.7913	0.0175
1.919	0.8432	0.0173
1.939	0.8243	0.0173
1.961	0.7953	0.0175
1.980	0.8160	0.0174
2.000	0.8118	0.0174
2.020	0.8361	0.0171
2.039	0.8176	0.0173
2.061	0.8197	0.0174
2.081	0.8152	0.0172
2.100	0.8288	0.0174
2.120	0.8518	0.0174
2.139	0.8602	0.0172
2.161	0.8442	0.0170
2.181	0.8185	0.0176
2.200	0.8030	0.0174
2.220	0.8464	0.0171
2.239	0.8231	0.0173
2.259	0.8113	0.0175
2.281	0.8551	0.0167
2.300	0.8146	0.0173
2.320	0.8206	0.0174
2.339	0.8172	0.0173
2.359	0.8310	0.0173
2.381	0.8172	0.0174
2.400	0.8441	0.0170
2.420	0.8336	0.0173
2.440	0.8107	0.0174
2.459	0.8123	0.0173
2.481	0.8241	0.0174
2.501	0.8003	0.0172
2.520	0.8337	0.0171
2.540	0.8072	0.0173
2.559	0.7914	0.0175
2.581	0.7920	0.0176
2.601	0.8015	0.0175
2.620	0.8118	0.0173
2.640	0.8078	0.0174
2.659	0.8129	0.0177
2.679	0.8202	0.0174
2.701	0.7639	0.0177
2.720	0.8167	0.0173

Polarization vs. target position



POS.	POL.	d(POL.)
55000	0.8053	0.0116
55200	0.7958	0.0090
55400	0.8186	0.0083
55600	0.8276	0.0075
55800	0.8200	0.0070
56000	0.8288	0.0063
56200	0.8231	0.0058
56400	0.8330	0.0054
56600	0.8282	0.0051
56800	0.8214	0.0048
57000	0.8291	0.0046
57200	0.8344	0.0044
57400	0.8256	0.0043
57600	0.8284	0.0041
57800	0.8184	0.0041
58000	0.8238	0.0041
58200	0.8230	0.0041
58400	0.8273	0.0042
58600	0.8245	0.0043
58800	0.8216	0.0046
59000	0.8216	0.0050
59200	0.8172	0.0054
59400	0.8247	0.0059
59600	0.8088	0.0066
59800	0.8279	0.0073
60000	0.8044	0.0082

Precision, Absolute Proton Beam Polarimeter at 200MeV



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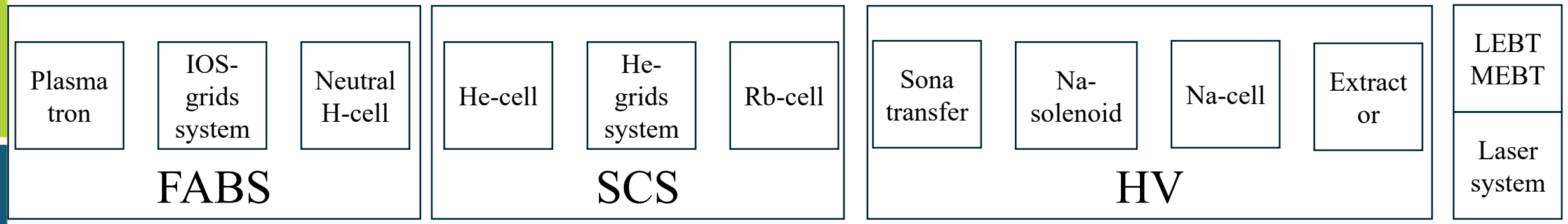
Ion Source Development

Since 2012, when FABS was implemented, we have made many adjustments to improve the beam parameters. We achieved the best polarization volume of over 85%, intensity over 1000μA, and a beam pulse duration of over 400μs compared to the average volume of polarization at last run-26 of ~82% and an intensity of ~420μA.

Now, our goal is to have OPPIS maintain the best parameters for several months by improving monitoring and simplifying control, as well as making it fast and easy to repair and completely safe. Our goal for the future is stability and safety with the best performance.

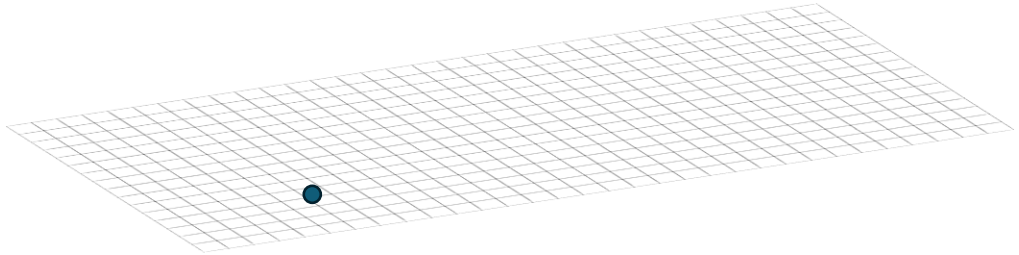
As a first approximation, the main parameters of the quality of the formed beam is intensity, polarization and emittance.

FABS Subsystems

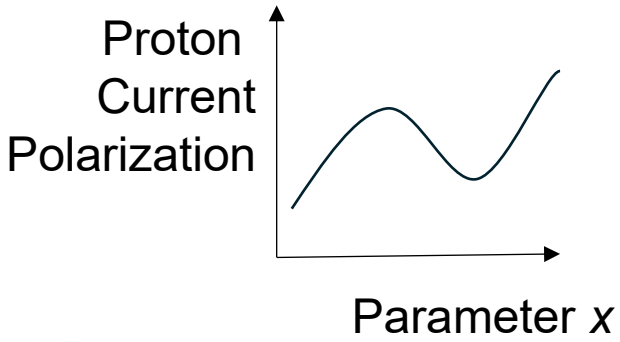


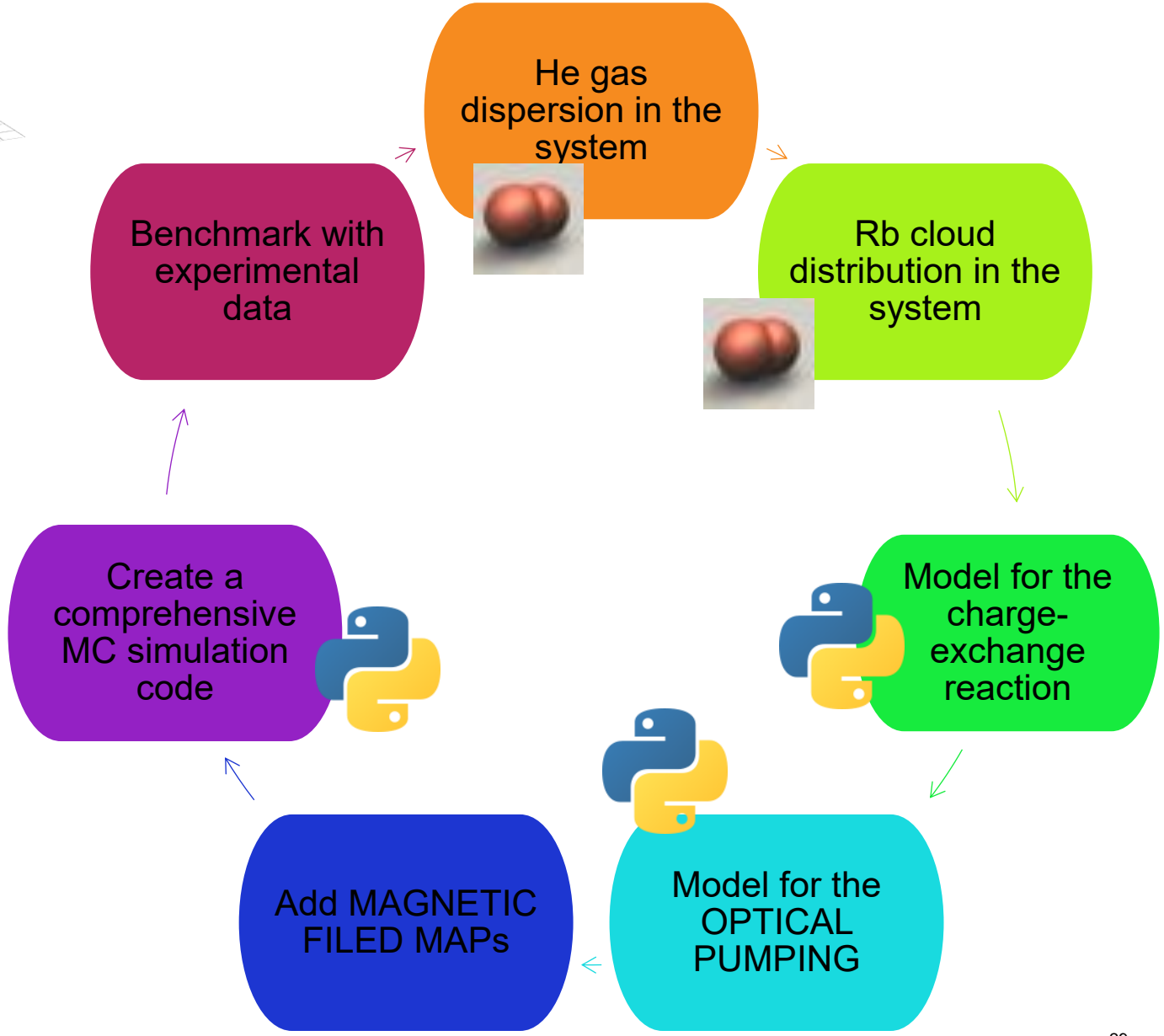
Subsystem	Critical components	Operational Status	MC simulation	R&D required	Rebilde	Power Suply
Plasmatron	Pulsed valve	Good		Yes	Yes	Yes
	Cathod	Good				Yes
IOS grids system	Grigs	Good		Yes		Yes
Neutral H-cell	Pulsed valve	Good	Yes	Yes	Yes	Yes
SCS		Good	Yes			
LCC		OK	Yes		Yes	
He-cell	EM-valve	Good		Yes	Yes	Yes
	Cell	OK	Yes	Yes	Yes	
He grids system	Grids	?		Yes	Yes	
Rb-cell	Cell	OK	Yes	Yes	Yes	
Sona transfer	Sona-cell	OK	Yes	Yes		
	Coiles	OK	Yes	Yes	Yes	Yes
Na-solenoid	Coiles	OK		Yes	Yes	
Na-cell	Cell	Good	Yes	Yes		
Extractor	EL	OK			Yes	Yes

Create a comprehensive MC simulation code



```
state = {
  'n_Rb_total': from_Molflow, # [cm^-3]
  'P_Rb': from_optical_pumping_model, # [dimensionless]
  'I_laser': laser_intensity_here, # [W/cm^2]
  'Gamma_pump': pumping_rate, # [s^-1]
  'Gamma_relax': relaxation_rate, # [s^-1]
  'flux_H_plus': proton_flux_here, # [cm^-2 s^-1]
  'rate_CE': charge_exchange_rate, # [cm^-3 s^-1]
}
```





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Summery

Significant work will be required to upgrade the source.

- Many components of this source are unique and commercially unavailable. They have undergone intensive operation over many years and require replacement.
- The obsolete components of source will be replaced with modern and more reliable systems.
- Based on the results of tests and measurements of individual source components, a comprehensive modeling system will be developed. This modeling will enable:
  - ✓ Optimization of the dimensions, geometry, and relative positioning of the elements (He-cell, Rb-cell, collimator system…);
  - ✓ Determine the optimal distribution of He gas, Rb vapor, Na jet, etc.;
  - ✓ Determine the magnetic field configurations of the SCS, LCC, Sona-solenoids and Na-solenoid, with the aim of maximizing polarization;

  …

The combination of hardware upgrades and advanced modeling will enable the optimization of the OPPIS source to achieve higher beam current and polarization values, as well as the development of a polarized proton source for the EIC with the required parameters.

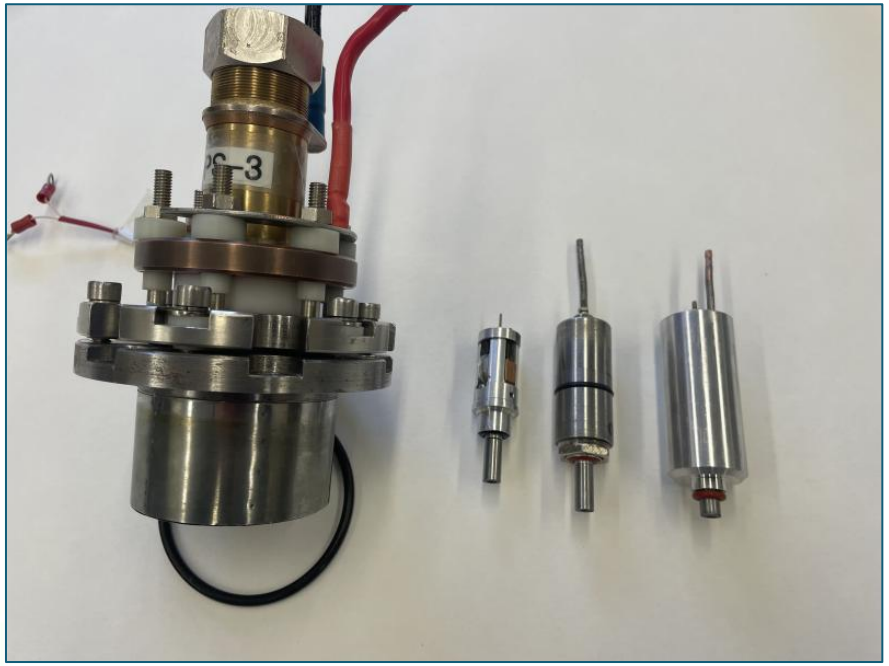
Backup

Plasmatron (cathode and pulse-valve)

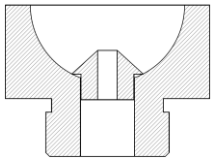
*One of the most important elements of plasma formation for a stable operation of the source is the **pulse valve** for injection of the hydrogen-containing gas and the **cathode** (arc current ~500A).*

Pulse valve

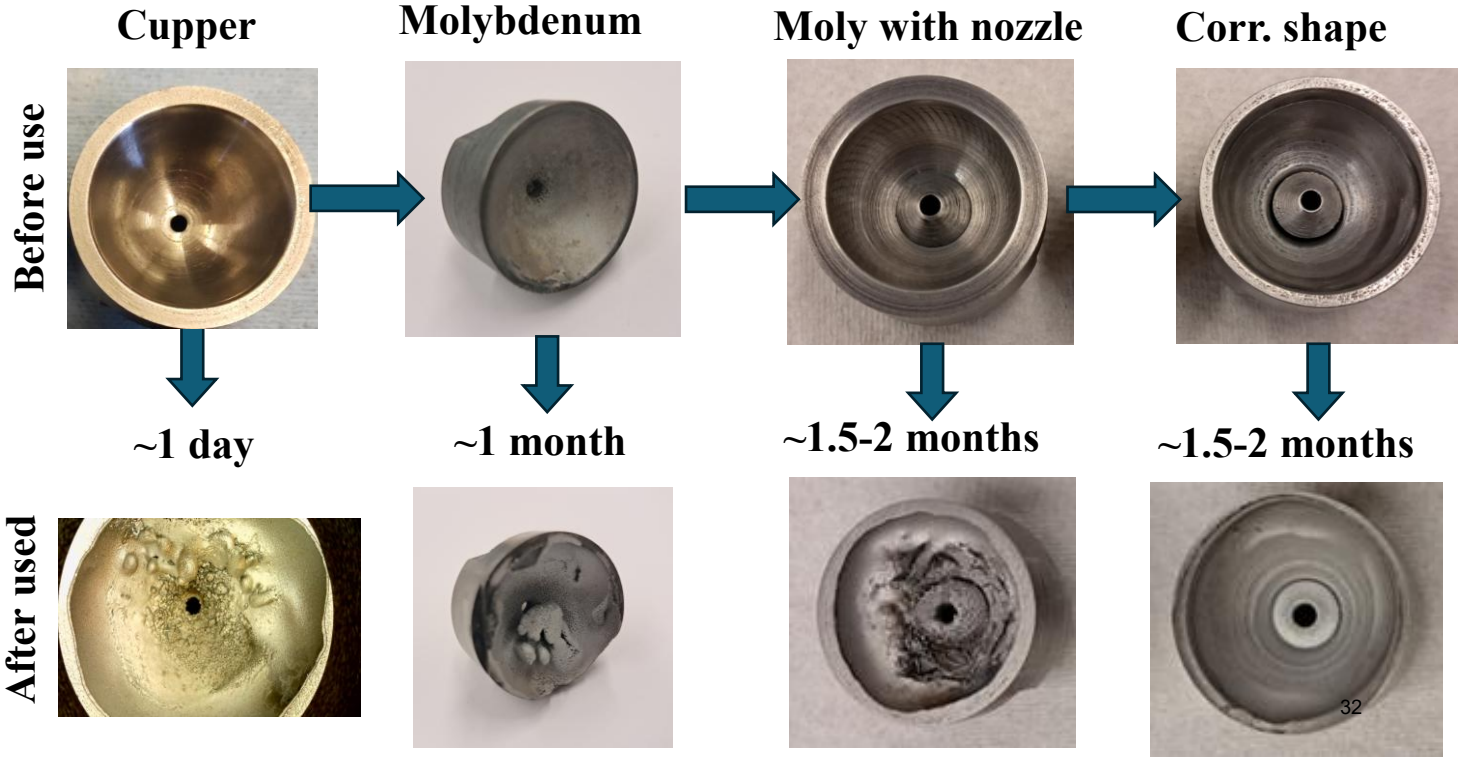
The pulse valve has been upgraded several times to provide precise control and long-term stable hydrogen supply to the plasmatron to form a stable plasma.
The same type of valve is used in the helium neutralization cell.



Cathode



The original copper cathode (~1085*C) in this high current cold cathode only lasted a few days (~$5 \cdot 10^5$ arc pulses). Using molybdenum cathode (~2600*C) significantly improved the service life to ~$5 \cdot 10^6$ arc pulses (~1-2 months).
Improving the geometric shape of the cathode by inserting a small nozzle and enlarging the outer rim, as well as improving the vacuum sealing of the plasmatron, limited the plasma dispersion, and increased the service life by more than 10^7 arc pulses (RUN-24).



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FABS 4-grid (spherical) Ion Optical System with “geometrical focusing”

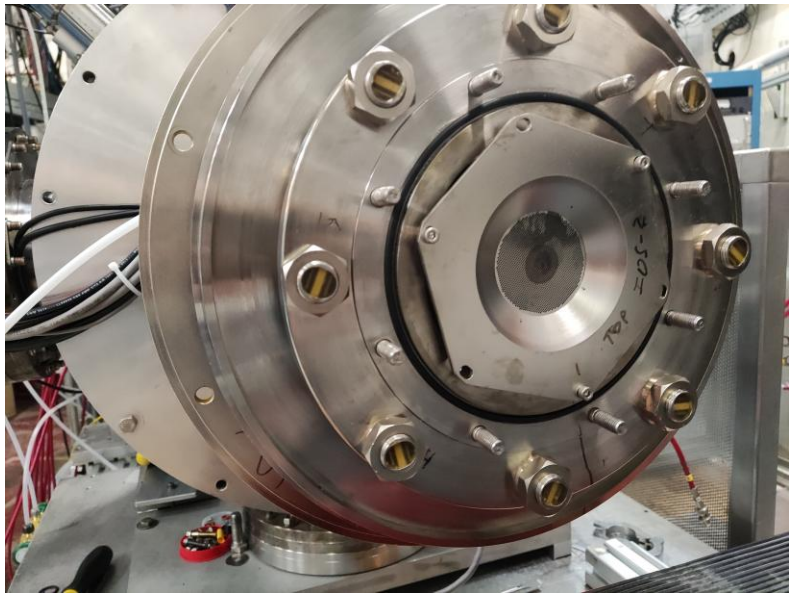
Grids system made by 0.4 mm thick molybdenum plates.

N grids	=	4
Diameter of grids	~	50 mm
N holes	=	1820
Diameter of holes	=	0.8 mm
Step of holes	=	1.1 mm
Transparency	~	53 %

Radii of the spherical grids:
R1~ grid1 ~ 180 cm
R2~ grid2 ~ 150 cm
R3~ grid3 ~ 120 cm
R4~ grid4 ~ 120 cm

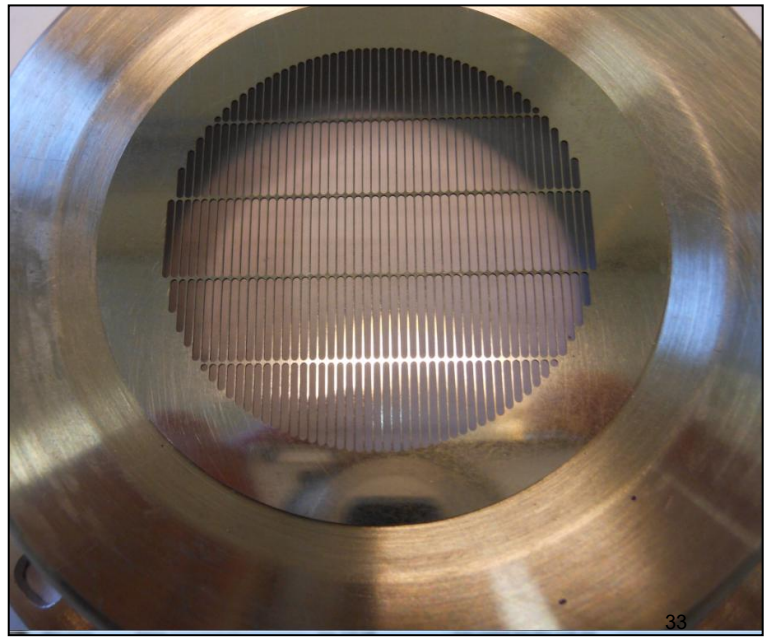
Gap of grids:
1→2 ~ 0.4-0.5 mm
2→3 ~ 1.0-1.4 mm
3→4 ~ 0.4-0.5 mm

Proton energy ~ 5-10 keV
Intensity ~ 2.5-5.0 A



IOS#	I^0,A	F, m	a, mrad	H^0, mA	H^-, mA
1	3.5	170	12	270	9
2	3.2	300	7	730	22
3	3	280	8	650	20

New slit-type IOS grid for higher brightness beam formation



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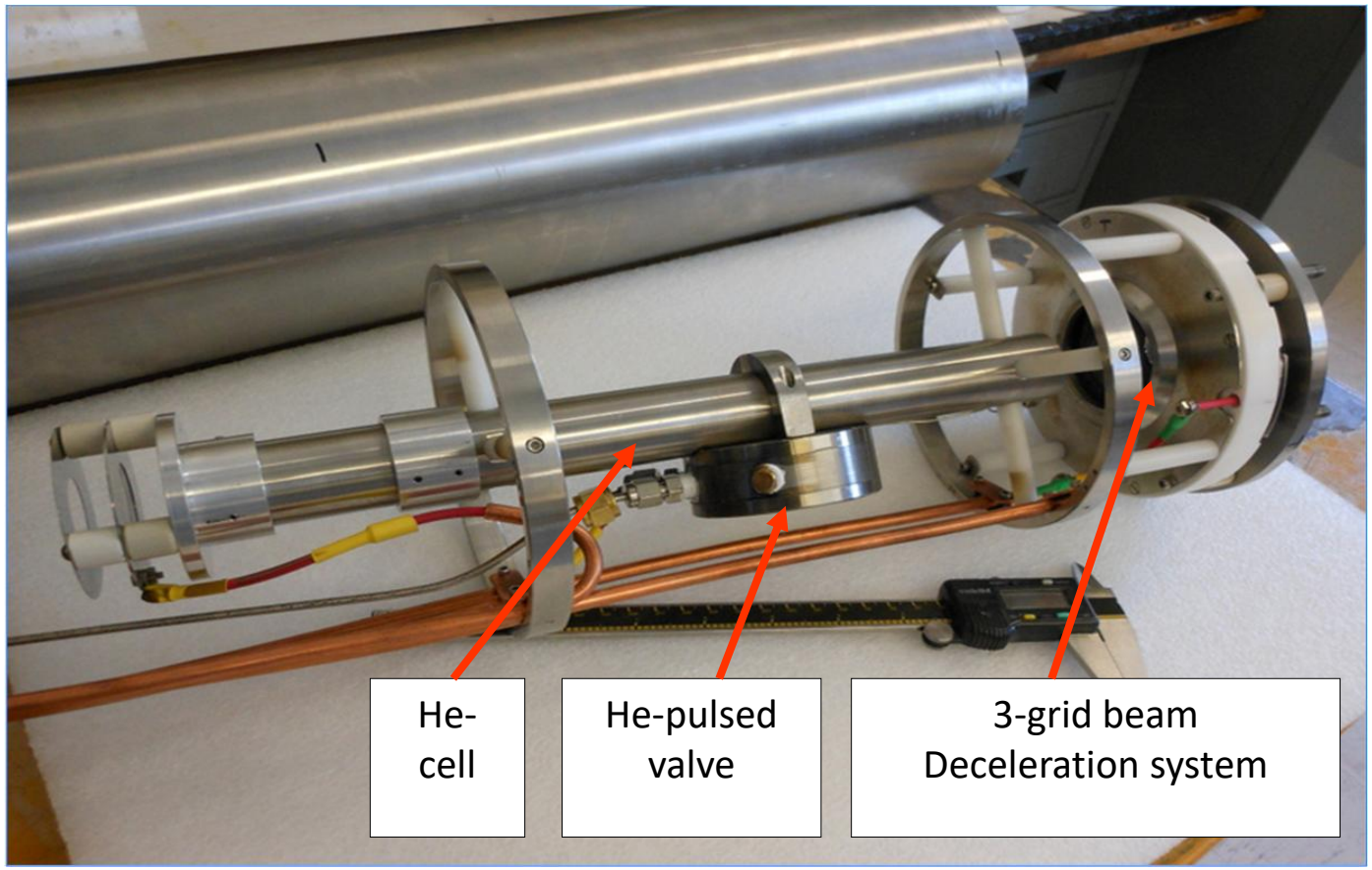
He-ionizer cell and 3-grid deceleration system

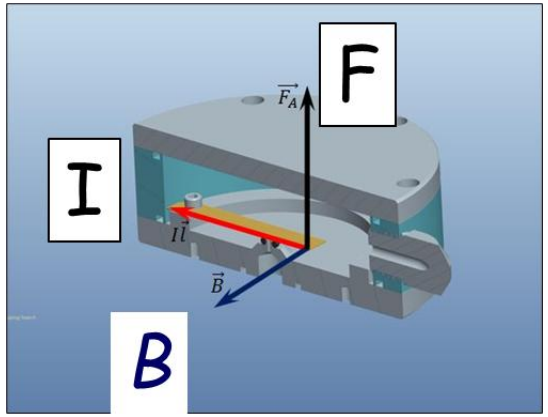
Two functions of the new He-cell with pulsed valve:

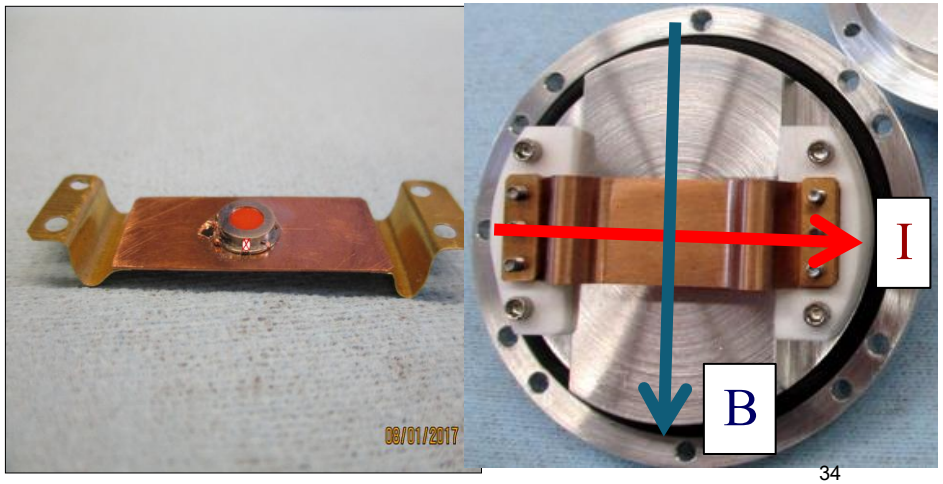
- **Ionization of the injected neutral beam in the He-cell**
- **Deceleration of the ionized part of the beam by 3-grids system to separate from the not ionized part**



"Electro-magnetic" pulse valve

Lorentz (Laplace) force moves the flexible conducting plate in the high (~ 2-5 T) magnetic field. For I=10 A, L=5 cm, F=2.5 N. Current pulse duration ~100-300 us





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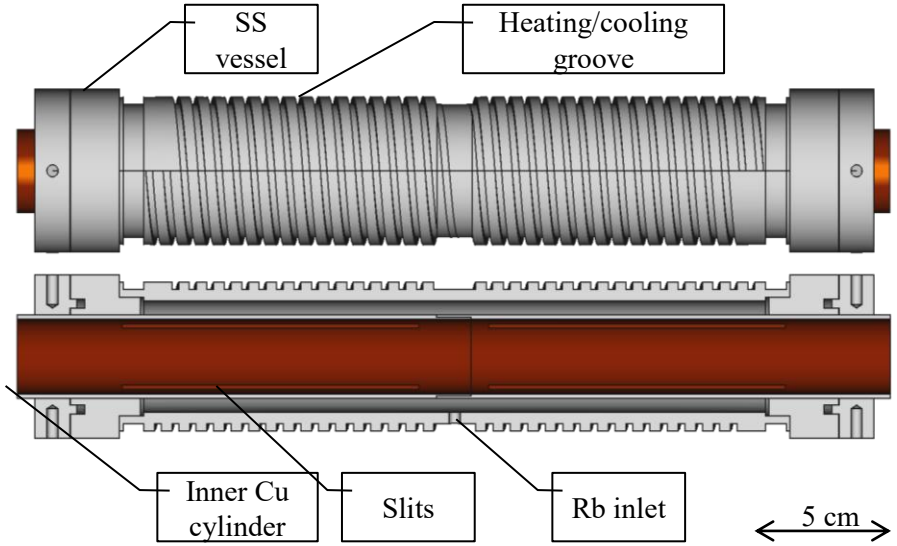
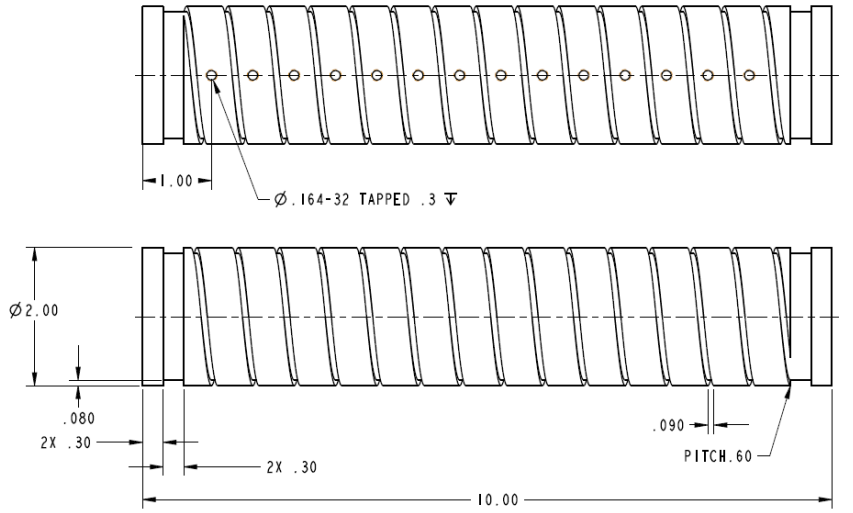
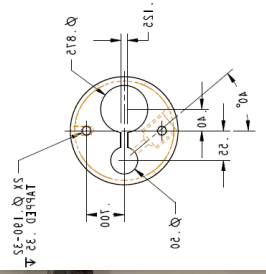
Neutralizing Rb-cell

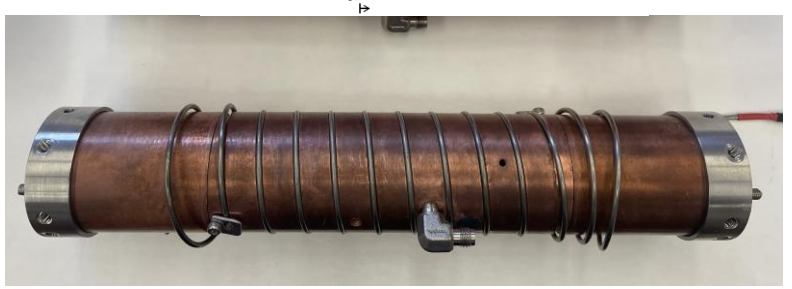
SS Cell (Run24)



Cupper Rb-cell

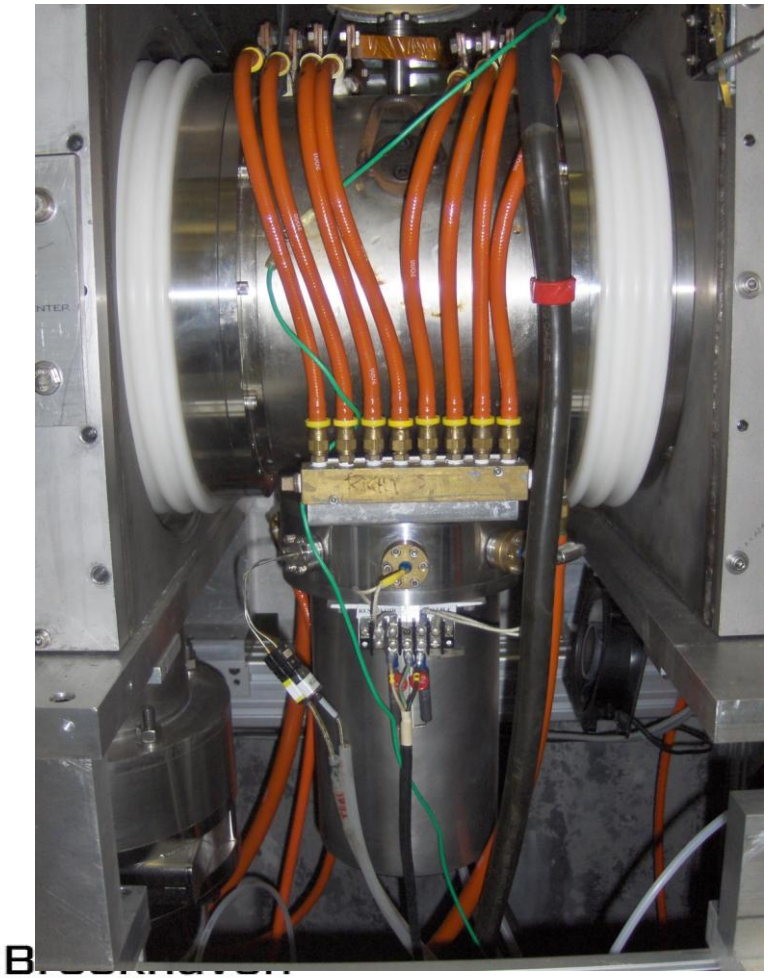


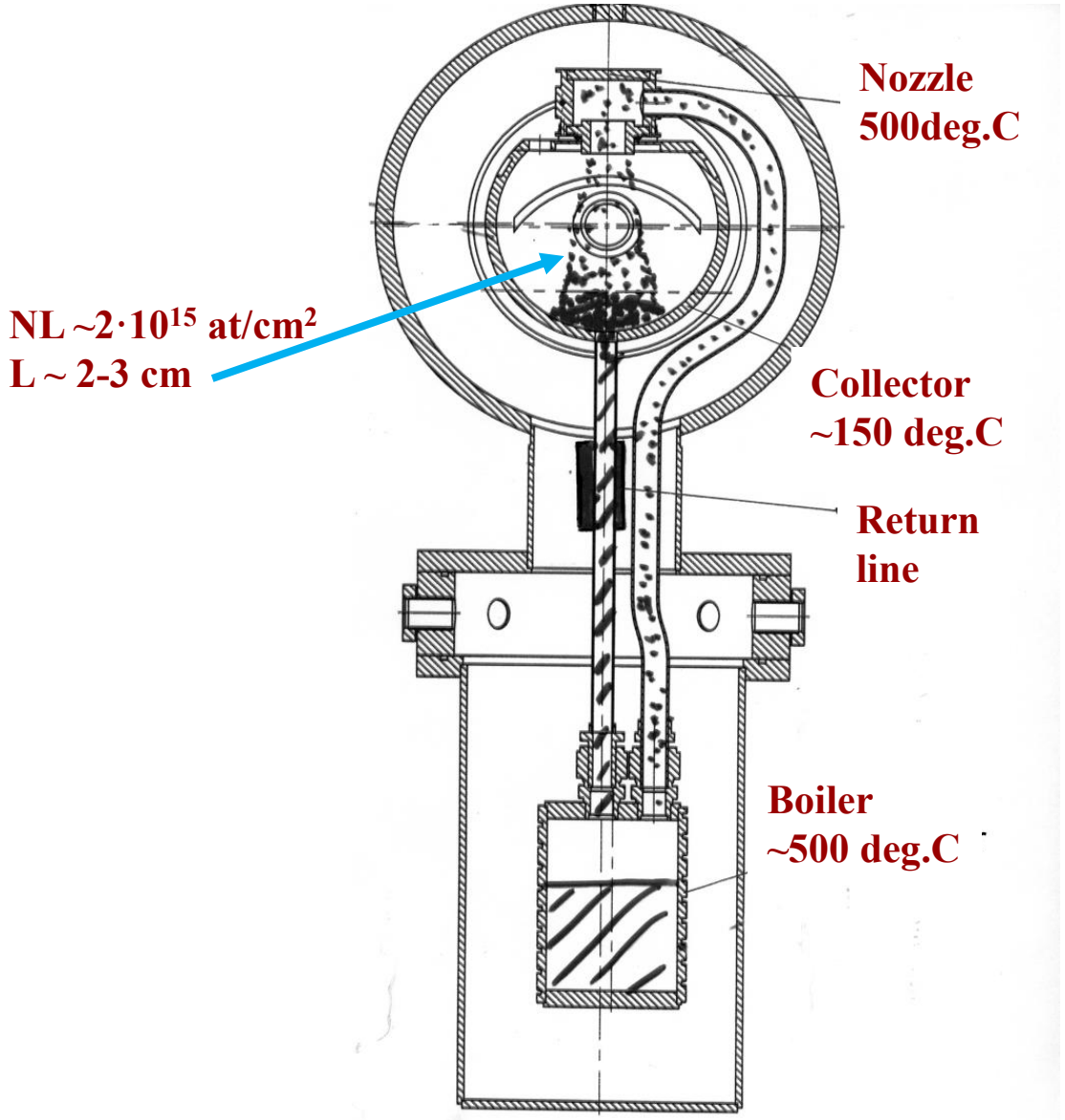




Sodium-jet ionizer cell

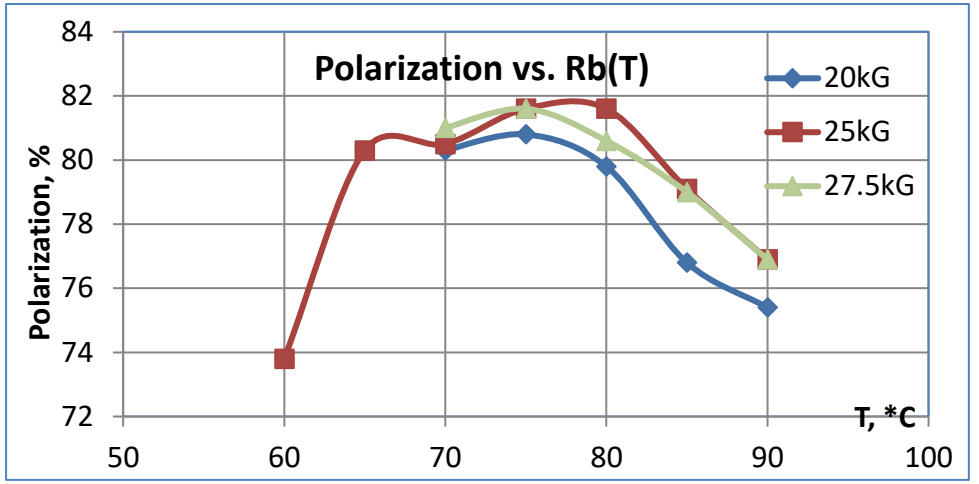
Transversal vapor flow in the Na-jet cell. Reduces sodium vapor losses for 3-4 orders of magnitude, which allow the cell aperture increase up to 3.0 cm .

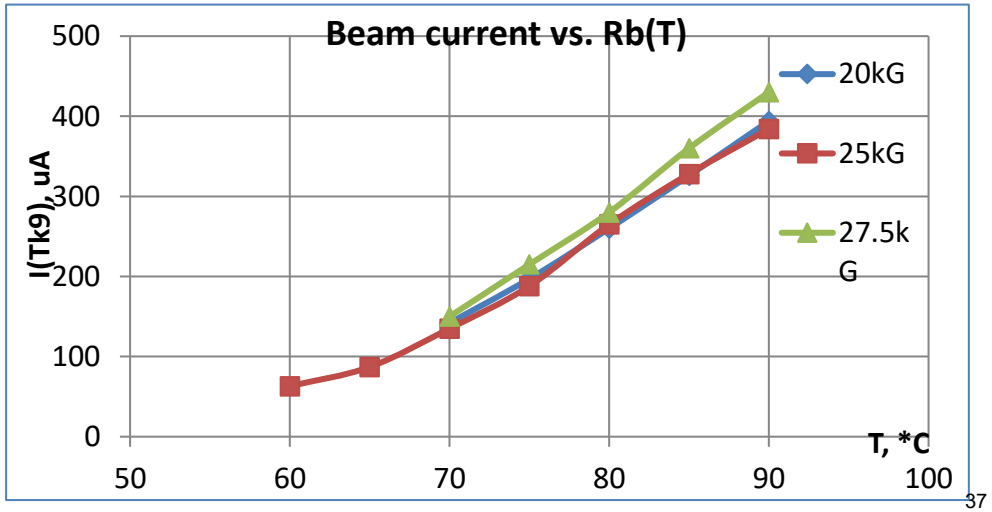




Superconducting Solenoid

The Solenoid is fully re-condensing with no measurable helium losses. 152 mm in diam. warm aperture, total length-115 cm. Flattop magnetic field (+/- 0.5%) is ~65cm.





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Depolarization factors

Depol. factor		Process	Estimate
1	E_H^0	Dilution due H^0 part of the beam (LEBT)	0.99 - 0.99
2	P_{Rb}	Rb-optical pumping (Laser system)	0.99 - 0.99
3	S	Rb polarization spatial distribution (Collimators)	0.97 - 0.98
4	B_{RG}	Proton neutralization in residual gas (Vacuum)	0.98 - 0.99
5	E_{LS}	Depolarization due to spin-orbital interaction	0.98 - 0.98
6	E_{ES}	Dilution due to incomplete energy separation not polarized component of the beam (LEBT)	0.98 - 0.99
7	E_{Sona}	Sona-transition efficiency (Adjustment)	0.96 - 0.98
8	E_{ion}	Incomplete hyperfine interaction breaking in the ionizer magnetic field	0.98 - 0.99

Total: 0.85 - 0.90

$$P = E_H^0 \cdot P_{Rb} \cdot S \cdot B_{RG} \cdot E_{LS} \cdot E_{ES} \cdot E_{Sona} \cdot E_{ion} \sim 85\text{-}90\%$$

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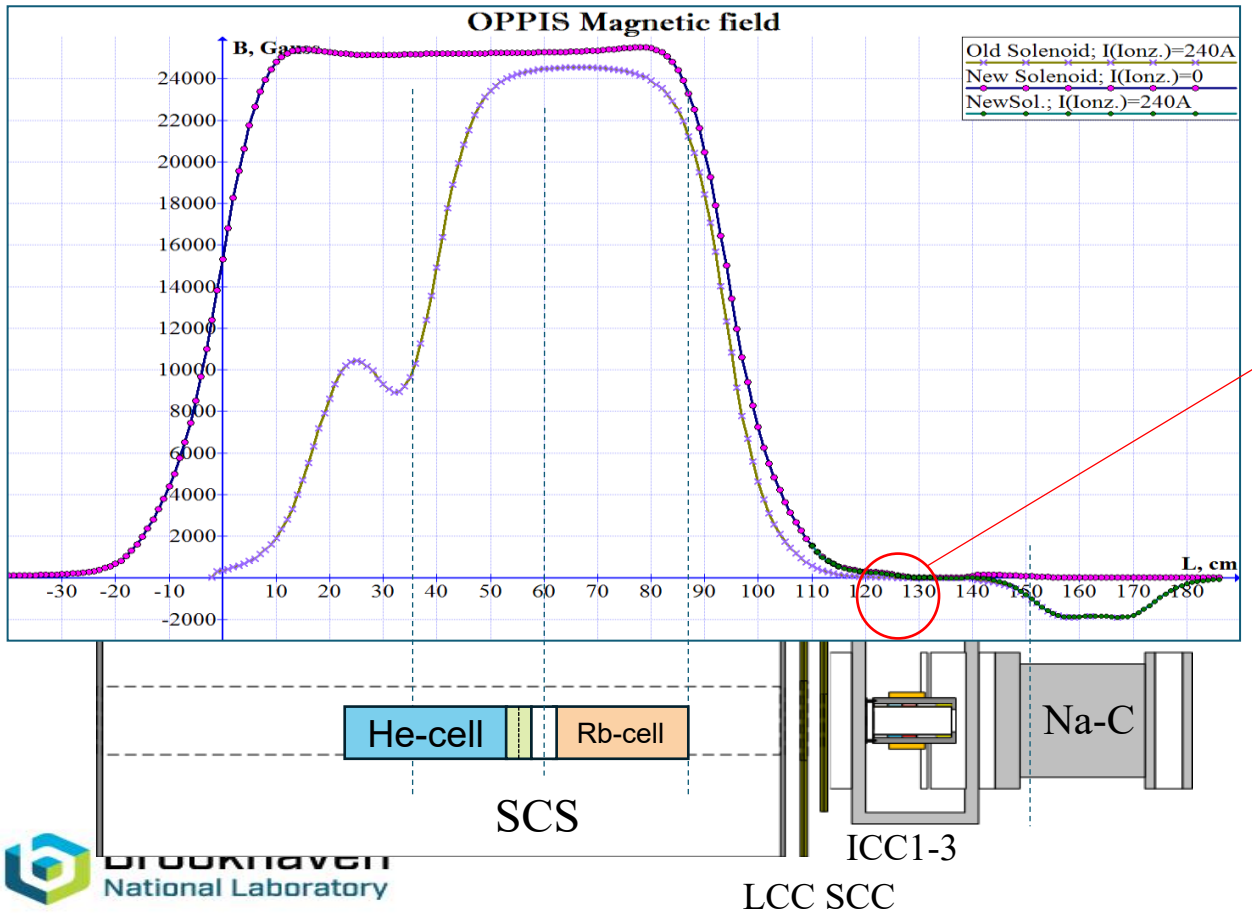
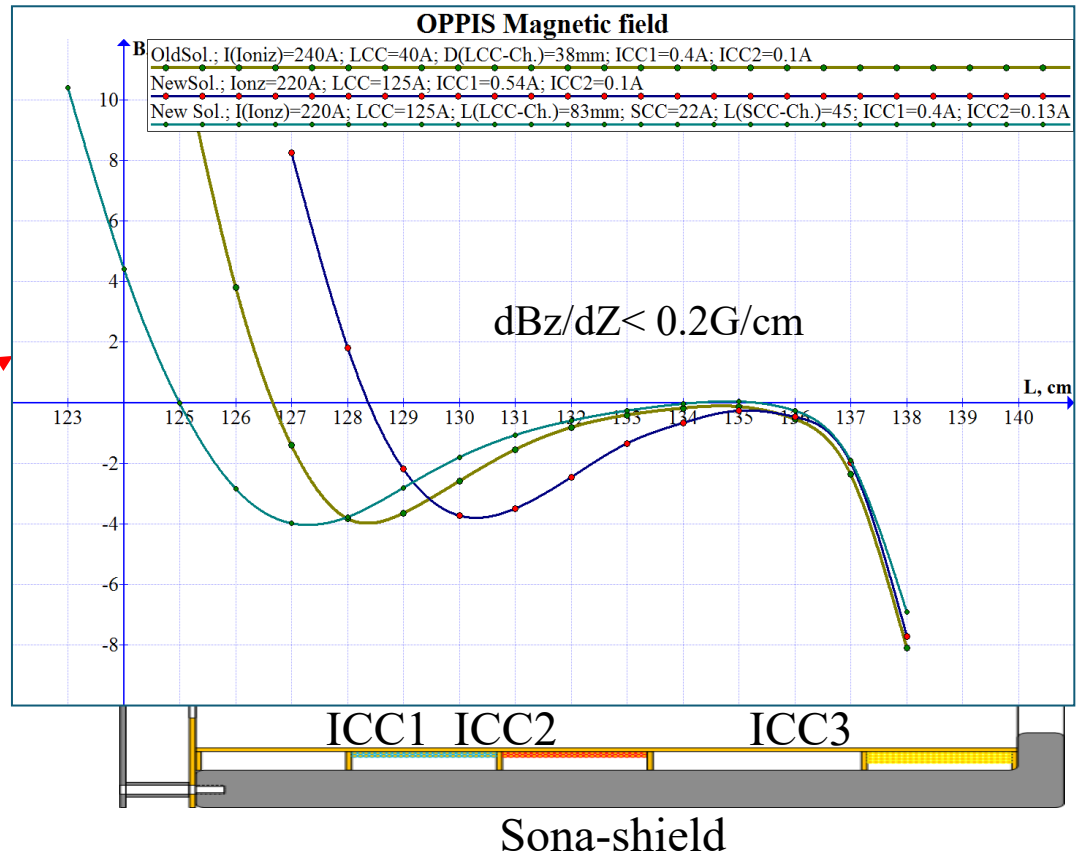
Sona-transition efficiency

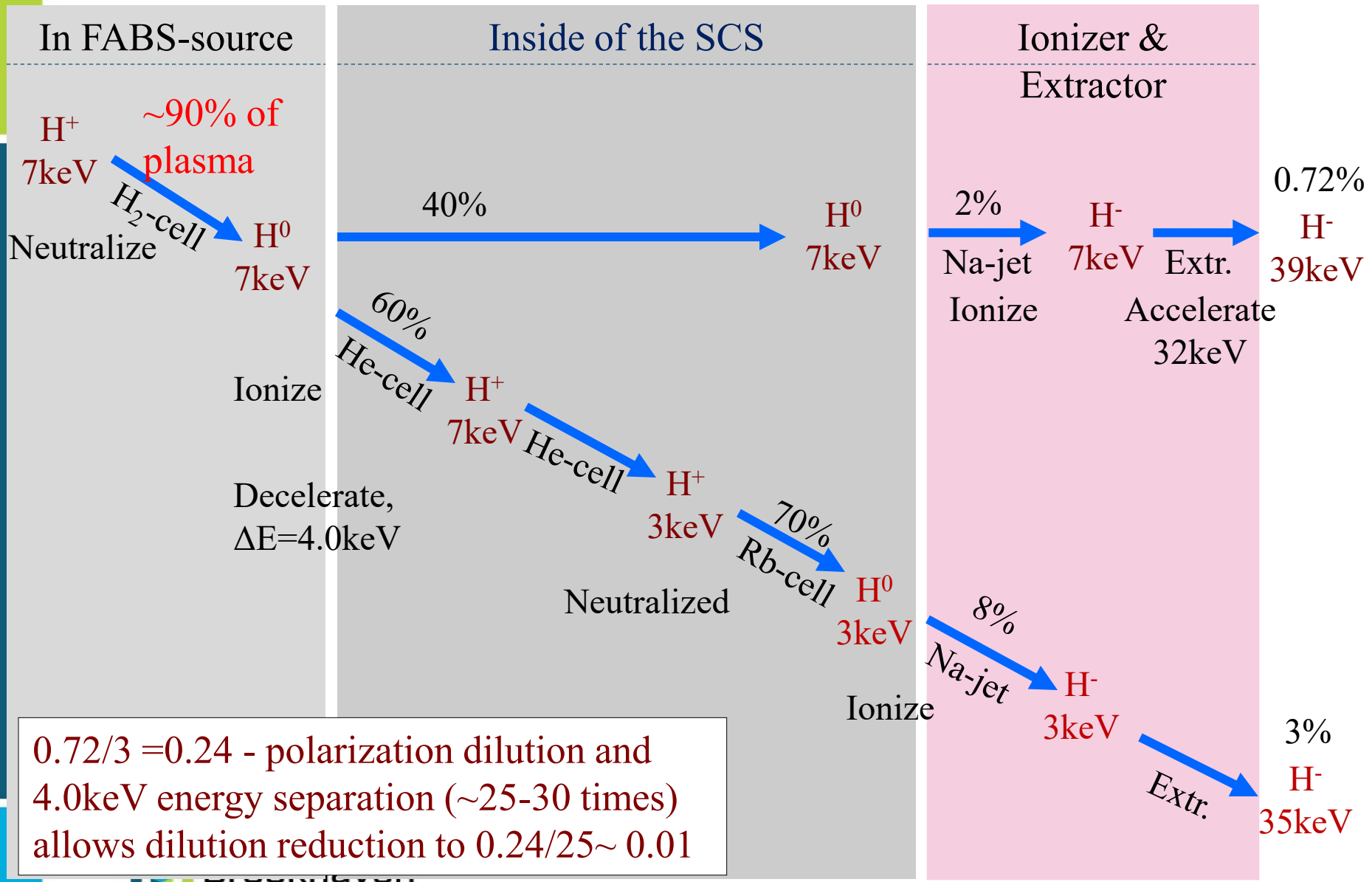
The shape of the magnetic field in the "Sona Transition" area depends on the following factors and can be adjusted by:

- The optimization of the solenoid position;
- 2 correction coils (LCC and SCC) with the field in the opposite direction to the SCS;
- 3 correction coils (ICC1-3) for fine field tuning inside the “Sona Transition”;
- “Sona-shield” (soft steel cylinder- of 100 mm diameter and 120 mm length).
- Na-cell coil (Na-C) - solenoid around sodium ionizer.



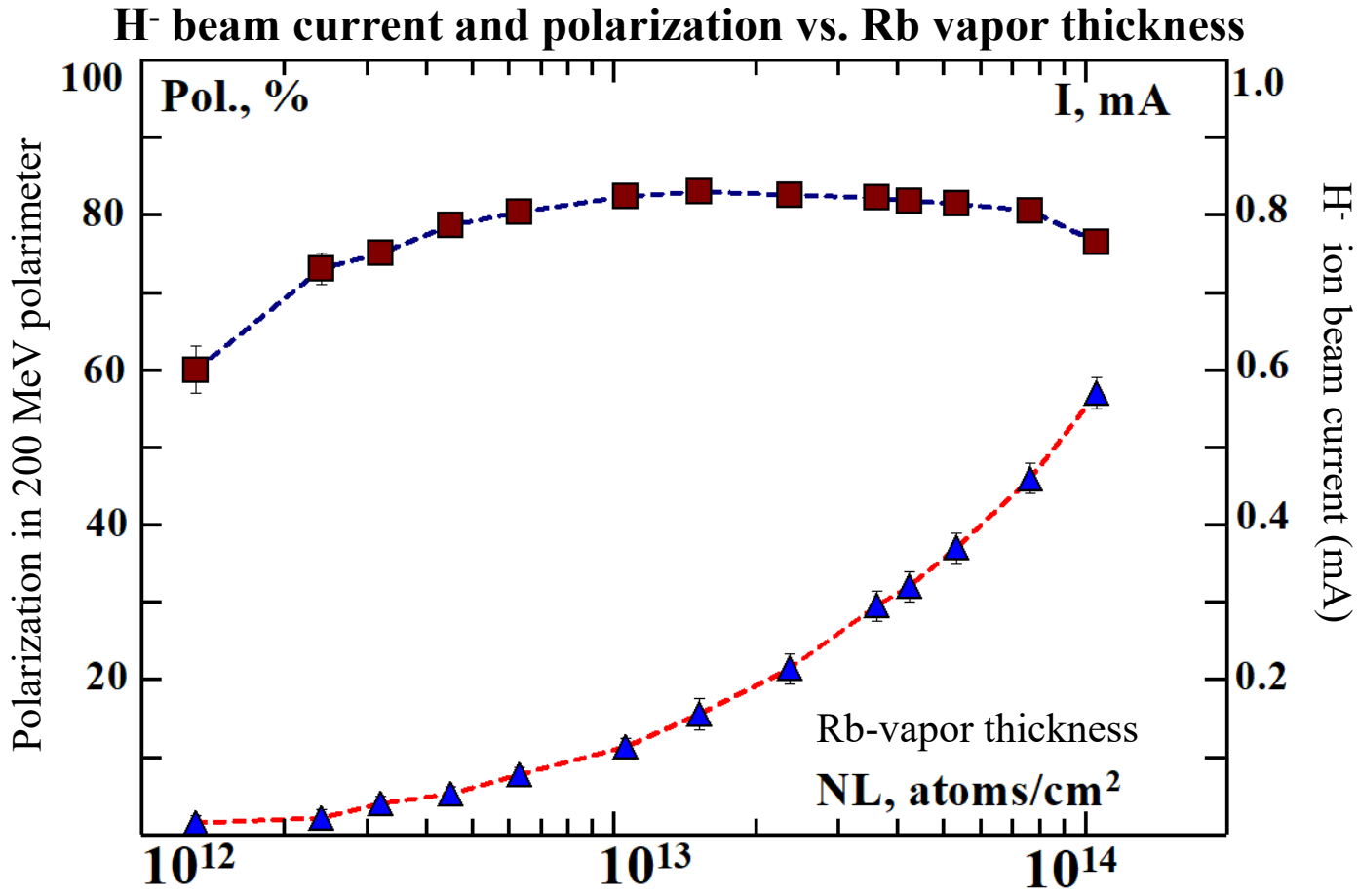


Polarization dilution due H^+ in the new source



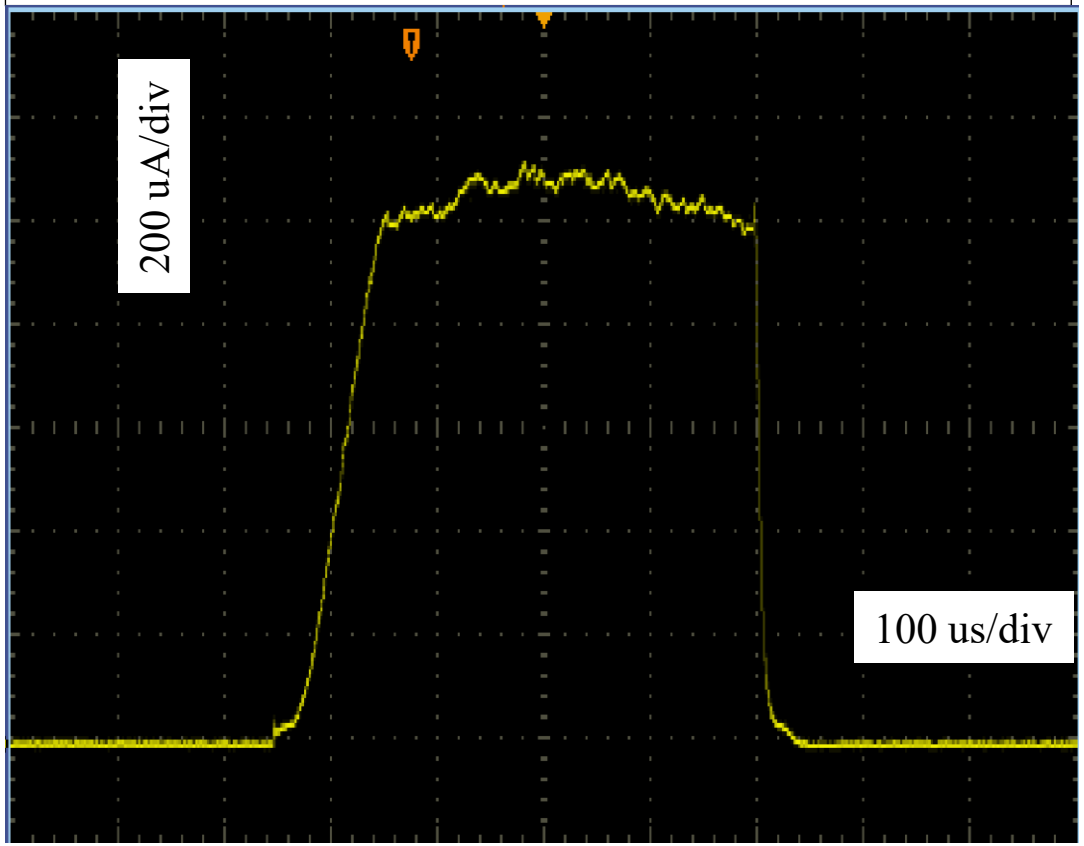
0.72/3 =0.24 - polarization dilution and 4.0keV energy separation (~25-30 times) allows dilution reduction to 0.24/25~ 0.01

H^- beam current and polarization at 200 MeV

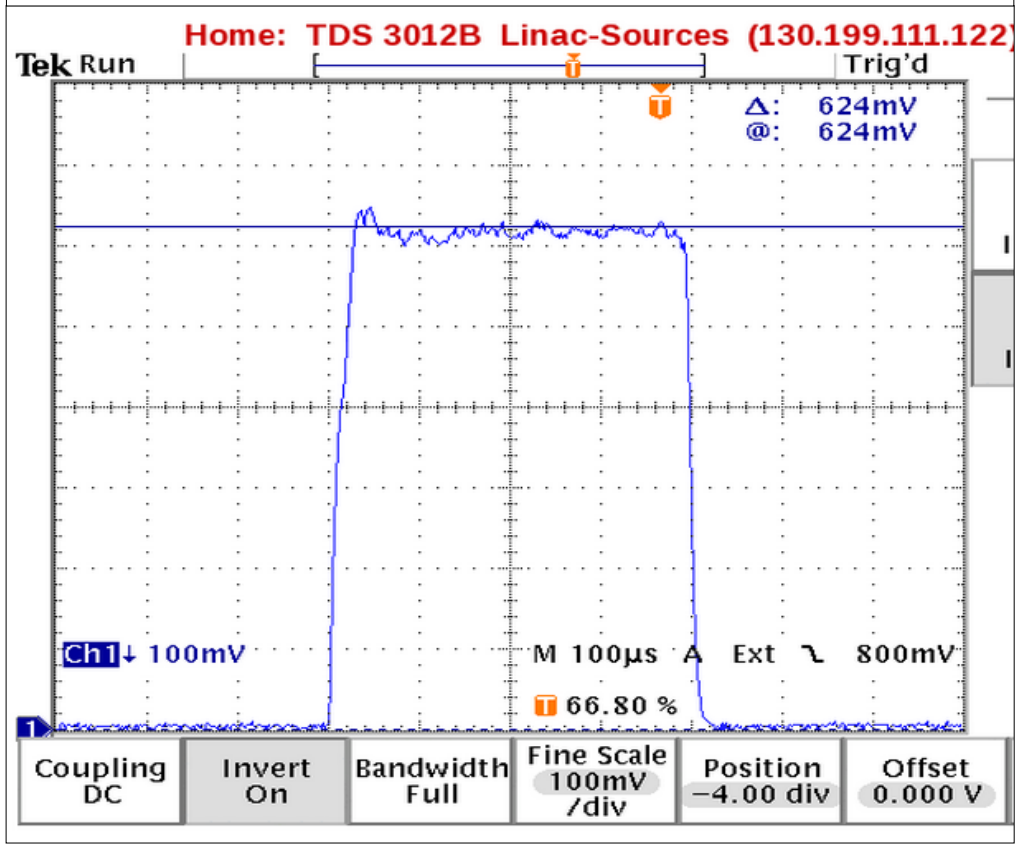


200 MeV polarized proton after Linac

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



~620 µA×400µs ~1.5·10^{12} p/pulse after LINAC



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