Polarized proton source for EIC

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Polarized Ion Sources and Beams at EIC

Stony Brook University, New York

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Brookhaven National Laboratory

U.S. Department of ENERGY

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EIC Accelerator Performance

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

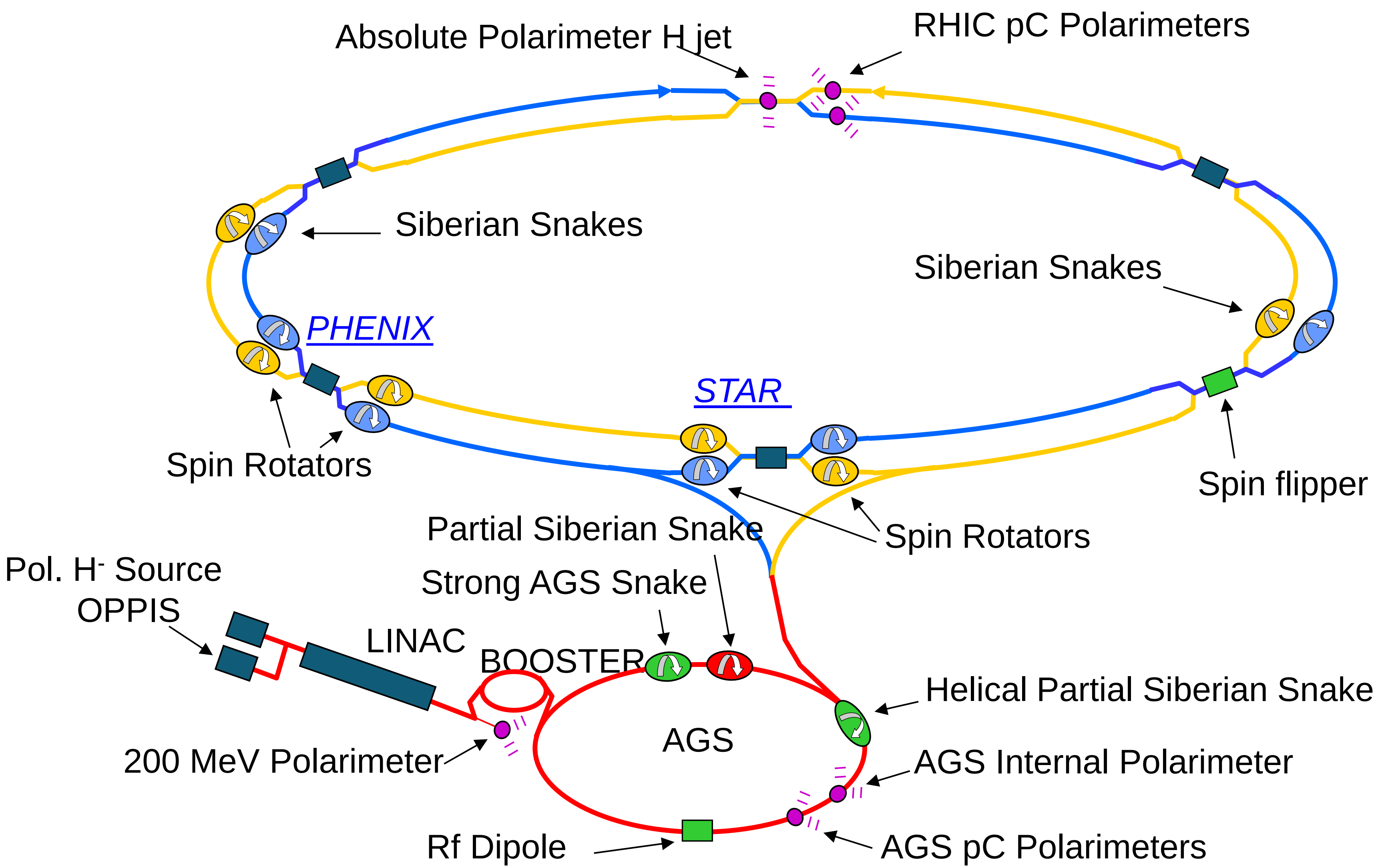
“In order to address the crucial scientific questions discussed in the previous sections, the EIC must provide:

- *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.”*

By the request of this White Paper we are looking to improve 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

Polarization facilities at RHIC



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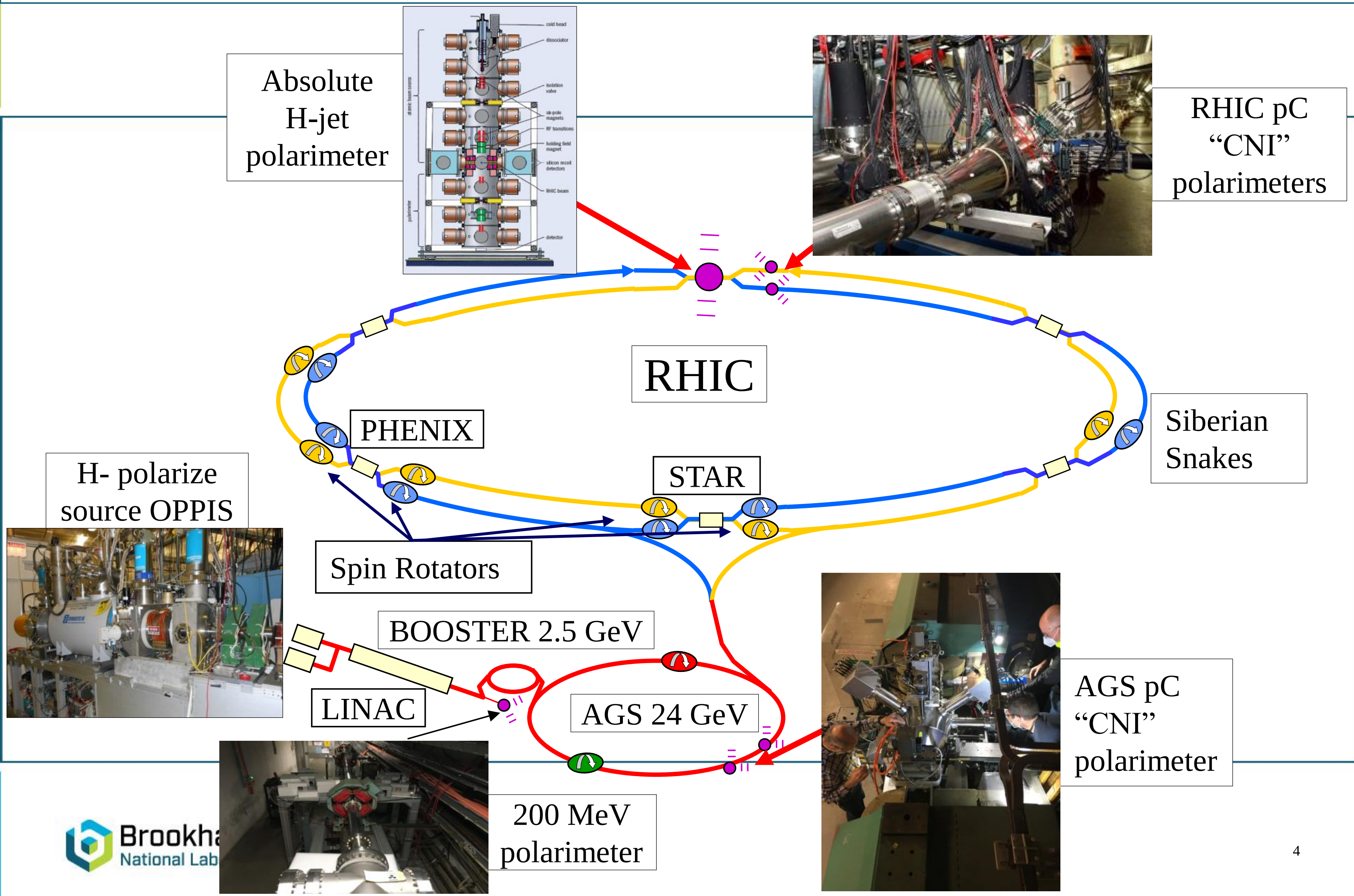
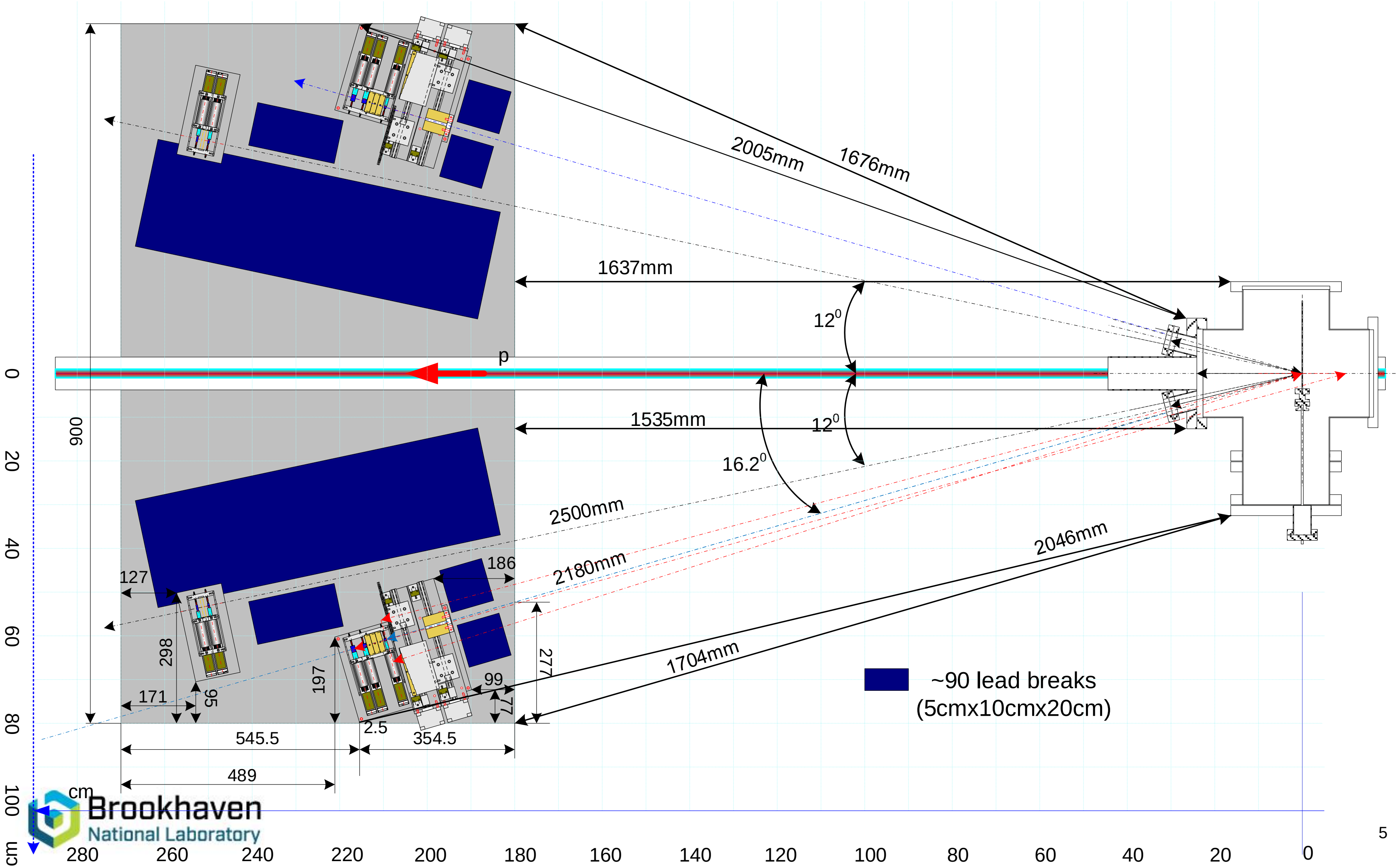
Polarization facilities at RHIC

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

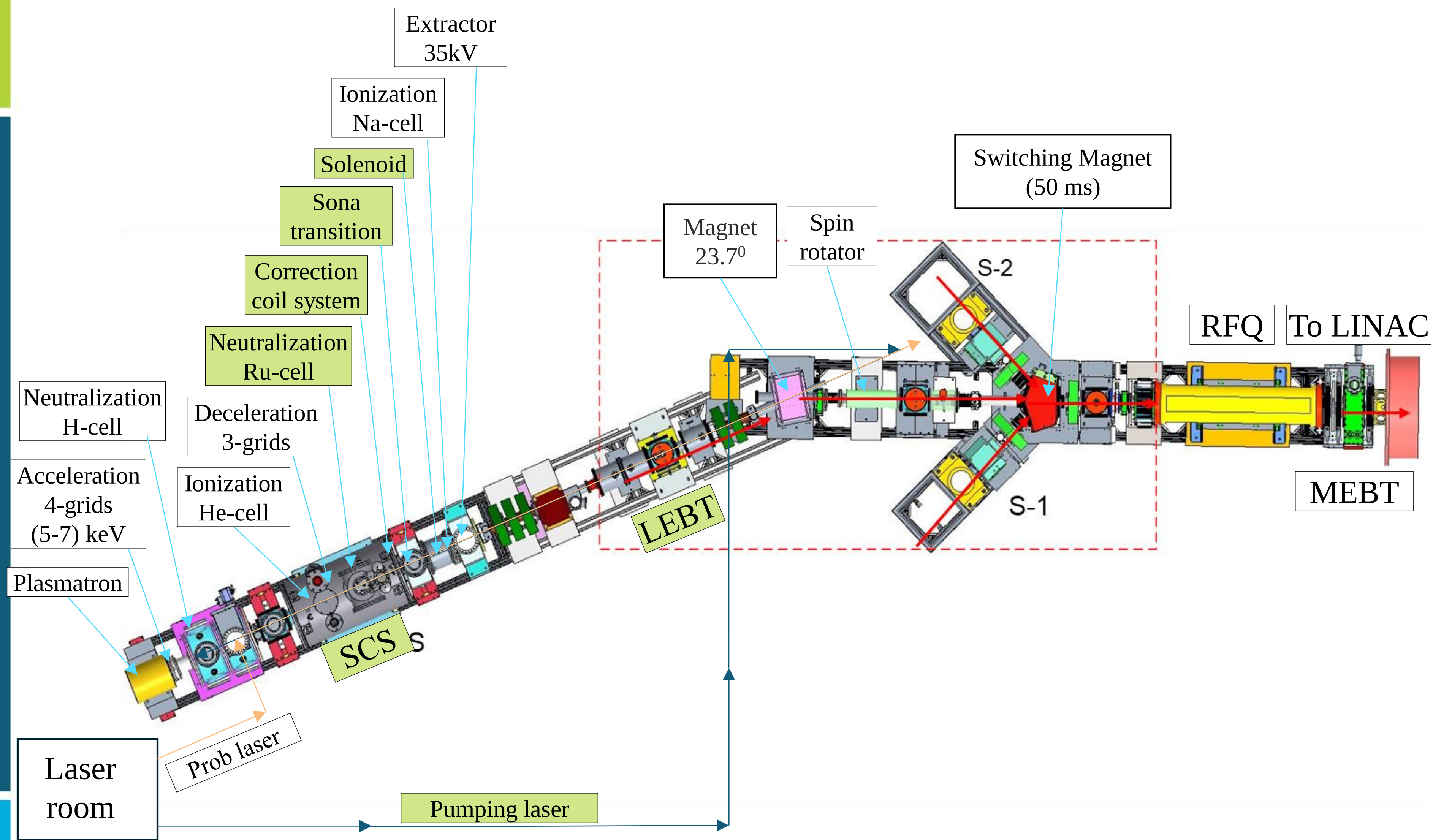


Absolute polarization measurements at 200MeV

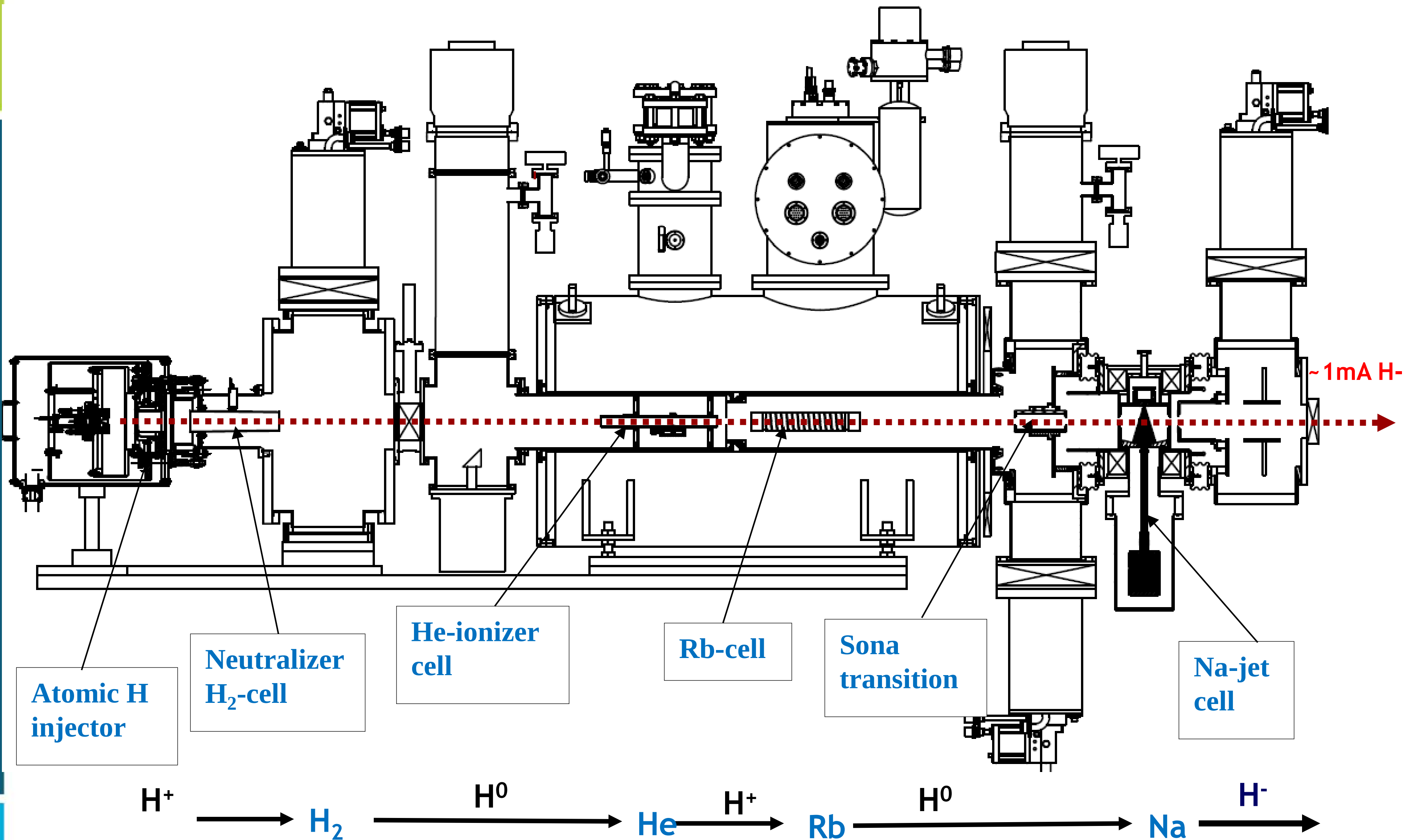
To determine the beam polarization, we measured the asymmetry of proton scattering off a thin carbon target. Since the analyzing power approaches 100% at a scattering angle of 16 degrees, the measured polarization is well-calibrated.



Optically Polarized proton source (OPPIS)



2013 OPPIS upgrade with FABS source



Ion Source Development

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

Since 2012, when FABS was implemented, we have made many adjustments to improve the beam parameters. We achieved the best polarization volume of over 86%, intensity over 1000uA, and a beam pulse duration of over 400us compared to the average volume of polarization of ~78-80% and an intensity of ~350uA.

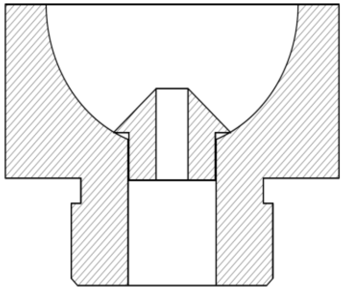
Now, our goal is to have OPPIS maintain the best parameters for several months by improving monitoring and simplifying control, as well as making it fast and easy to repair and completely safe. Our goal for the future is stability and safety with the best performance.

Optically Polarized proton source. Plasmatron

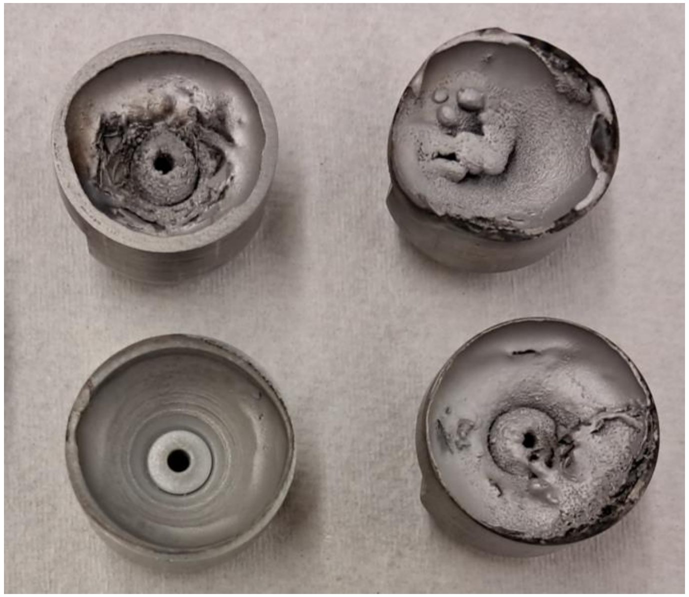
The original copper cathode (~1085 ^{0}C) in this high current cold cathode (arc current ~500A) only lasted a few days (~$5\cdot10^5$ arc pulses). Using molybdenum cathode (~2600 ^{0}C) significantly improved the service life to ~$5\cdot10^6$ arc pulses (~1-2 months). Next generation was change the cathode geometry by inserting a small nozzle and increasing the outer rim.

Old

New



Before

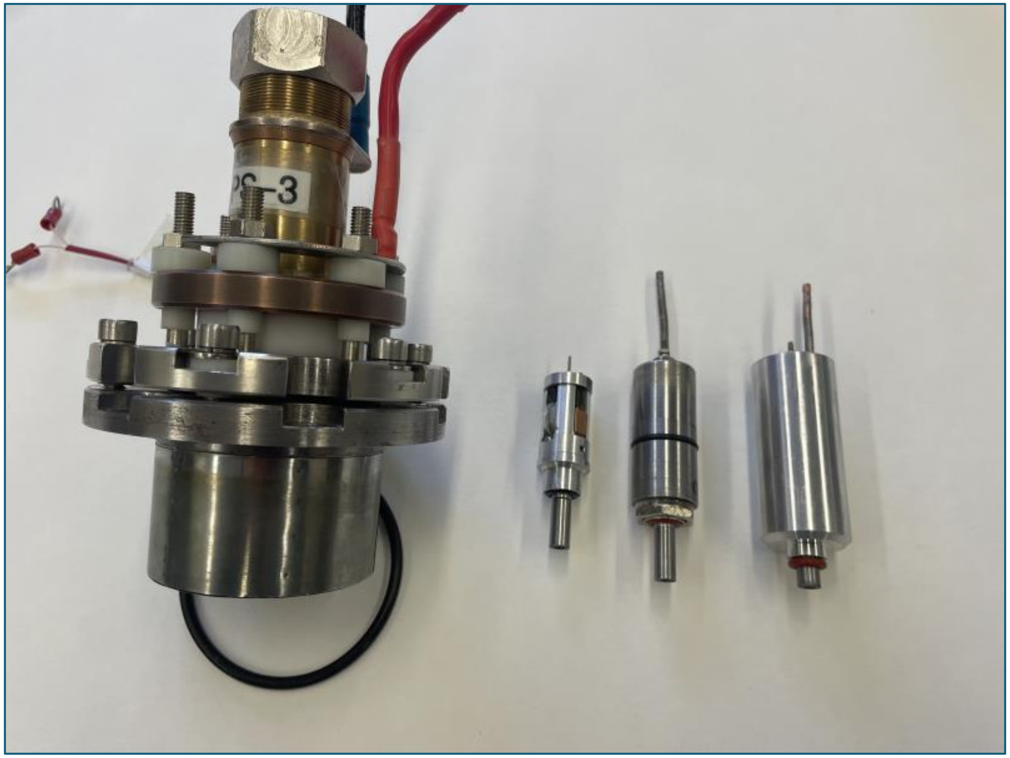


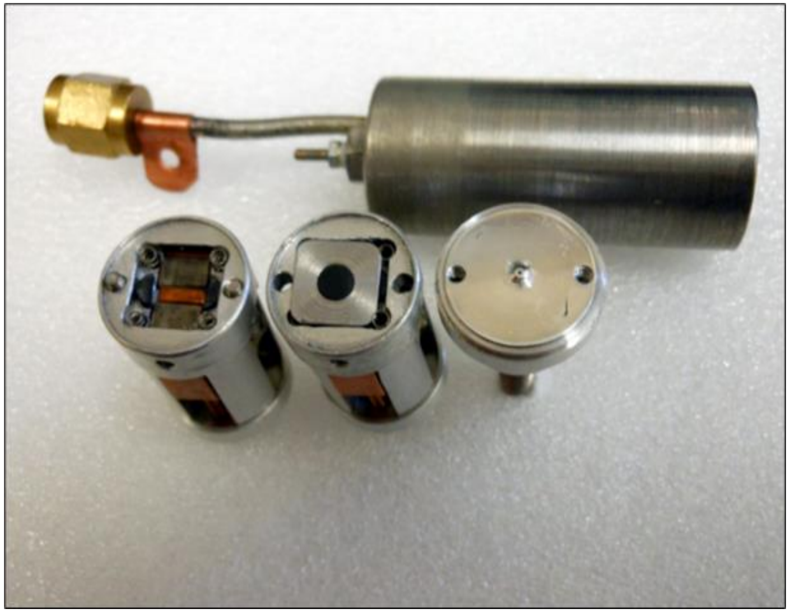
After

Optically Polarized proton source. Plasmatron

Improving the geometric shape of the cathode, as well as improving the vacuum sealing of the plasmatron, limited the plasma dispersion, and increased its service life by more than 10^7 arc pulses (RUN-24).

Other critical part of plasmatron is the pulsed valve for creating stable plasma for months. As a resalt of continuous modernization of the valve over many years, we have stable, easily adjustable valve.





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

Grids system made by 0.4 mm thick molybdenum plates.

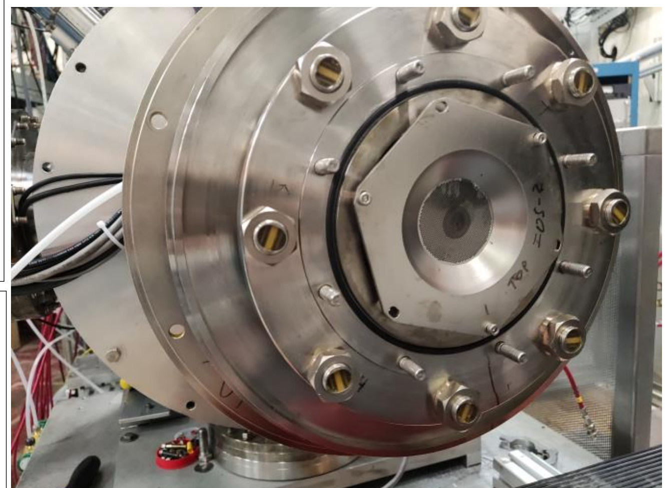
IOS#	I^0,A	F, m	a, mrad	H^0, mA	H^-, mA
1	3.5	170	12	270	9
2	3.2	300	7	730	22
3	3	280	8	650	20

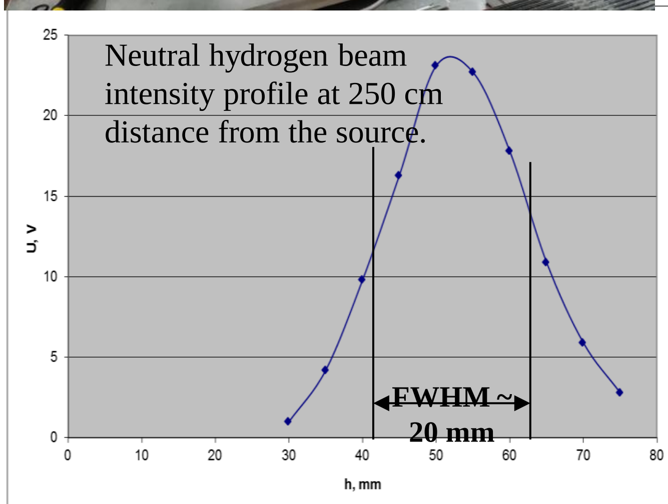
N grids = 4
Diameter of grids ~ 50 mm
N holes = 1820
Diameter of holes = 0.8 mm
Step of holes = 1.1 mm
Transparency ~ 53 %

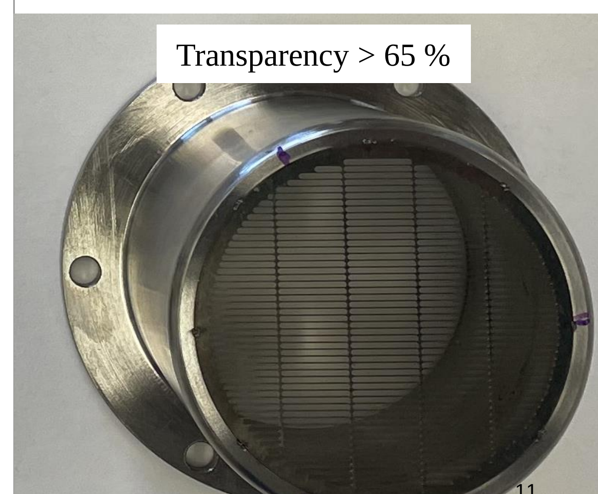
Radii of the spherical grids:
R1~ grid1 ~ 180 cm
R2~ grid2 ~ 150 cm
R3~ grid3 ~ 120 cm
R4~ grid4 ~ 120 cm

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







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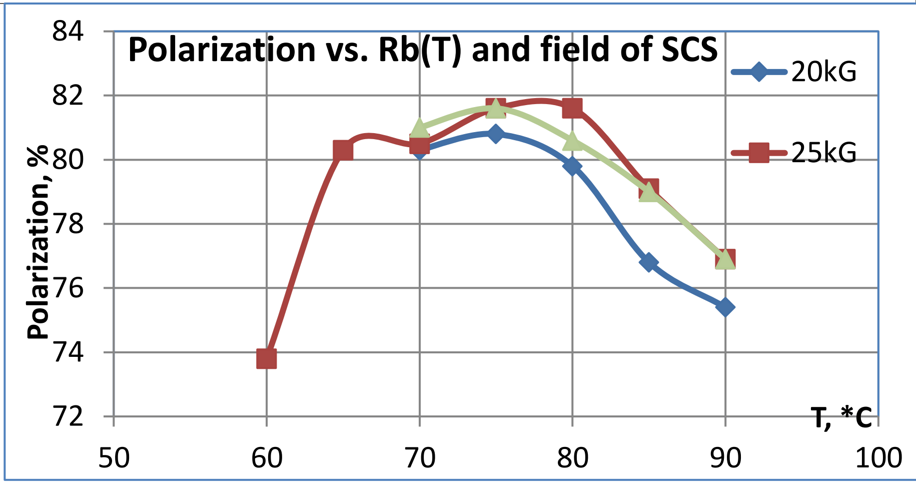
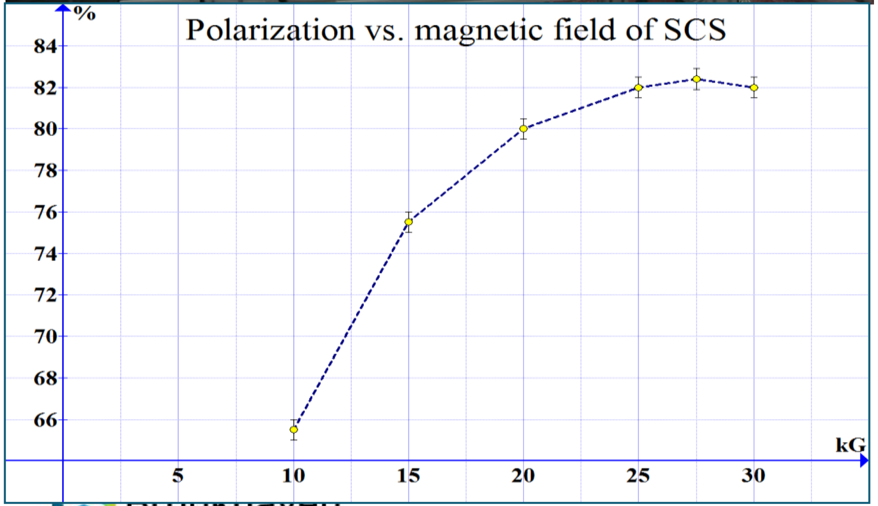
Superconducting Solenoid

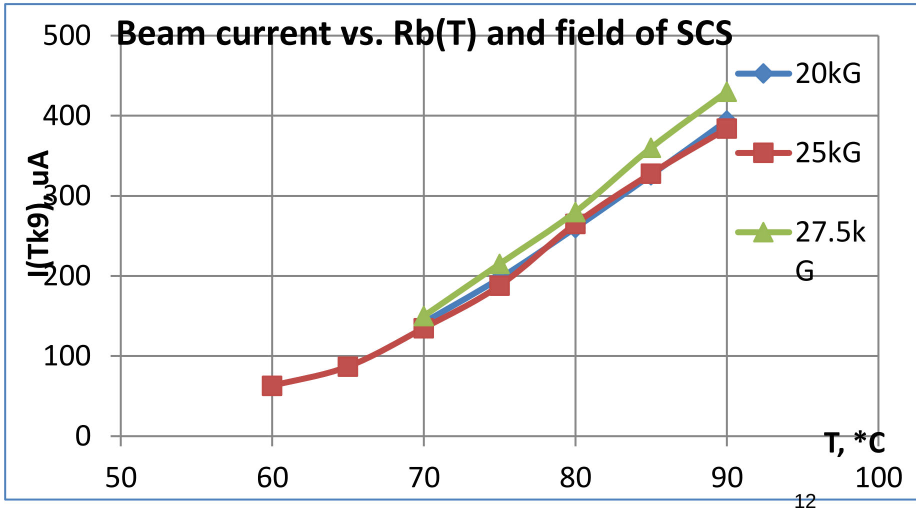
In 2012, the SCS magnet is designed and built by “Cryomagnetics” through BNL’s specification.

Five independently energized coils of solenoid can operate with a double hump field shape for ECR and a long flat mode in FABS mode with a max field of 3T. The soft steel plate is attached to the solenoid.

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







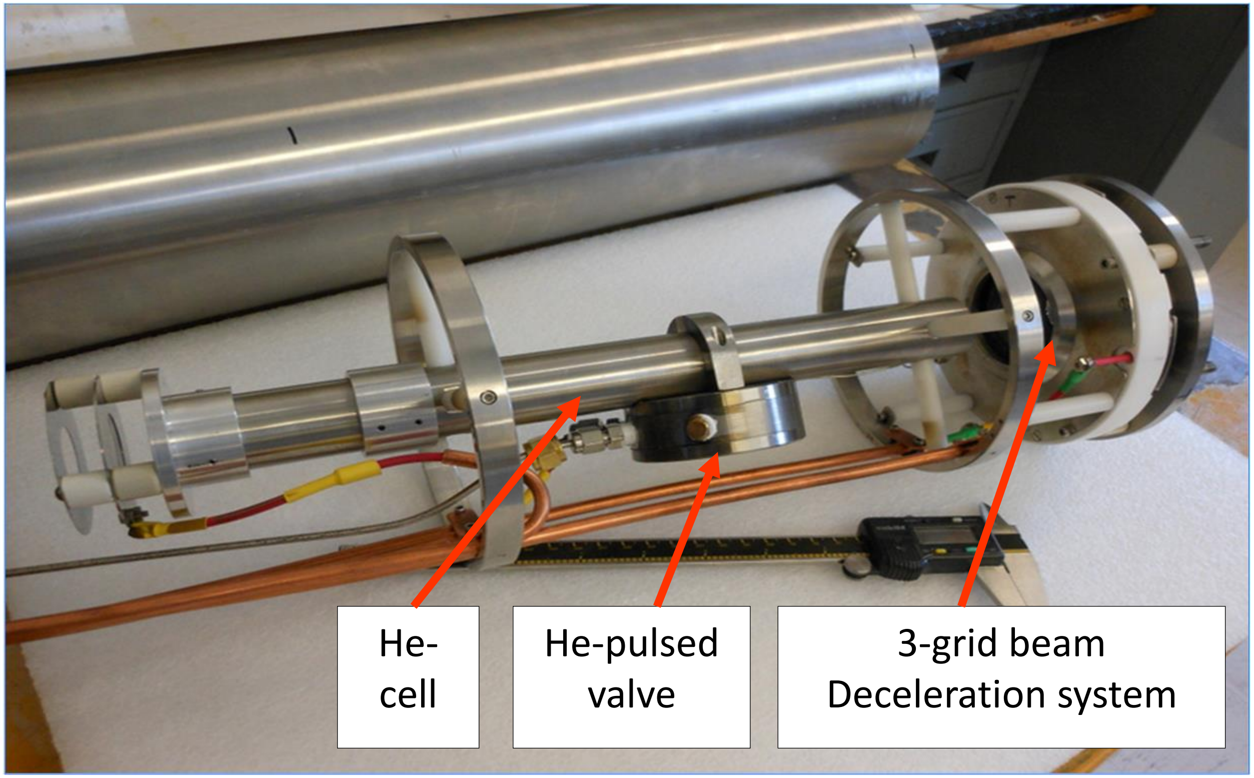
He-ionizer cell and 3-grid energy separation system.

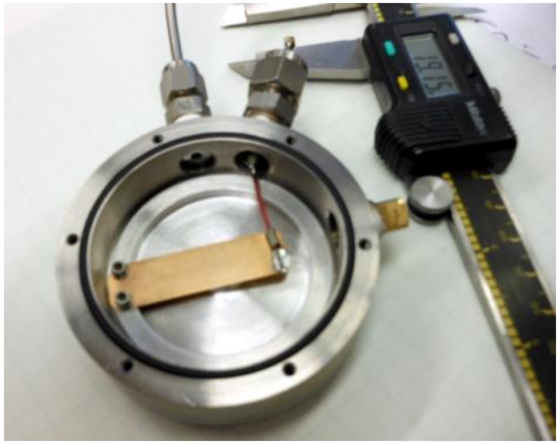
Two functions of the new He-cell with pulsed valve:

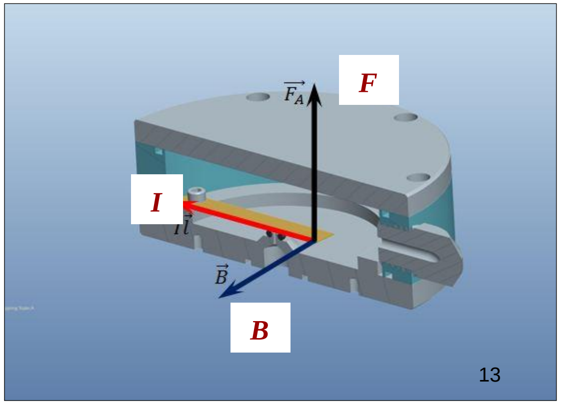
- Ionization of the injected neutral beam
- Deceleration of the ionized part of the beam to separate from the not ionized part

He-valve operating in high magnetic field ~1-3T.

At I=100 A, L=5 cm, F=15 N. $d\overrightarrow{F_A} = I[d\vec{l}\,\vec{B}]$

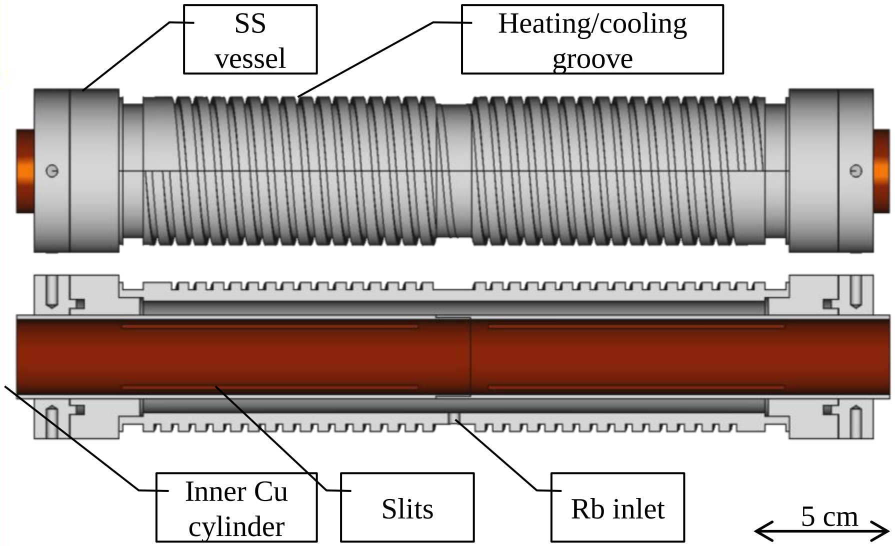


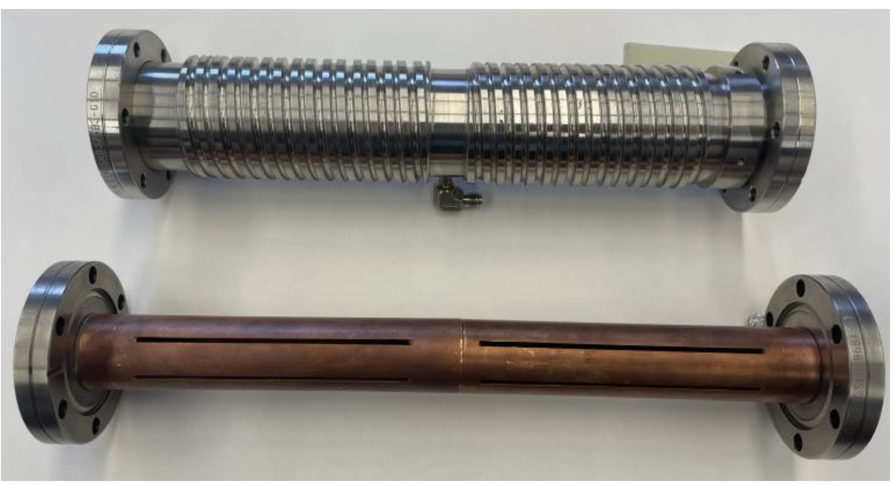




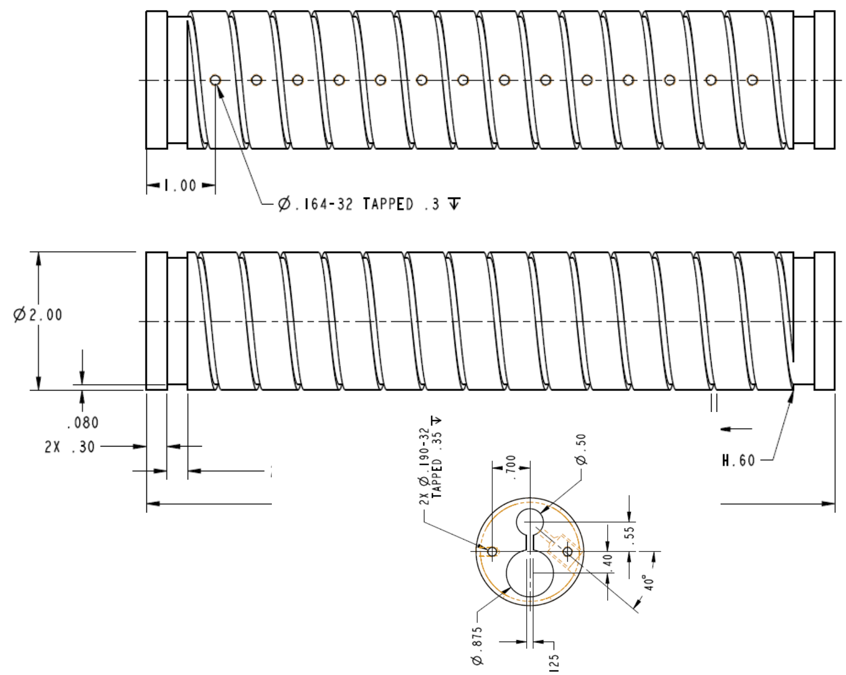
Rb-neutralization cell system

SS Cell (Run24)

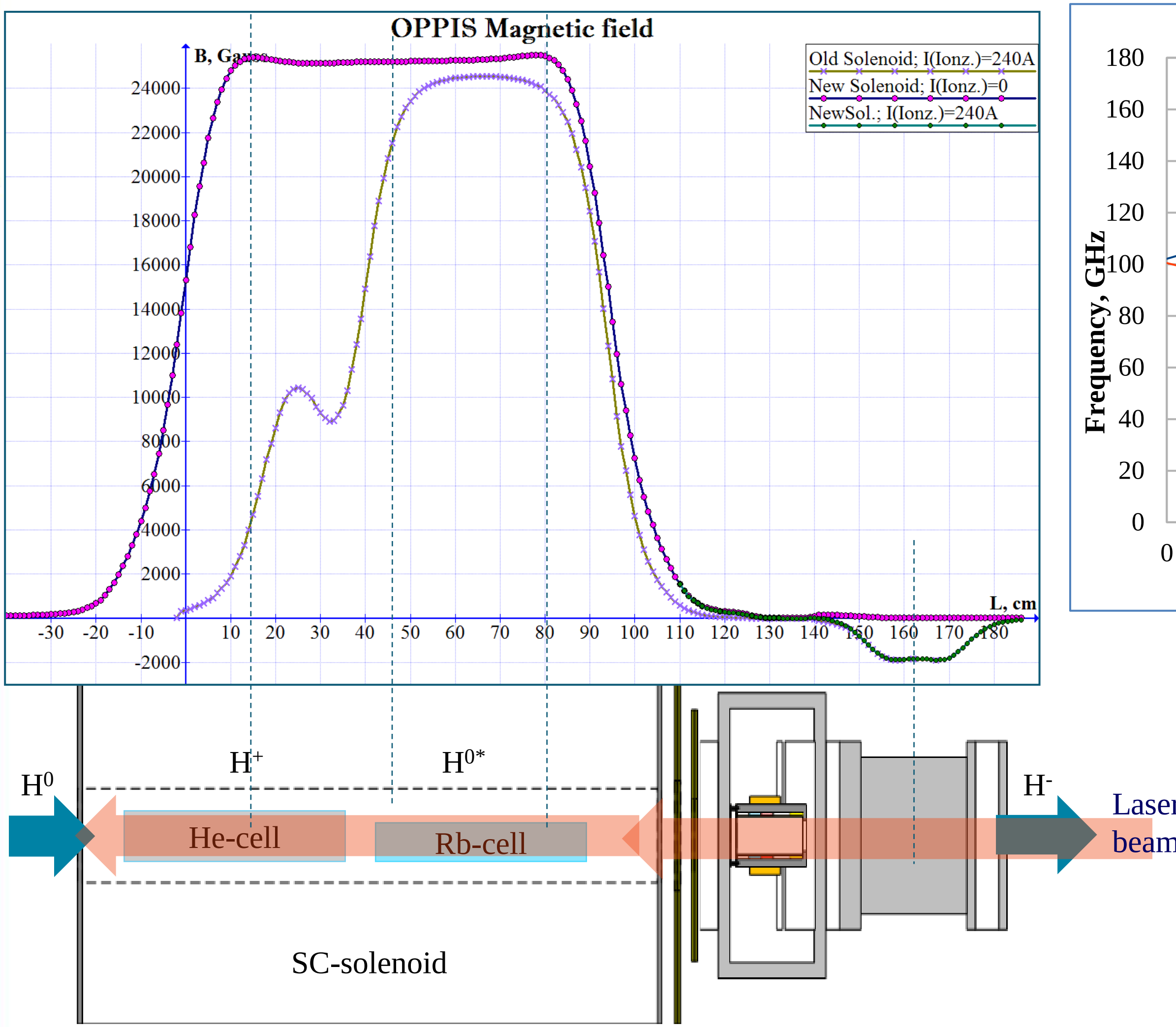


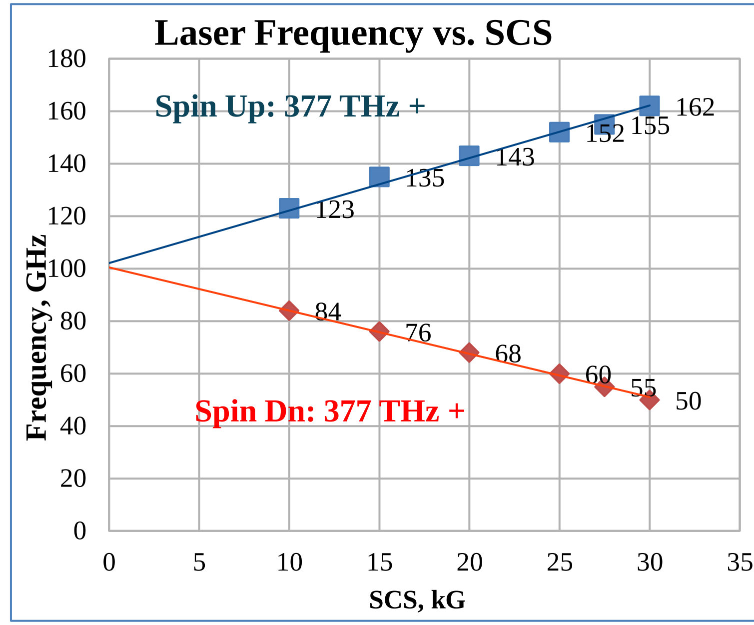


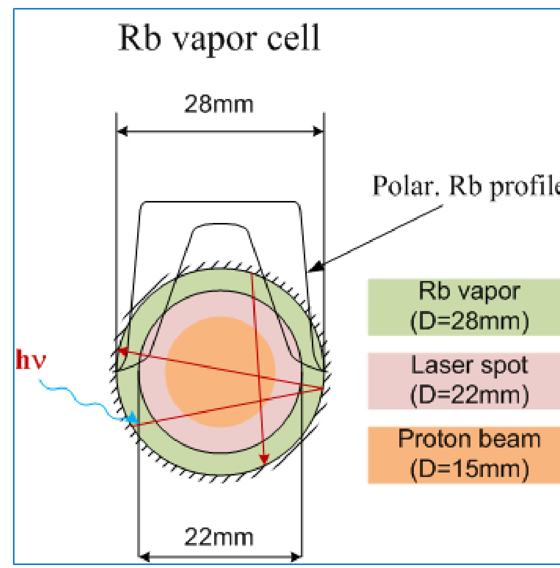
Cupper Rb-cell



Pumping laser

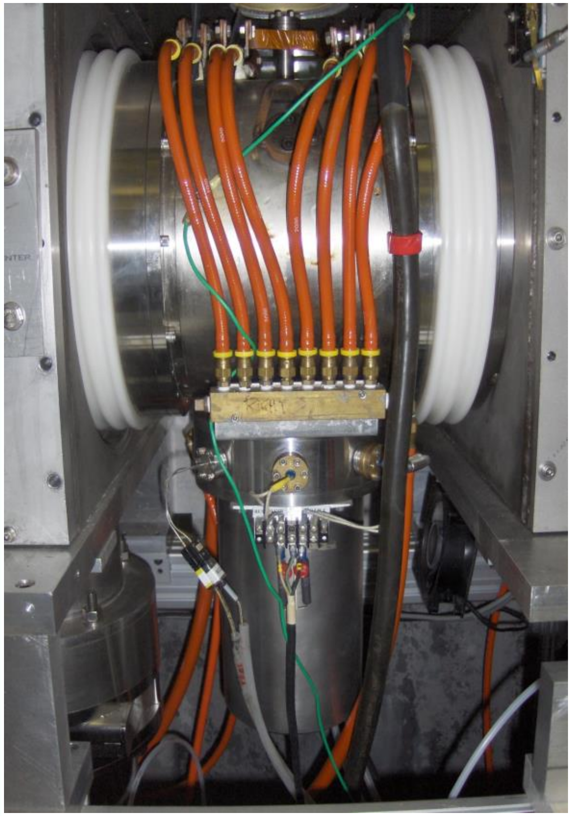






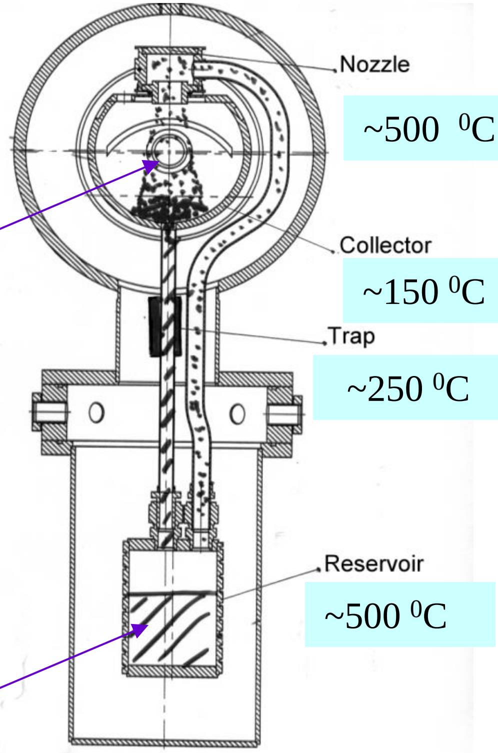
Sodium-jet ionizer cell

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 ~2·10^{15} atoms/cm^2
L ~ 2-3 cm

Reservoir consists of ~100g of sodium which was enough ~6-7 months



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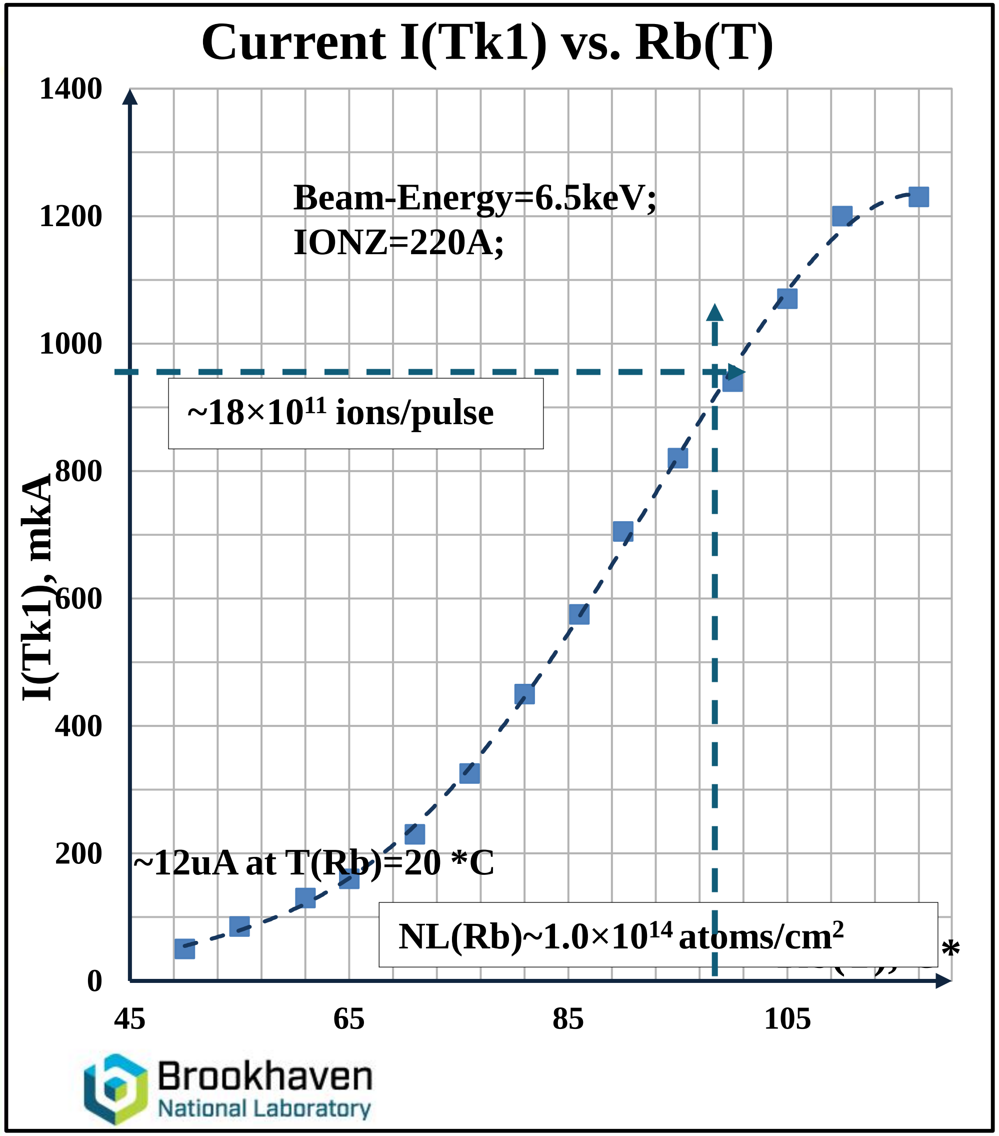
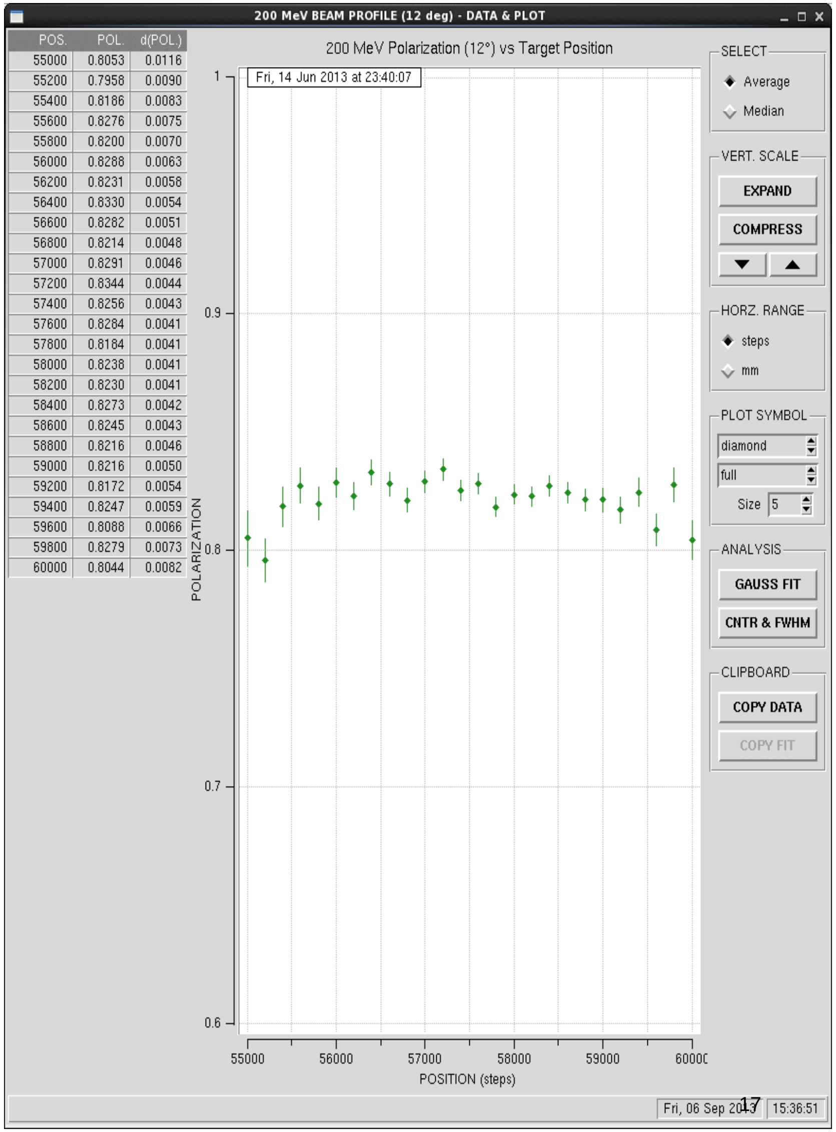
Polarized proton source performance

Beam intensity and polarization profile measurements

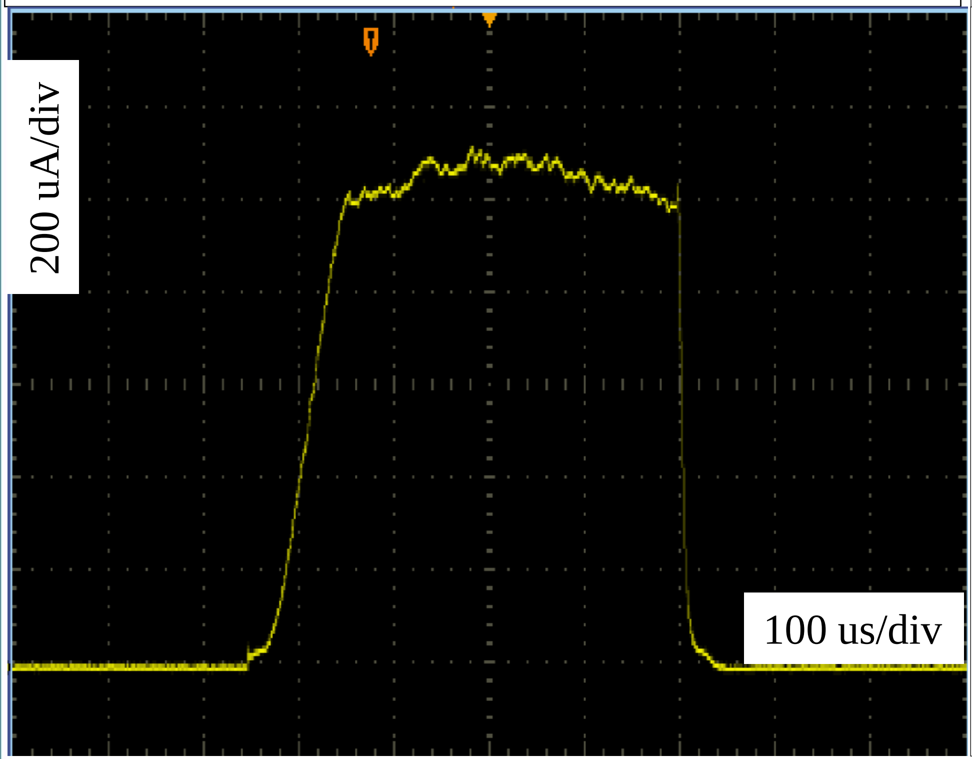




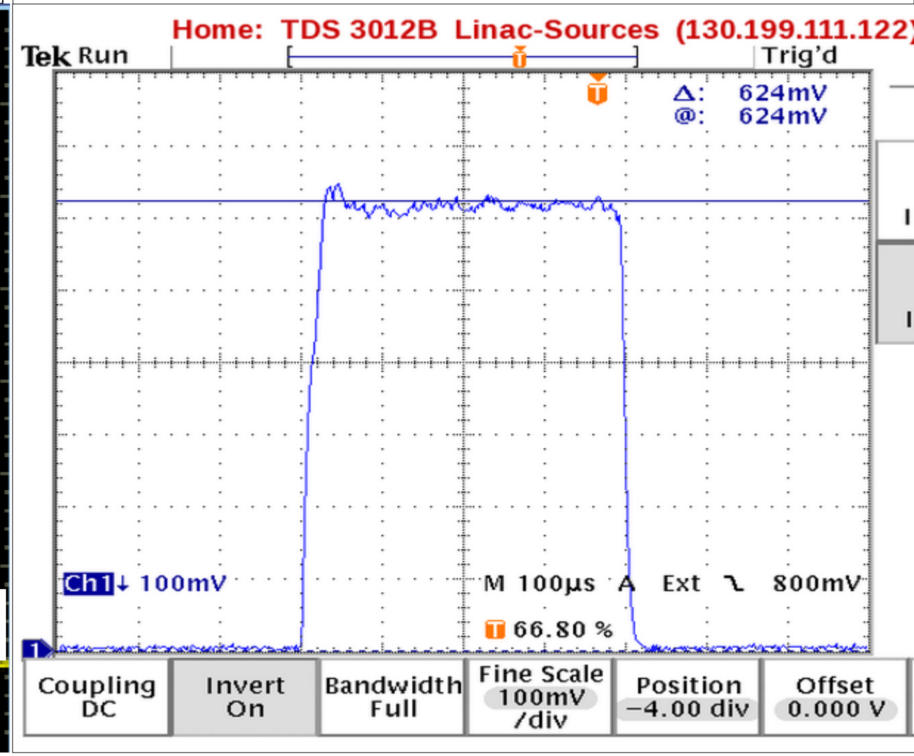
POS.	POL.	d(POL.)
55000	0.8053	0.0116
55200	0.7958	0.0090
55400	0.8186	0.0083
55600	0.8276	0.0075
55800	0.8200	0.0070
56000	0.8288	0.0063
56200	0.8231	0.0058
56400	0.8330	0.0054
56600	0.8282	0.0051
56800	0.8214	0.0048
57000	0.8291	0.0046
57200	0.8344	0.0044
57400	0.8256	0.0043
57600	0.8284	0.0041
57800	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

200 MeV polarized proton before and after LINAC

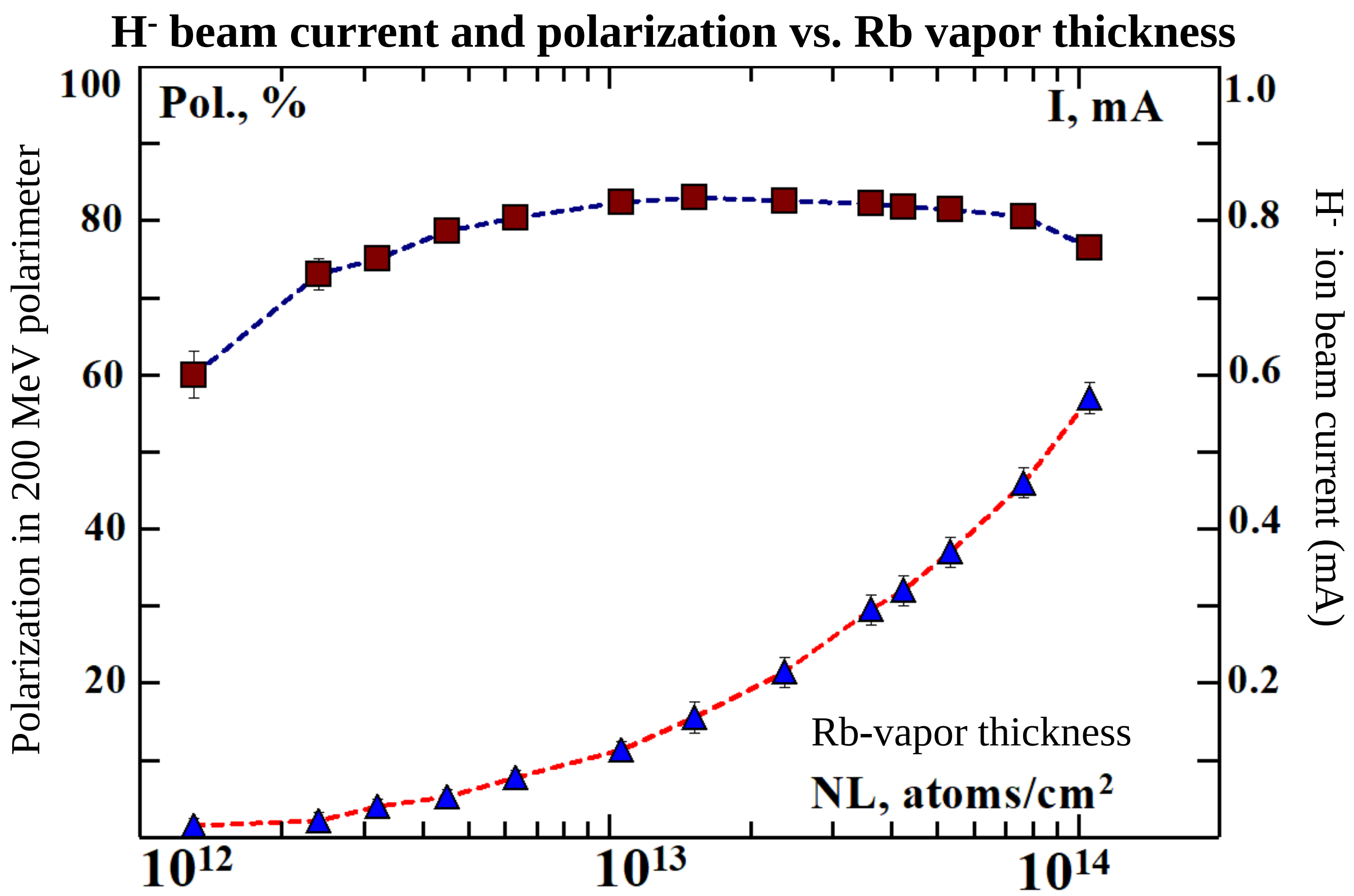
Polarized H^- current-1.05 mA, after RFQ 750 keV



620 µA×400µs ~$1.5\cdot10^{12}$ p/pulse after LINAC



H^- beam current and polarization at 200 MeV



Polarization transfer technique (OPPIS)

Polarized light → **Polarized electron** → **Polarized proton**

Production of circular polarized tunable wavelength (~795nm) laser beam

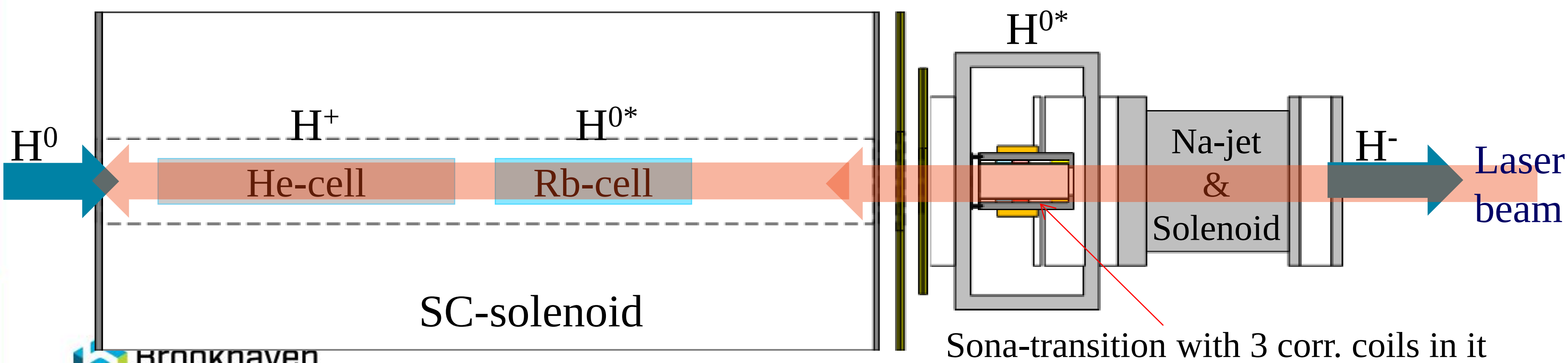
Polarization of the Rb-atom (Rb-cell)

Ionization of hydrogen atom by He (He-cell).

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

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

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



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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

$$P = E_{H2} \cdot P_{Rb} \cdot S \cdot B_{RG} \cdot E_{LS} \cdot E_{ES} \cdot E_{Sona} \cdot E_{ion} \sim 85\text{-}90\%$$

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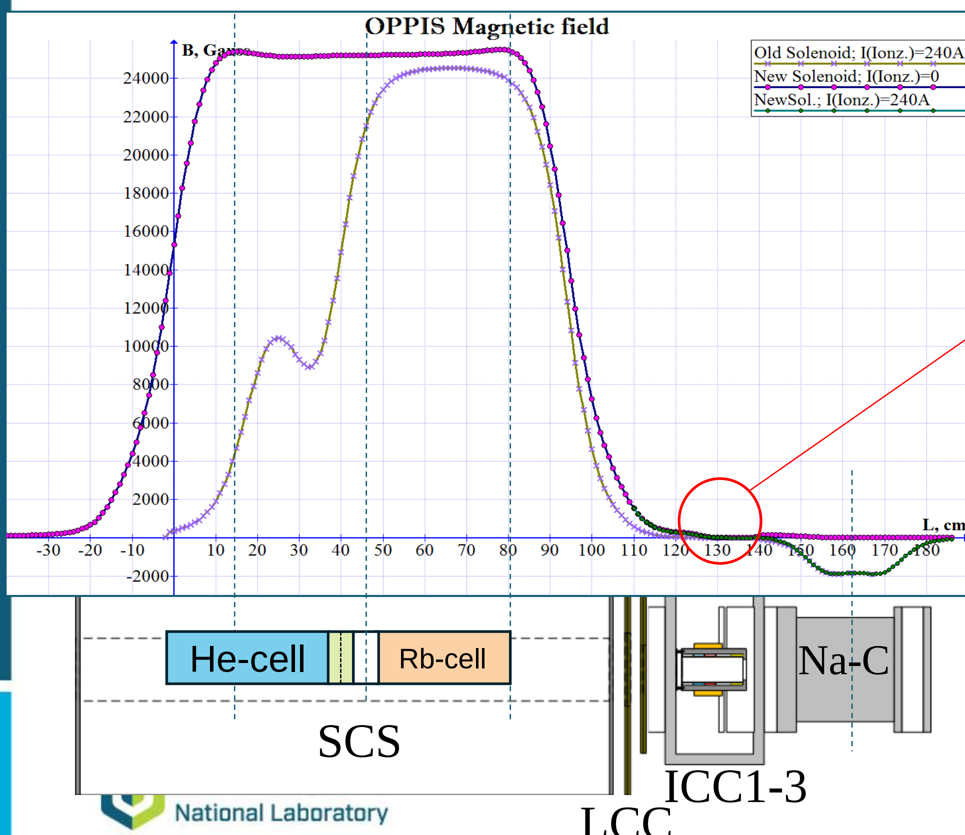
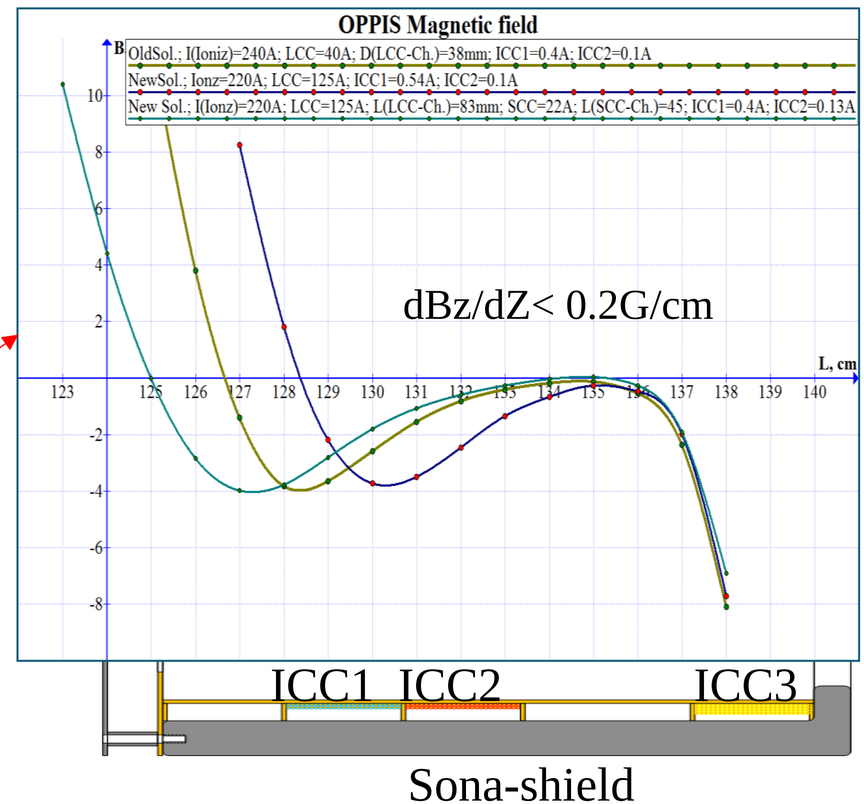
Depolarization factors by the shape magnetic field

The magnetic field in Ru cloud area and in the “Sona-transition” depends on and can be adjusted by:

- The optimization of the SCS and LCC solenoids 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 solenoid (solenoid around sodium ionizer) – Na-C

The fine correction coil field tuning is done by measuring polarization vs. coil current

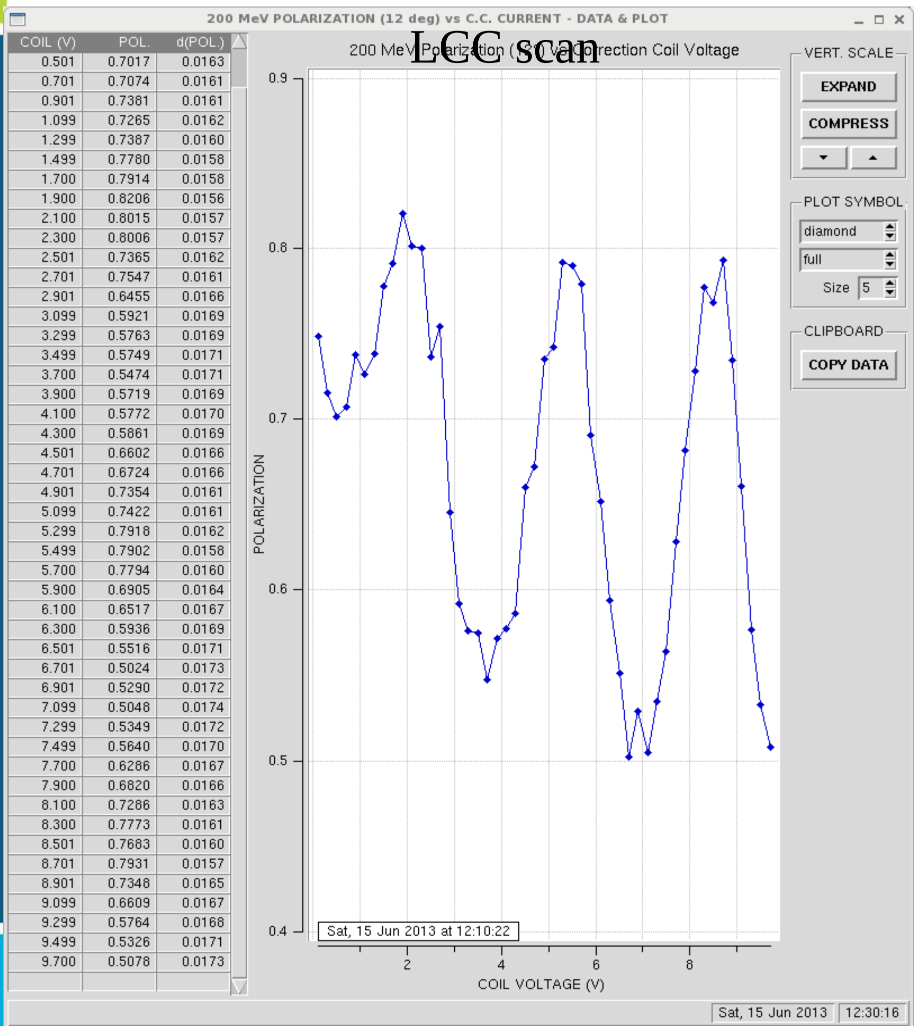




Depolarization factors by the shape magnetic field

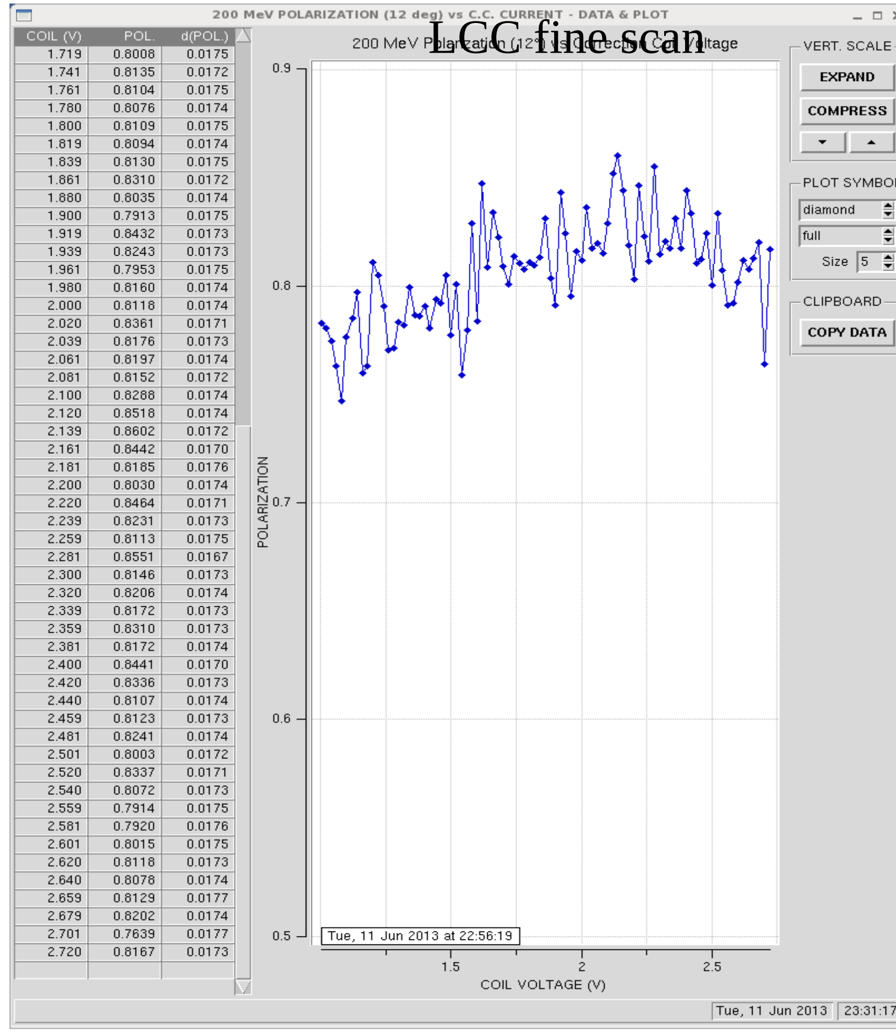
For maximum polarization there must be an accurate selection of settings for all correction coils. Any change in the magnetic field of coils, SCS or ionizer as well as their position requires a new setting.

LCC scan



COIL (V)	POL.	d(POL.)
0.501	0.7017	0.0163
0.701	0.7074	0.0161
0.901	0.7381	0.0161
1.099	0.7265	0.0162
1.299	0.7387	0.0160
1.499	0.7780	0.0158
1.700	0.7914	0.0158
1.900	0.8206	0.0156
2.100	0.8015	0.0157
2.300	0.8006	0.0157
2.501	0.7365	0.0162
2.701	0.7547	0.0161
2.901	0.6455	0.0166
3.099	0.5921	0.0169
3.299	0.5763	0.0169
3.499	0.5749	0.0171
3.700	0.5474	0.0171
3.900	0.5719	0.0169
4.100	0.5772	0.0170
4.300	0.5861	0.0169
4.501	0.6602	0.0166
4.701	0.6724	0.0166
4.901	0.7354	0.0161
5.099	0.7422	0.0161
5.299	0.7918	0.0162
5.499	0.7902	0.0158
5.700	0.7794	0.0160
5.900	0.6905	0.0164
6.100	0.6517	0.0167
6.300	0.5936	0.0169
6.501	0.5516	0.0171
6.701	0.5024	0.0173
6.901	0.5290	0.0172
7.099	0.5048	0.0174
7.299	0.5349	0.0172
7.499	0.5640	0.0170
7.700	0.6286	0.0167
7.900	0.6820	0.0166
8.100	0.7286	0.0163
8.300	0.7773	0.0161
8.501	0.7683	0.0160
8.701	0.7931	0.0157
8.901	0.7348	0.0165
9.099	0.6609	0.0167
9.299	0.5764	0.0168
9.499	0.5326	0.0171
9.700	0.5078	0.0173

LCC fine scan



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

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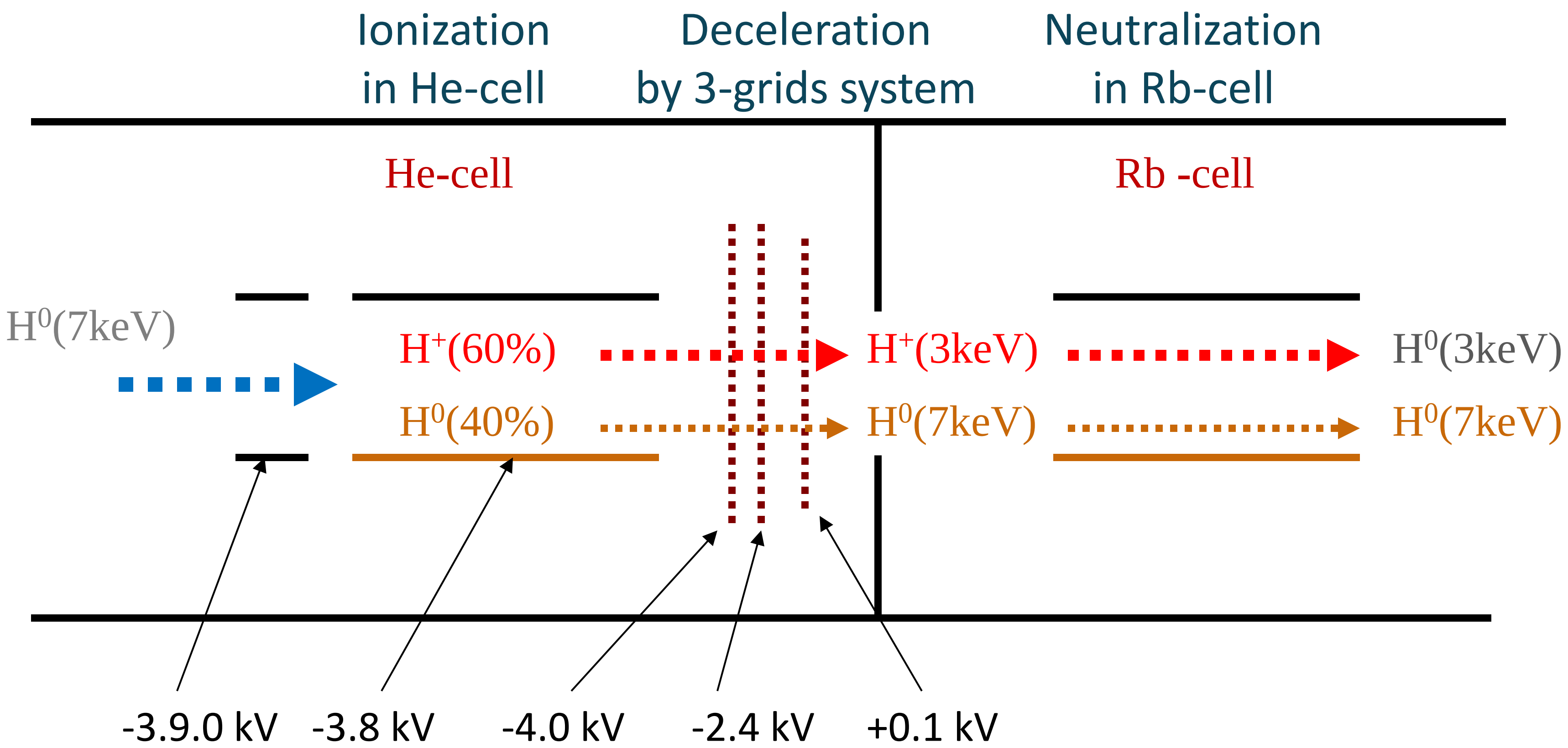
Energy separation a residual un-polarized H^0 component

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

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



The polarized part of the beam separates from the un-polarized by the bending magnet and collimators. Energy separation is better by 25-30 times.

Key parameters for the simulation of the H--Rb cells

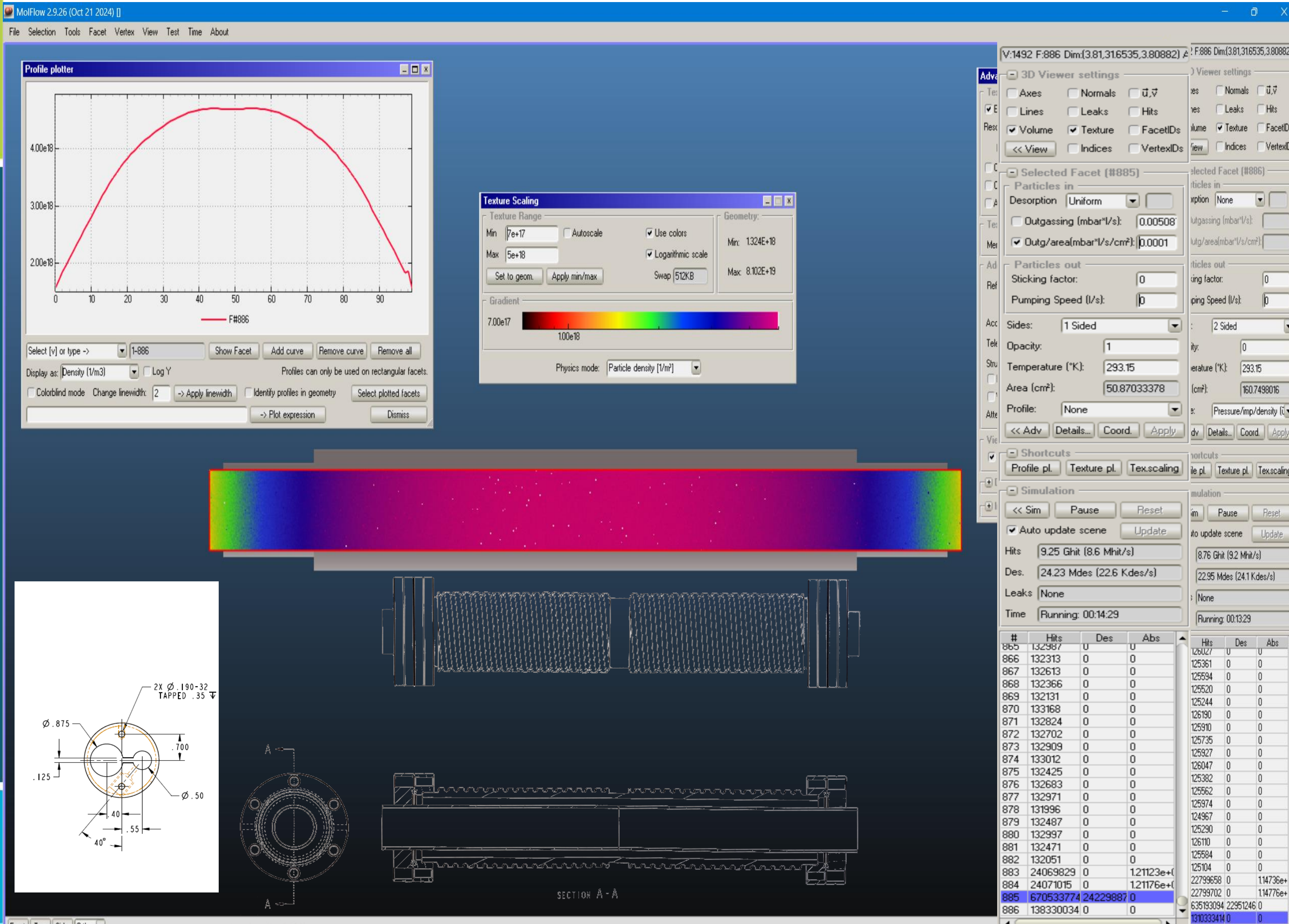
- Rb cloud density profile: Molflow
- Ionization H0 in He gas
- Neutralization Charge-exchange cross section
- Pumping laser absorption within the Rb cloud…
- Depolarization factors:
  - Neutral H not ionized in the He cell
  - H- neutralization by collisions with residual gas and He
  - Rb depolarization due to its collisions with wall and residual gas…

Nagengast, W. /Nass, A. /Grosshauser, C./ Rith, K./ Schmidt, F.
Relaxation of electron polarization for optically pumped rubidium atoms
1998-06 *Journal of Applied Physics* , Vol. 83, No. 11 AIP

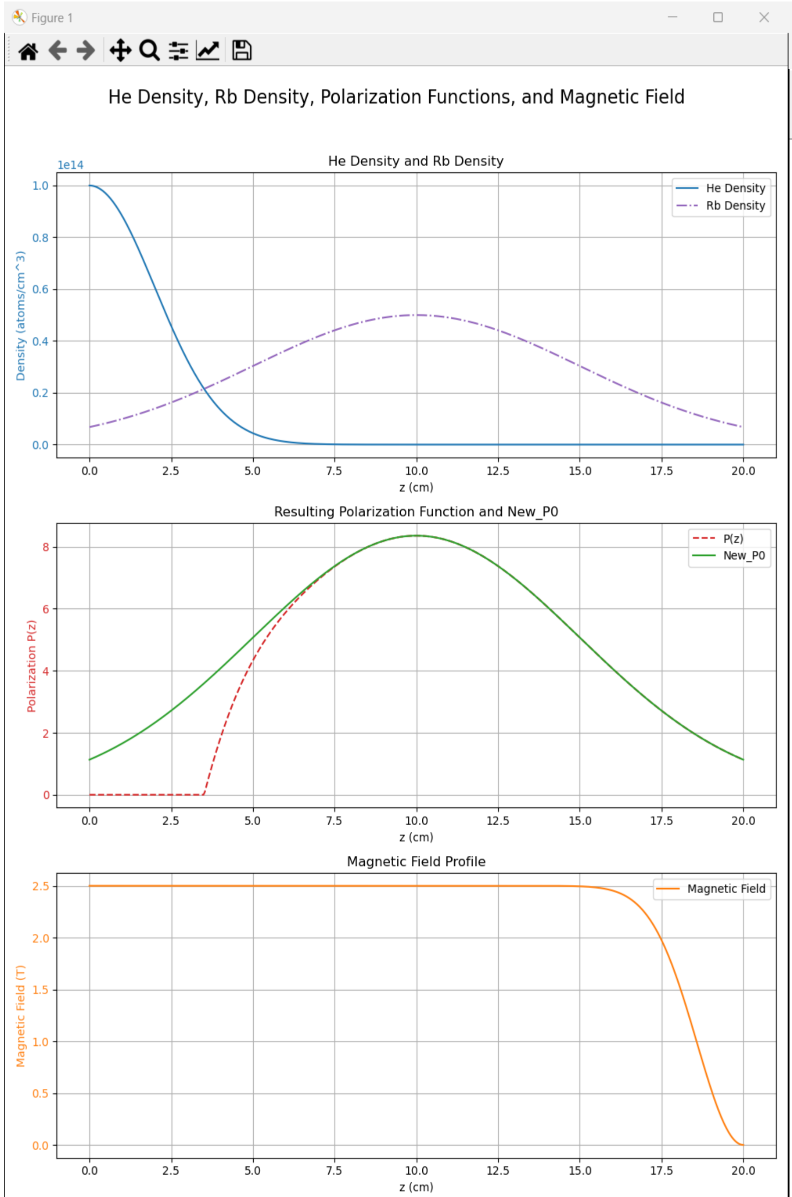
Girnius, R. J. / Anderson, L. W. / Staab, E.
Charge exchange collisions of deuterium in a rubidium vapor target
Nuclear Instruments and Methods , Vol. 143, No. 3

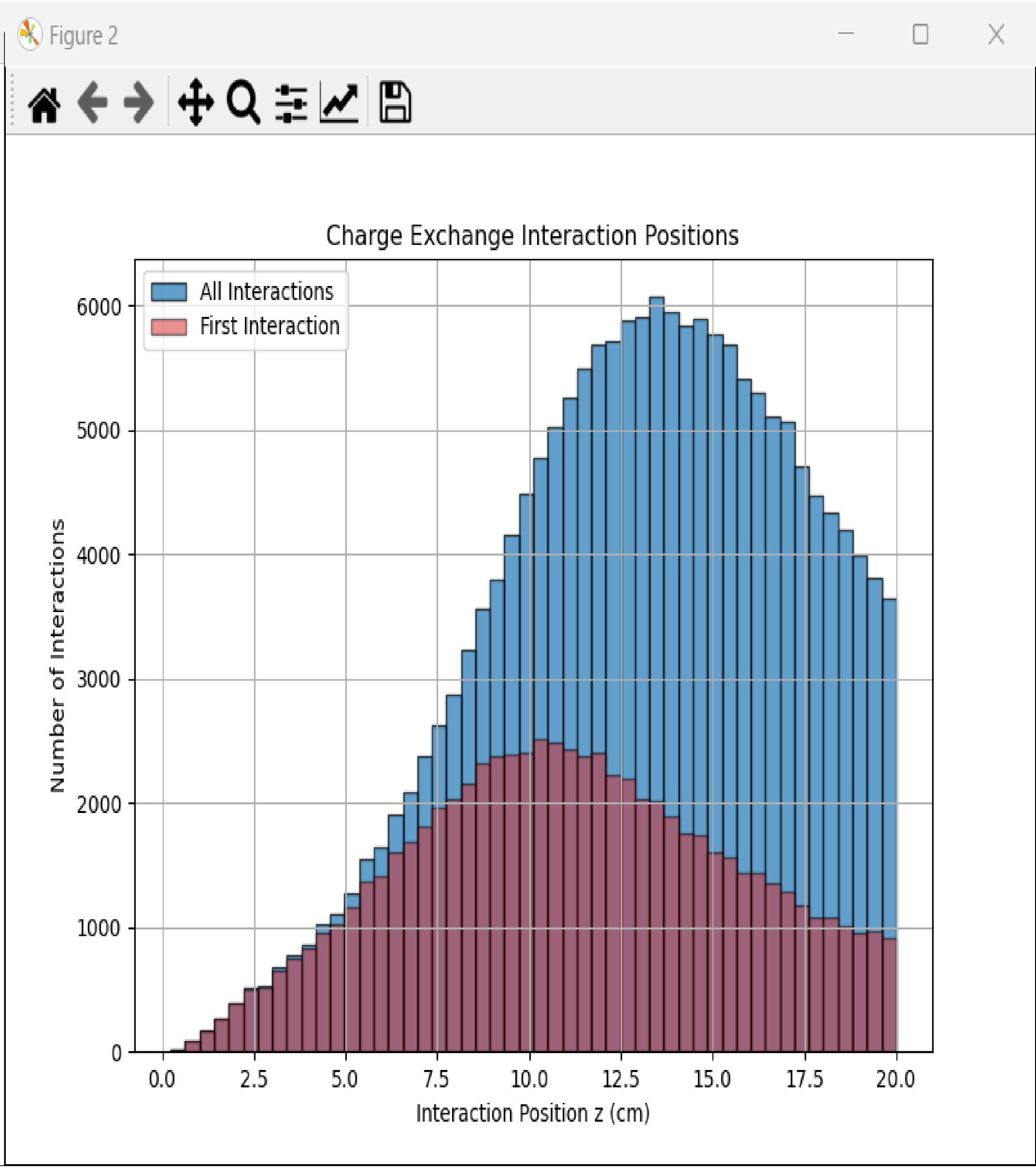
Sakae, T. / Yamamoto, T. / Zelenski, A. N. / Levy, C. D. P.
Optical pumping of thick alkali vapor for high-intensity polarized ion source
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment , Vol. 402, No. 2–3

Simulation tools



Preliminary





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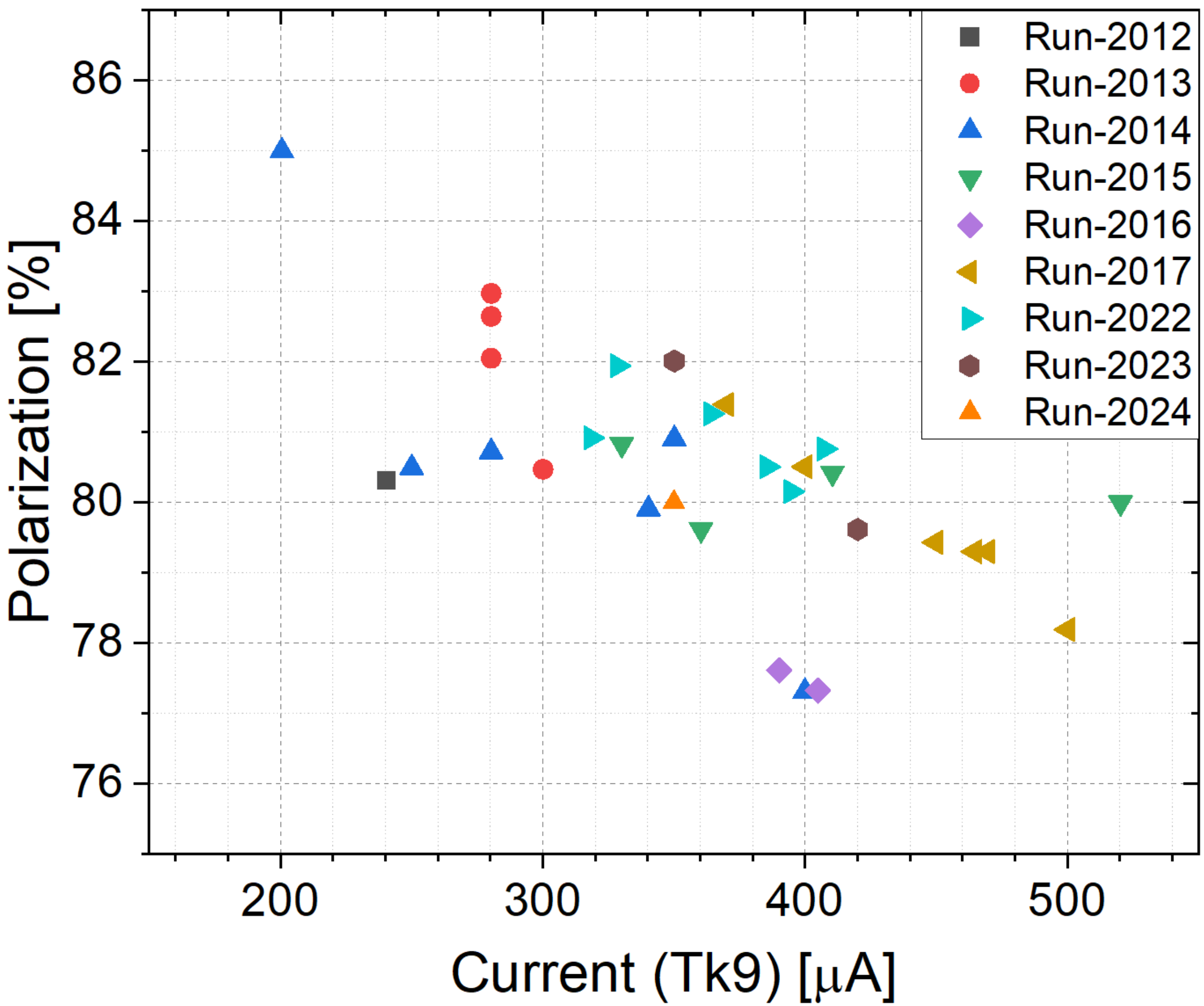
Polarize Proton Beam Performance



Brookhaven National Laboratory

Summary

OPPIS is one of the main parts of the "world's only polarized proton collider" with ~ 60% polarization.

For 25 years OPPIS reliably delivered a high intensity polarized proton beam for the RHIC spin physis program. Since 2012, after the FABS implementation and numerous upgrades, the OPPIS is in good shape to meet any challenges for future EIC operations. Our goal for the future is to make OPPIS stable and safe with the best performance.