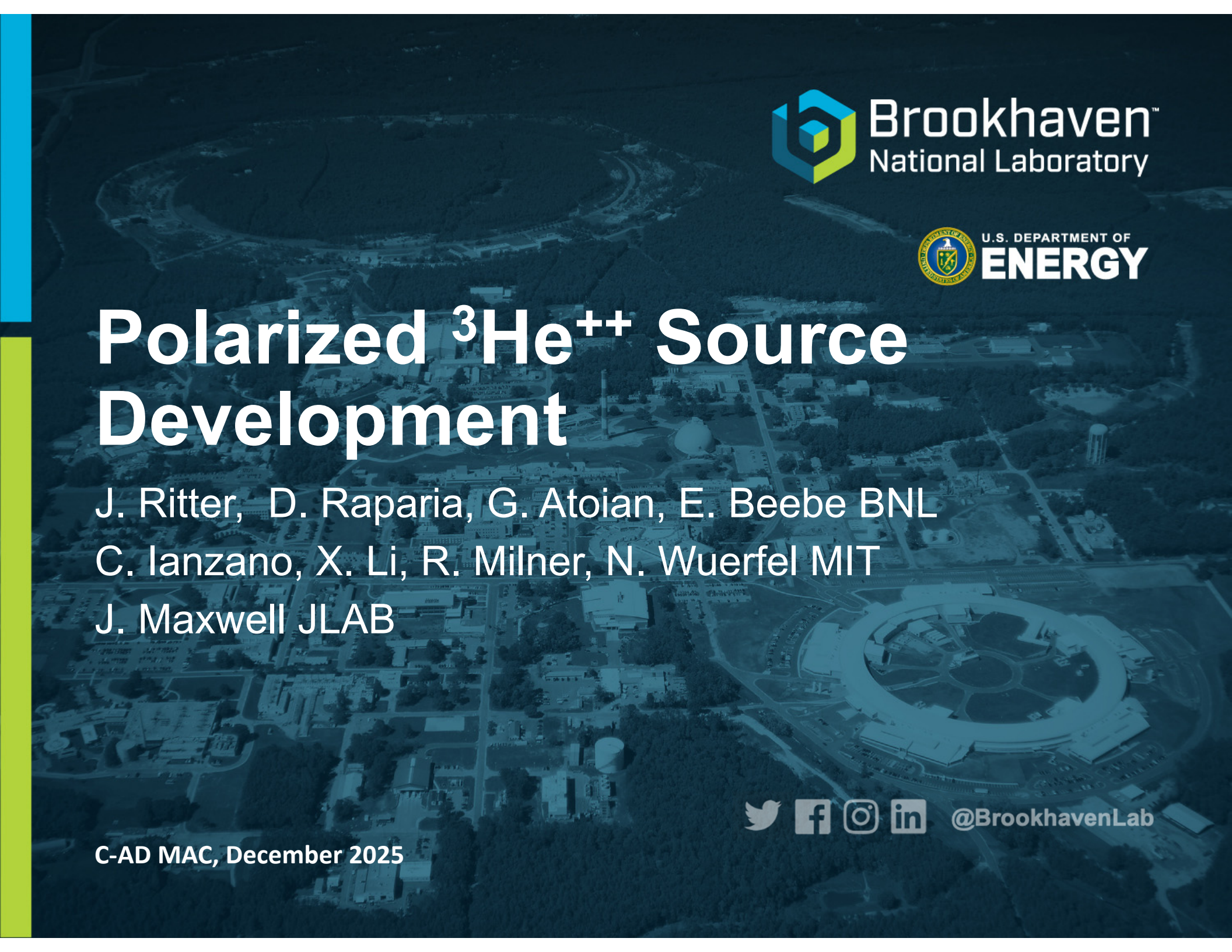


Polarized $^3He^{++}$ Source Development

J. Ritter, D. Raparia, G. Atoian, E. Beebe BNL

C. Ianzano, X. Li, R. Milner, N. Wuerfel MIT

J. Maxwell JLAB

C-AD MAC, December 2025

Outline

- Introduction
- Development of Polarized $^3He^{++}$ source
  - $^3He^{++}$ Source integrated into EBIS
  - Spin Rotator Chicane
  - 6 MeV Polarimeter

  Schedule

  Summary

3He Source at BNL

- Originally proposed by A. Zelenski and J. Alessi in ICFA Newsletter in 2003.

  (A. Zelenski, J. Alessi, "Proposal of production of polarized $^{3}He^{++}$ beam in EBIS" , ICFA Beam Dynamics Newsletter 30, p.39, (2003)

- Identified as High Priority R&D for EIC by EICAC review in 2009, continued by Office of Nuclear Physics community review in 2017, again in 2018 by assessment of US National Academy of Sciences, and highlighted in the 2023 Long Range Plan for Nuclear Science.

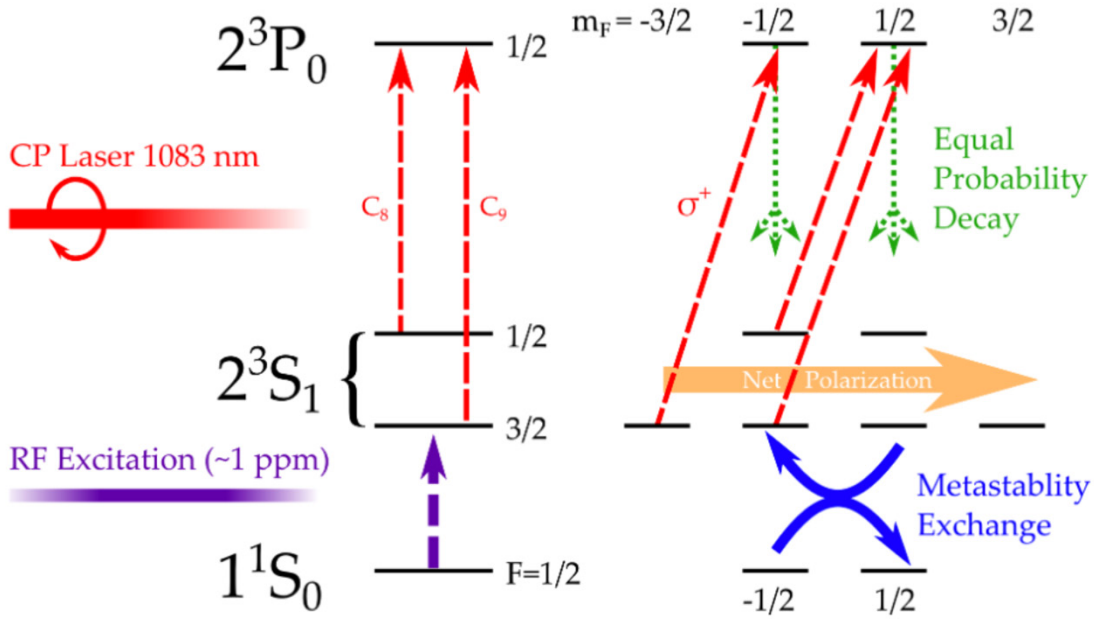
- Development of the polarized ^{3}He ion source is a BNL MIT collaboration that began in 2013.

Requirements for $^{3}He^{++}$ Source

- Intensity ~ $2.5 \cdot 10^{11}$ $^{3}He^{++}$ ions in 20 us pulse ~4 mA-peak current
- 85% polarization at source to meet EIC 70% ring requirement
- Compatibility with the operational EBIS for heavy ion physics and other programs.
- Spin flip every source pulse in beam transport line for spin measurements.

Metastability Exchange Optical Pumping MEOP

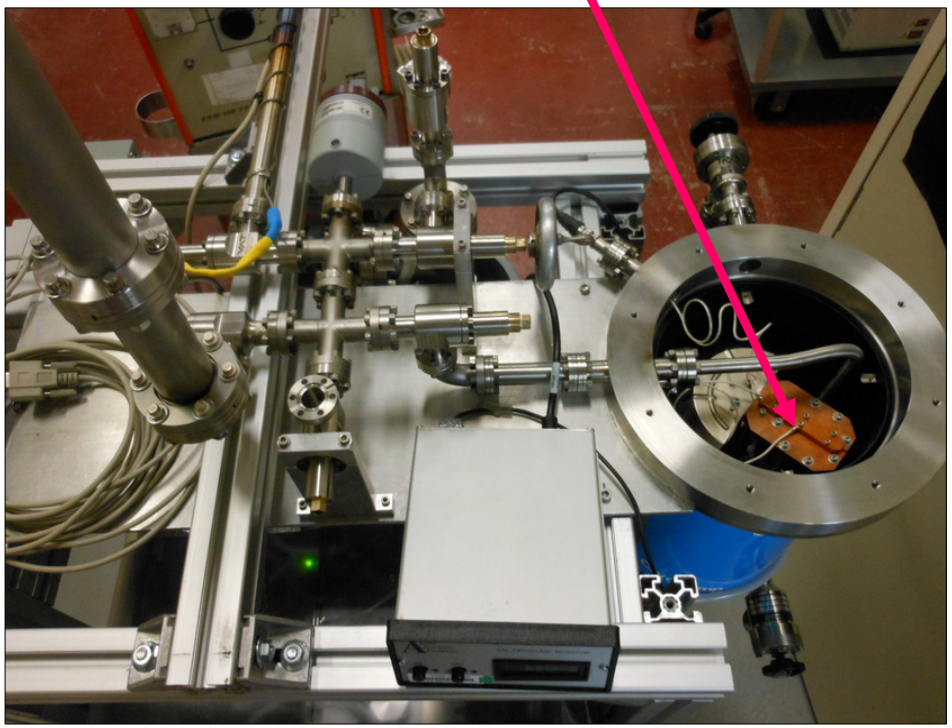
- Homogeneous magnetic field
- High Purity gas
- Electrical Discharge
- High-power laser

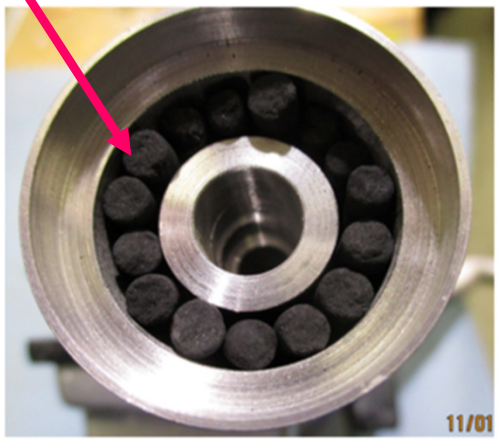


^{3}He-gas purification and filling system

Modified Cryo-pump for 3He purification and storage

Vessel filled with activated charcoal granules





The activated charcoal cryopumps ^{3}He gas.
The adsorbed gas is released by cartridge heater vessel heating ~20K.
This system provides gas storage and supply for ^{3}He-cell operation at the optimal pressure value (3-5 Torr).

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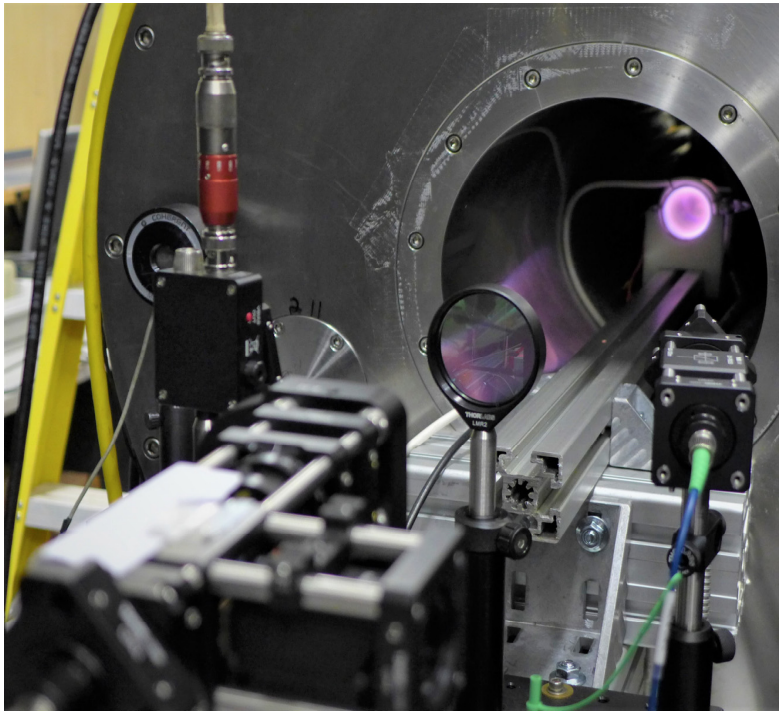
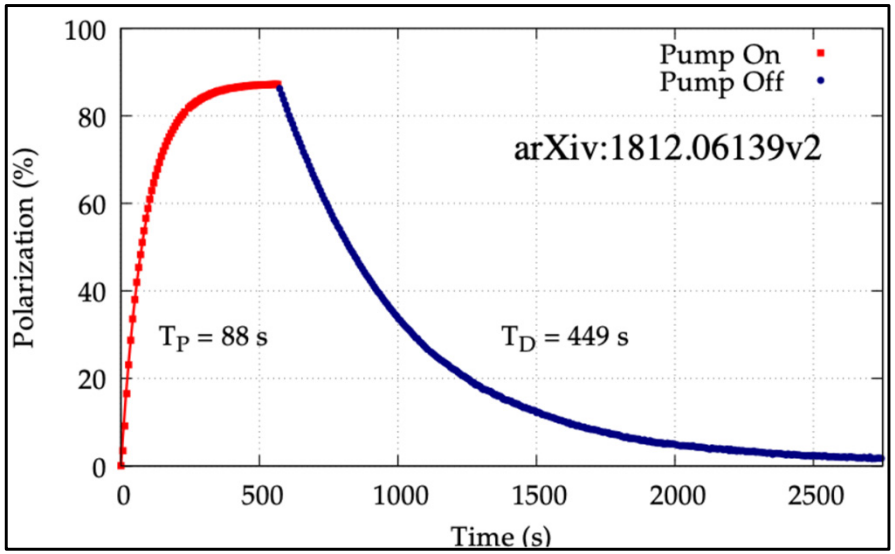
Project Developments

- Initial plan low field MEOP and transfer by gas tube through stray field into EBIS 2013
- High field MEOP showed better polarization than expected 2014 - 2015
- Switched to high field polarization inside EBIS
- New EBIS designed, built, tested and installed, 2015 - 2023
- Spare solenoid shipped 2017 for rebuild
- RHIC EBIS ACCEL solenoid operational for polarization studies in Test Lab 2024





- 89% polarization with sealed cell at 3T Maxwell & Zelenski - 2015

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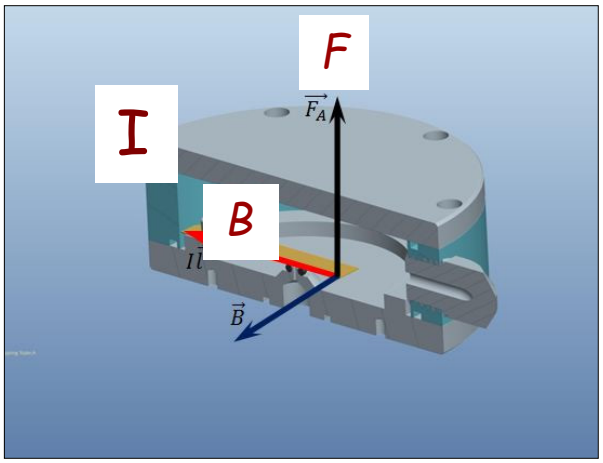
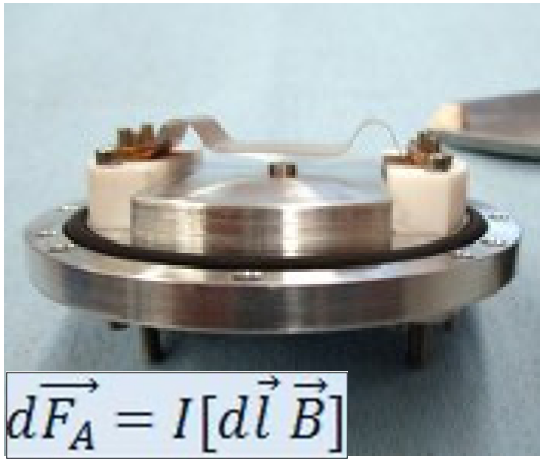
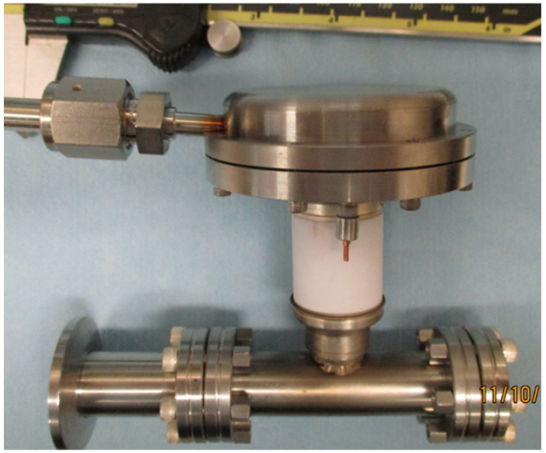
Fast Pulsed Gas Injection Valve

"Electro-magnetic", [IxB] valve operation principle

- Injection port is sealed by force from flat spring strip.
- Lorentz force in magnetic field opens the valve when current is passed through strip.
- Tested and currently used in EBIS for unpolarized 3He and other gases.

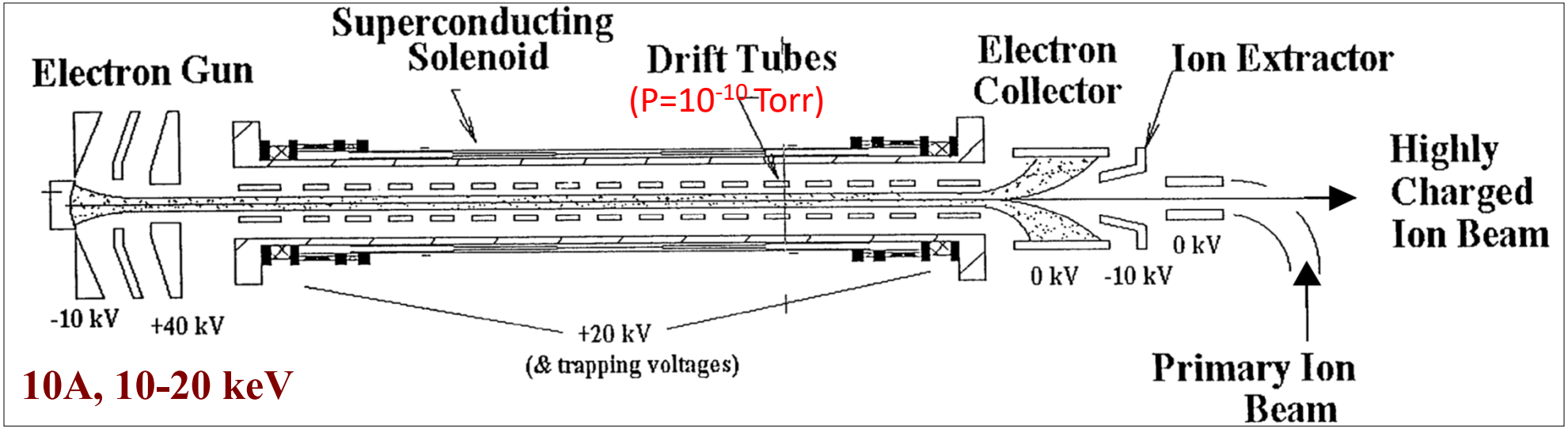






Pulsed valve for
Un-polarized gas
Injection to the EBIS

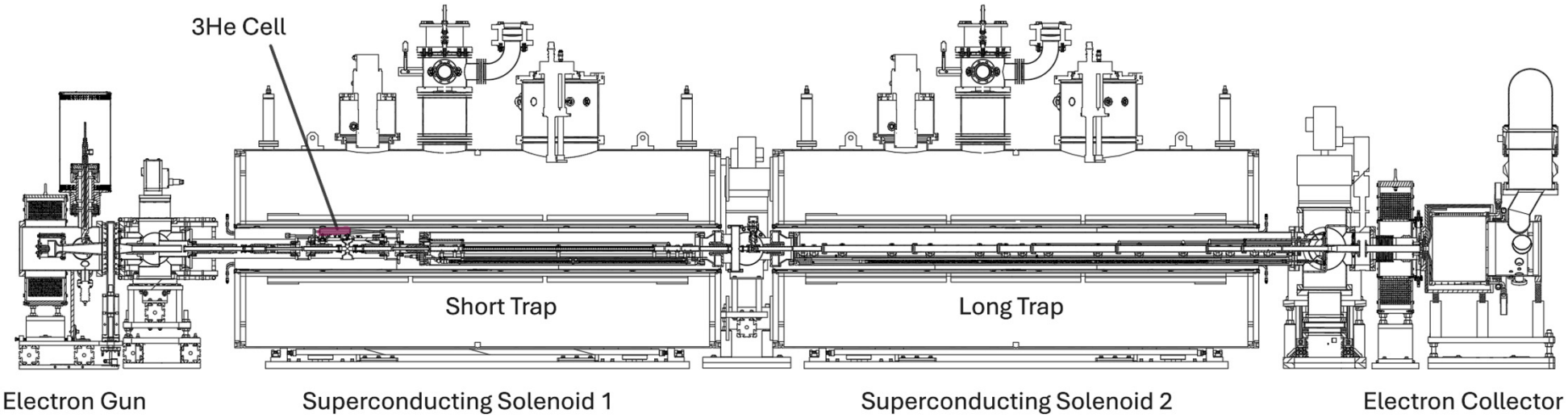
Principle of EBIS Operation



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

- *Ion output per pulse is proportional to the trap length and electron current.*
- ***Ion charge state increases with increasing confinement time.***
- *Output current pulse is independent of species or charge state!*

EBIS Polarized $^3He^{++}$



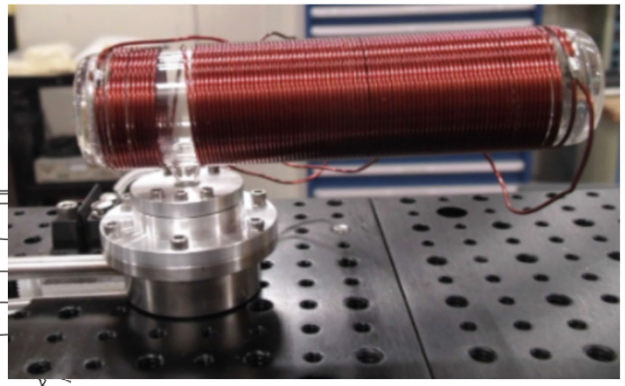
The polarized ^3He ion source will be installed inside Solenoid 1.

- The atoms of the ^3He gas will be polarized by MEOP technique
- The fast pulse valve will inject the polarized gas into the ion trap region of the EBIS.
- Inside trap the^3He ions will be stripped of electrons to the $^3He^{++}$ state.
- The trap barrier is lowered and beam sent to Booster.

^{3}He Polarizing Cell inside EBIS

Procedure to polarize the ^{3}He gas at high magnetic field

- Prepare the ^{3}He gas for polarization by the purification system; Valve1-open/ Valve2-close
- Polarize the ^{3}He gas inside the glass-cell by a MEOP technique; Valve1-close/ Valve2-close
- Continually control the polarization of the injected ^{3}He gas by using the Optical Probe polarimeter;
- Inject a portion of polarized ^{3}He into drift tube (beam line) through the pulsed valve Valve2-open
- Ionize the polarized atoms of ^{3}He by electron beam



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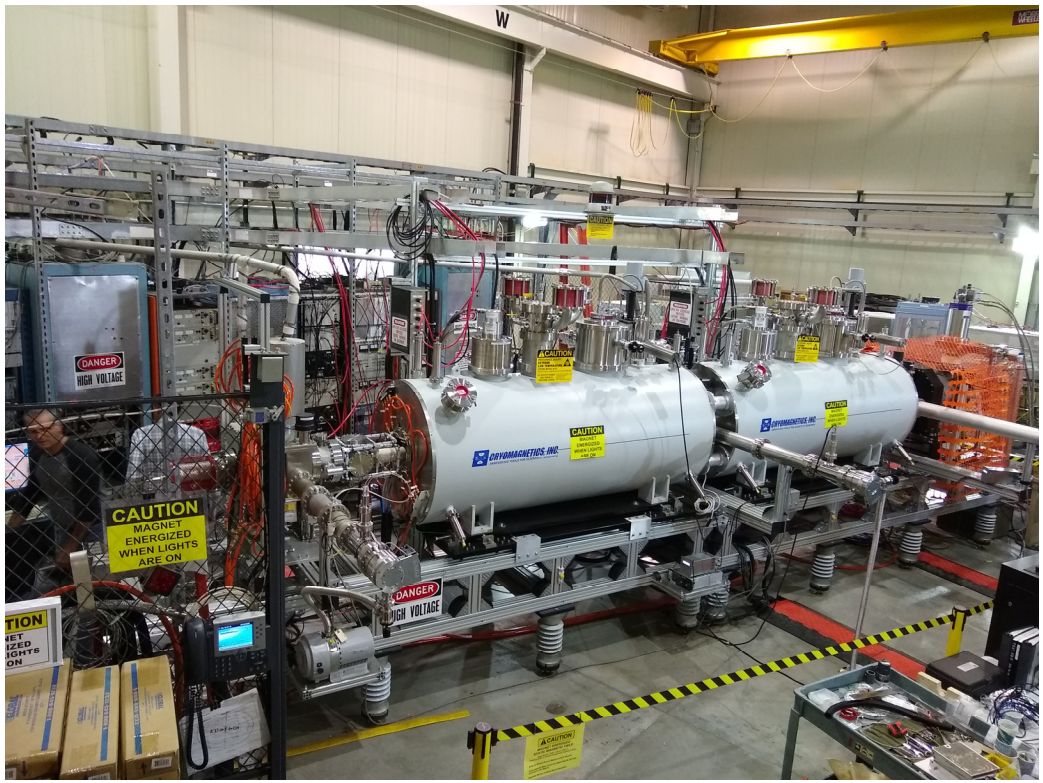
Extended EBIS Design

- Gas cell drift tube with differential pumping
- Vacuum separation and isolation valve between traps
- Trap length increase
- High-capacity NEG modules in drift tube chambers
- Pulsed gas valve and future integration of ^{3}He polarizer
- Two 5T 2.3m long solenoids with internal supports to allow operation with 20cm separation



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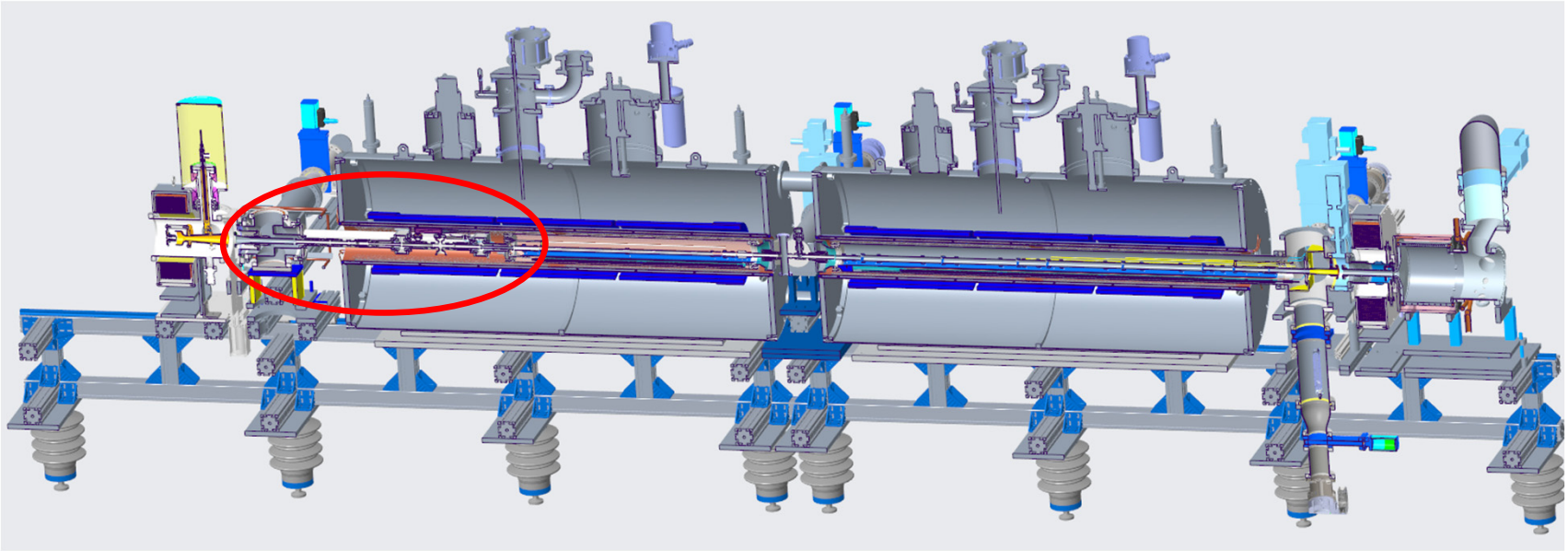
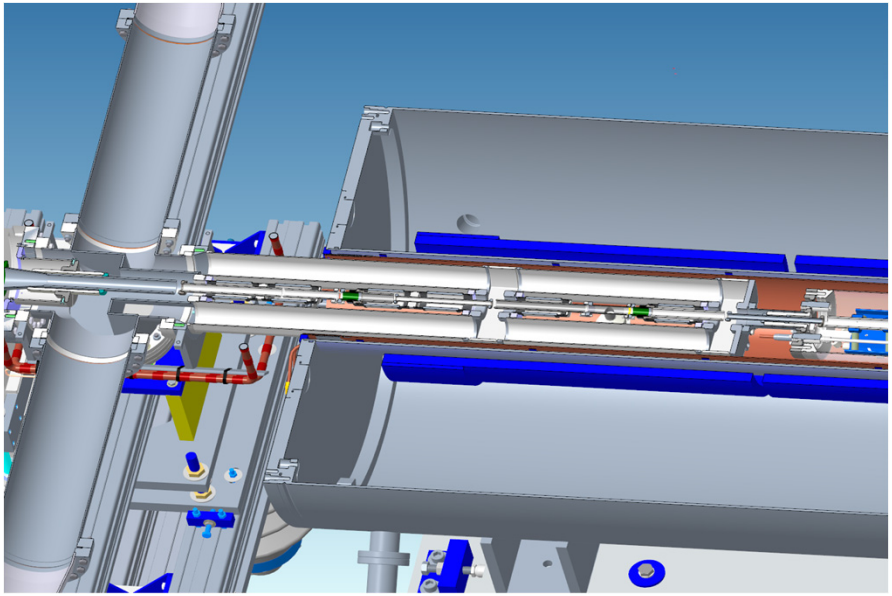
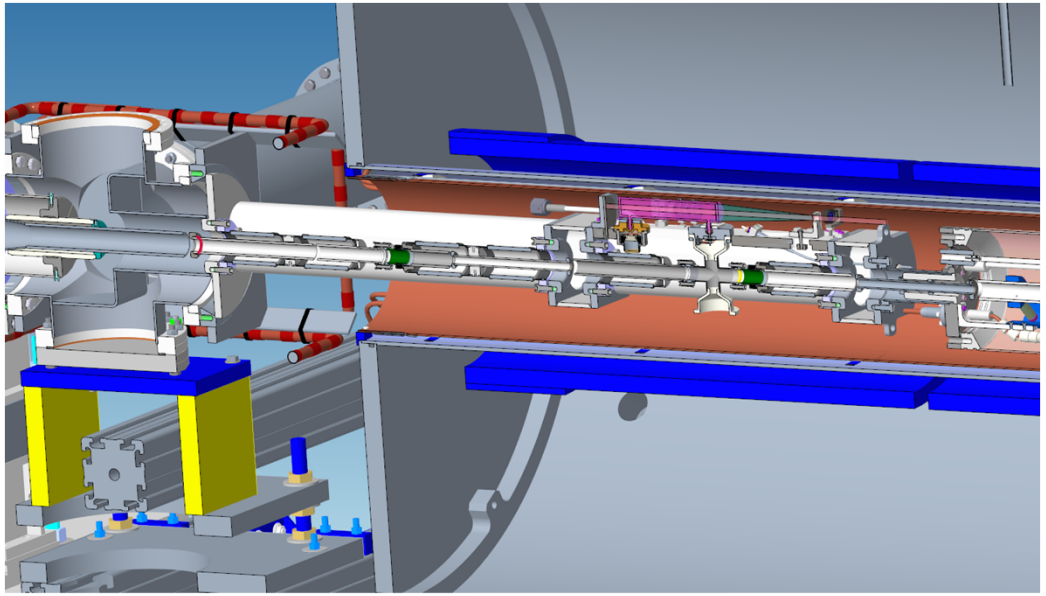
EBIS







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Vacuum Chambers

BNL Fabrication

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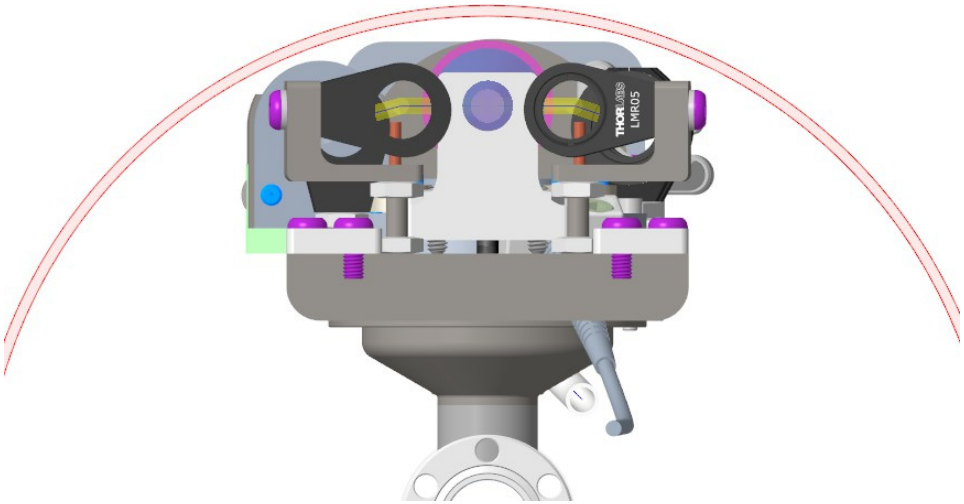
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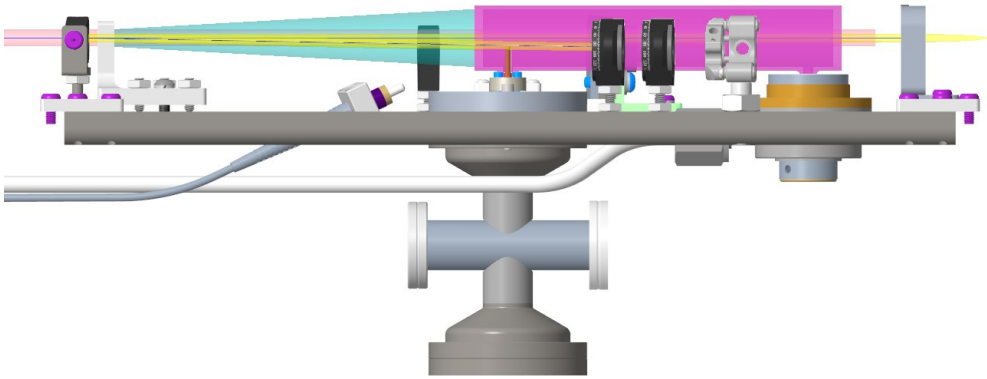

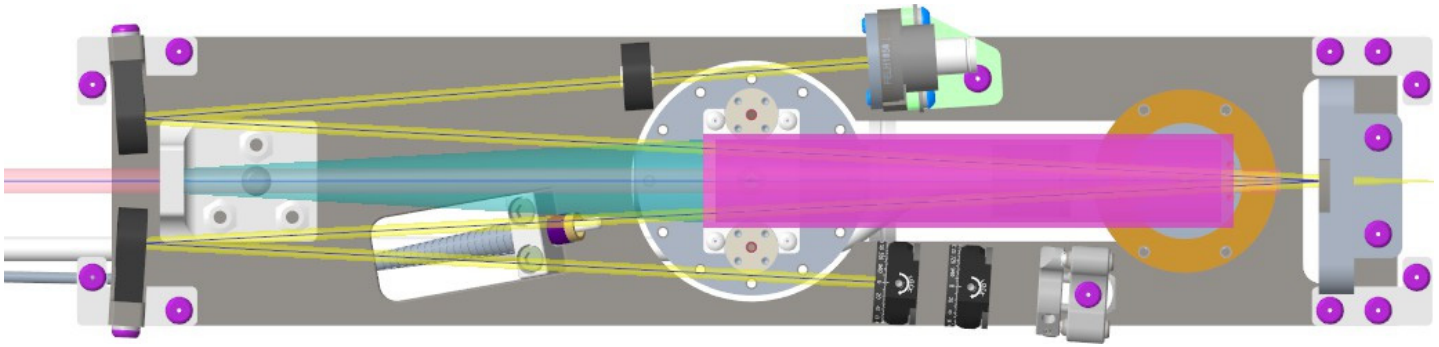

RHICEBIS in the test lab

RHICEBIS moving
to test lab Nov 2023

RHICEBIS inside Test Lab

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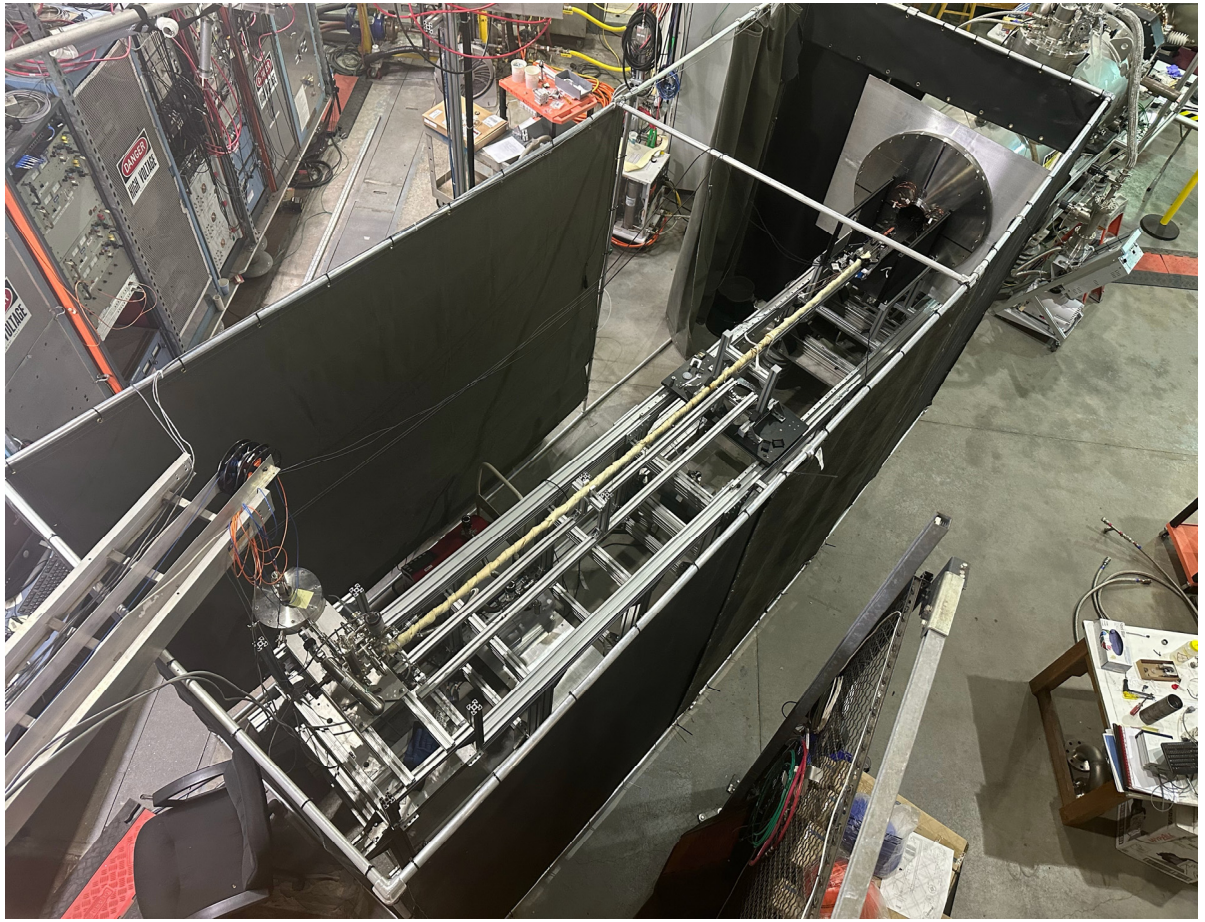
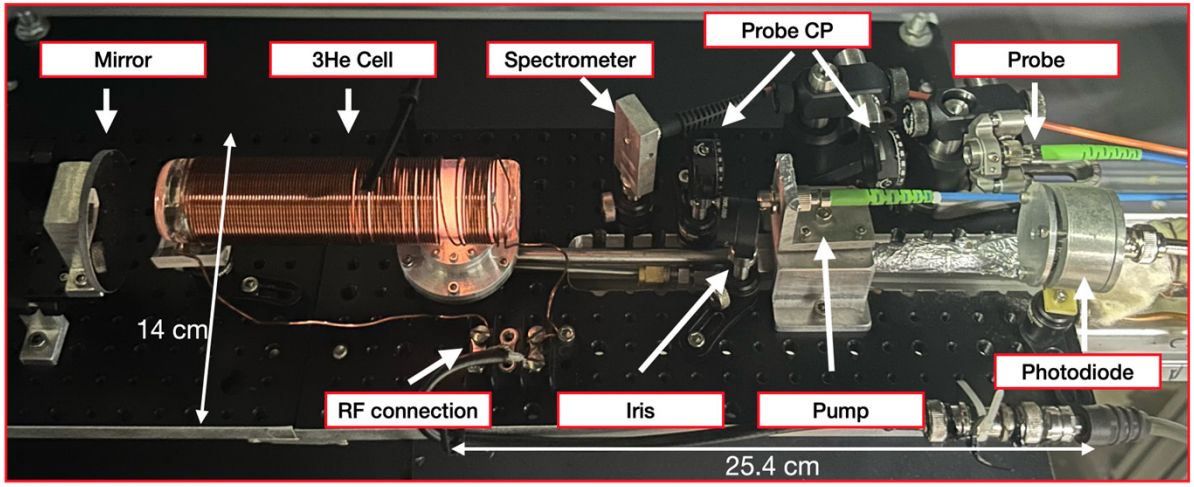
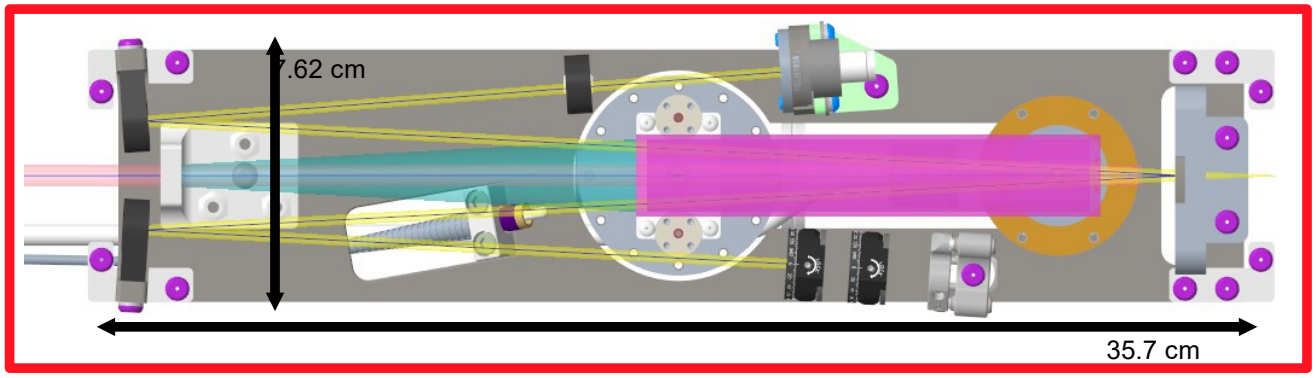
3He Test Lab Developments

- Since mid 2023 Noah Wuerfel (MIT) has led the polarized ^{3}He source effort.
- Moved gas purification system into test lab with the ACCEL EBIS magnet.
- New laser enclosure, interlock, and safety approvals, June 2024.
- Testing the compact optical polarization layout.



Reduced optical Footprint





Final layout designed to meet space constraints in EBIS.

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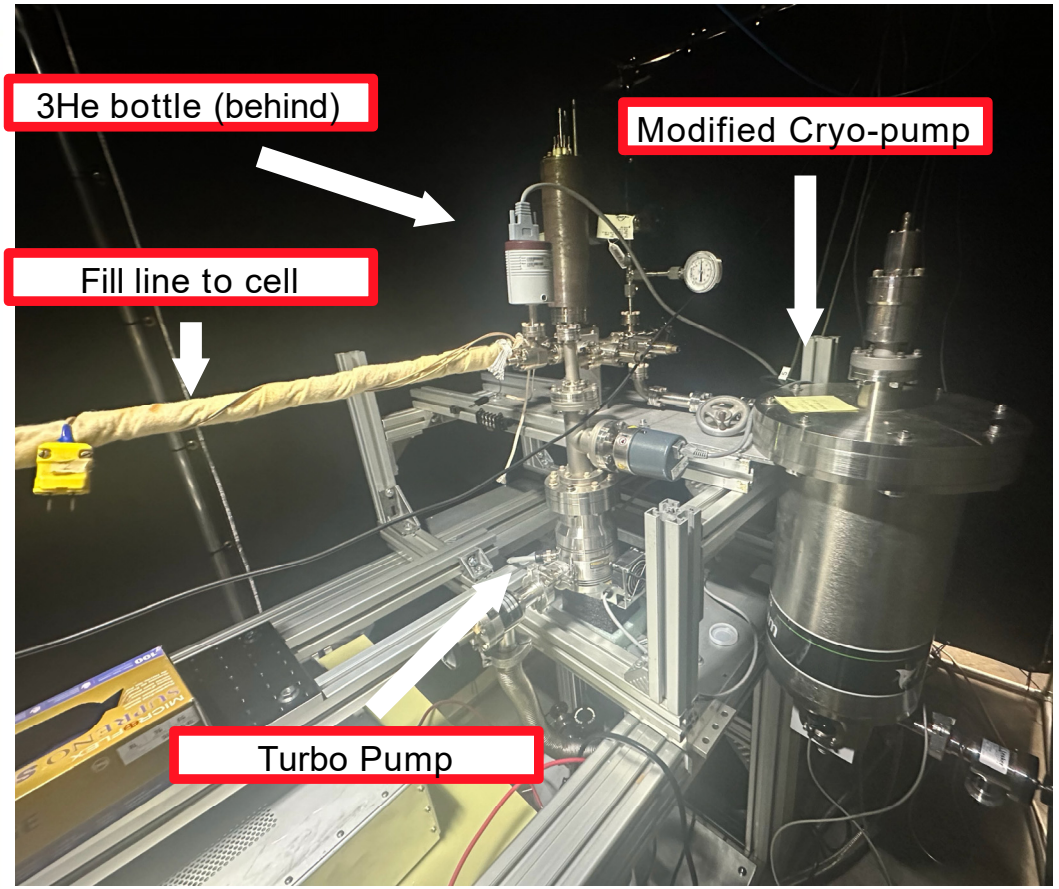
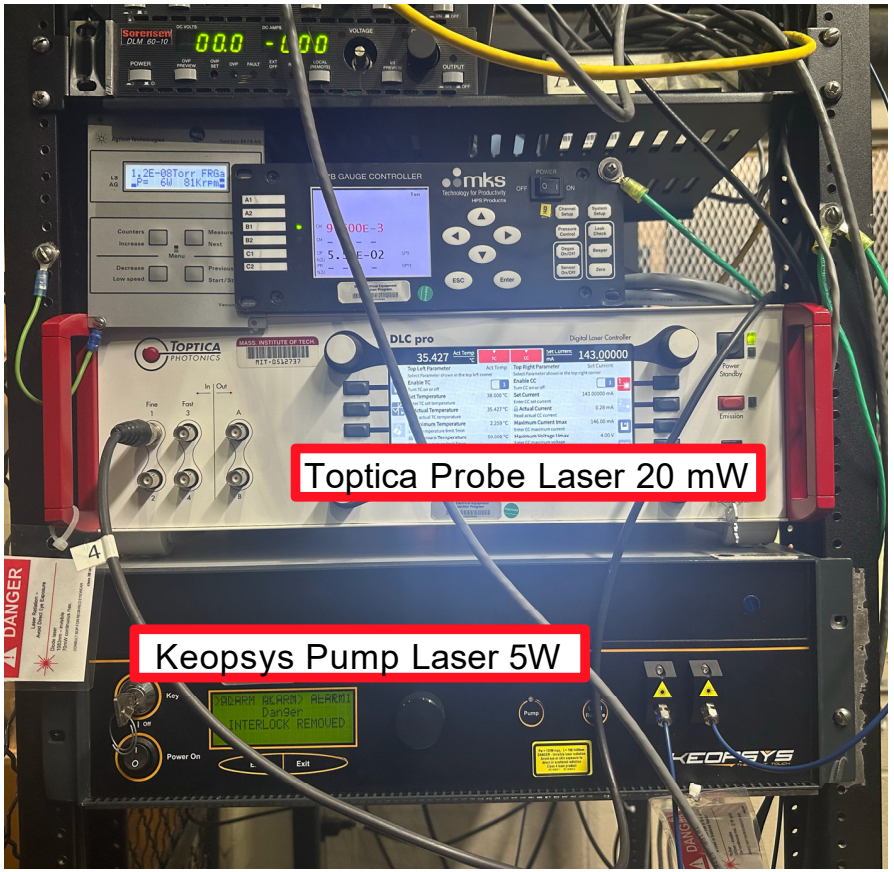
3He work in Test Lab



Cryogenic gas purification system



Controls rack with pump and probe

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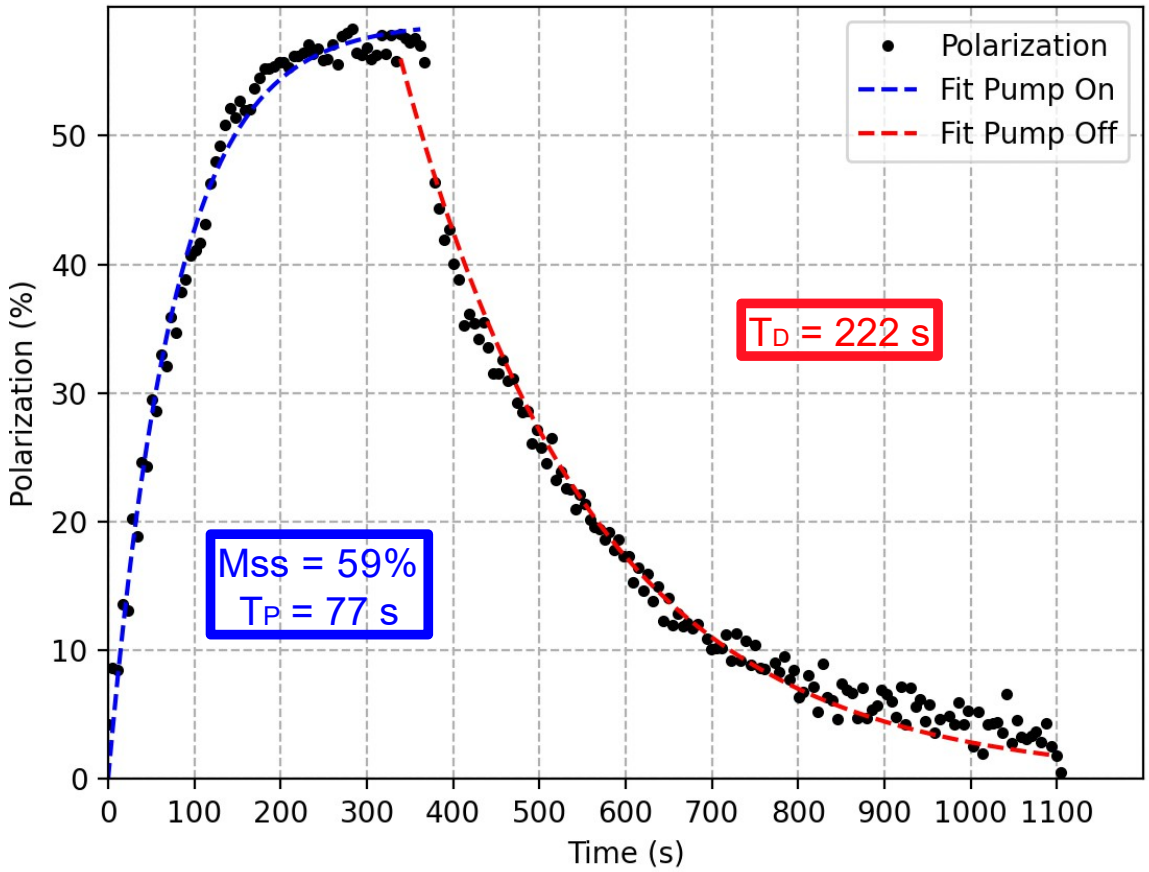
Polarization with New Setup

- Steady state polarizations near 60% at 3T and 2.5 Torr.
- Probe signal depends on brightness of plasma, but highest polarizations require dim plasma.
- At high field, plasma distributes near the edges of the cell, but probe is traveling through center.
- Probe and pump are poorly separated in the bore, further reducing signal.
- Outgassing from fill line introduces hydrogen contaminants.



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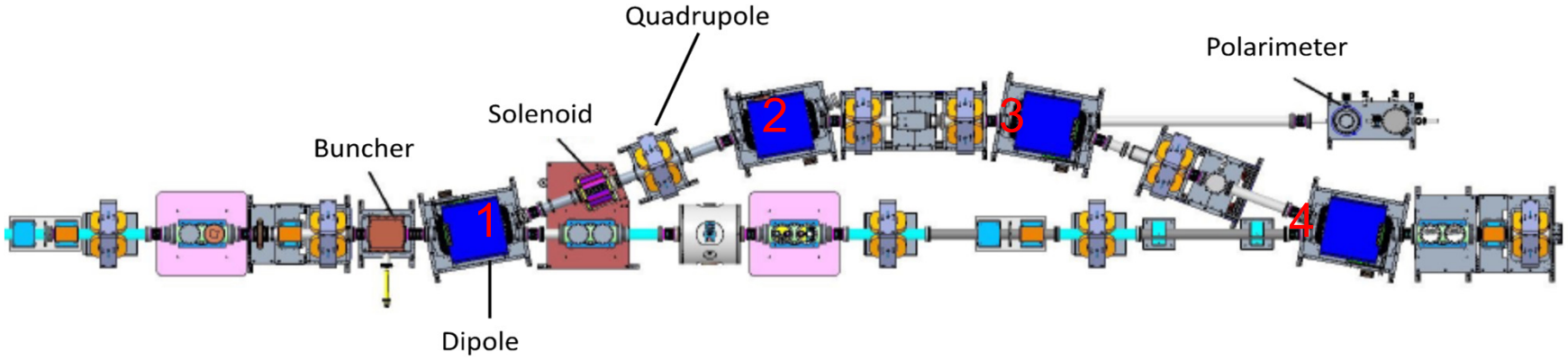
$^3He^{++}$ Spin-Rotator in the at 6.0 MeV Beam Energy

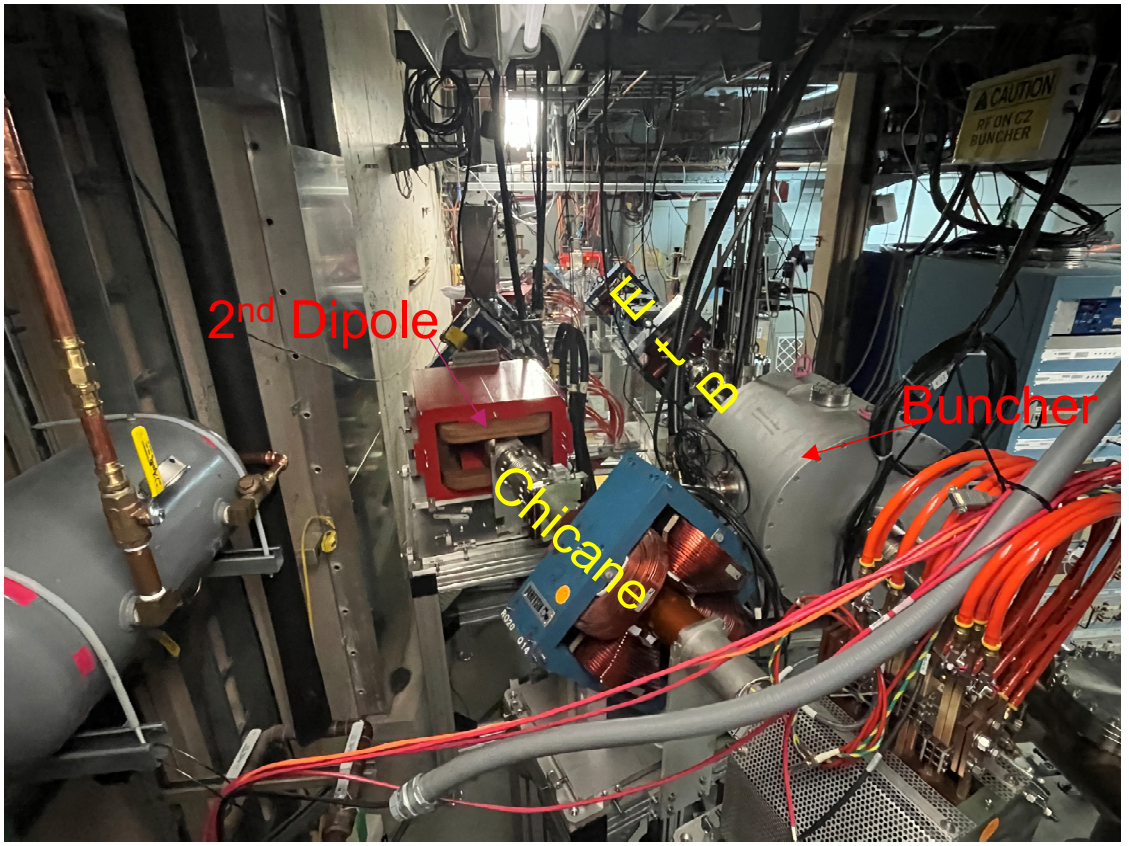
After acceleration by EBIS LINAC, the polarized $^3He^{++}$ beam will have an energy of 6MeV with a longitudinal spin direction.

- The longitudinal polarization of beam is at first rotated to transverse direction using the 21.5 deg bending magnet (Dipole-1) and after
- The Spin- solenoid will change the spin direction to the vertical . It is a pulsed solenoid with reversible field to enable spin-flip on an EBIS pulse-by-pulse basis.
- Vertically polarized beam will return to the straight HEBT line by the system of dipole magnets (2,3,4).
- The chicane was tested with 4He++ in 2023. Transmission was 90% of straight line.

The polarimeter will install in the straight section after the Dipole-3 magnet. With a spin-flip, we can measure polarization of the beam with a standard configuration of left/right symmetric Si-strip detectors).

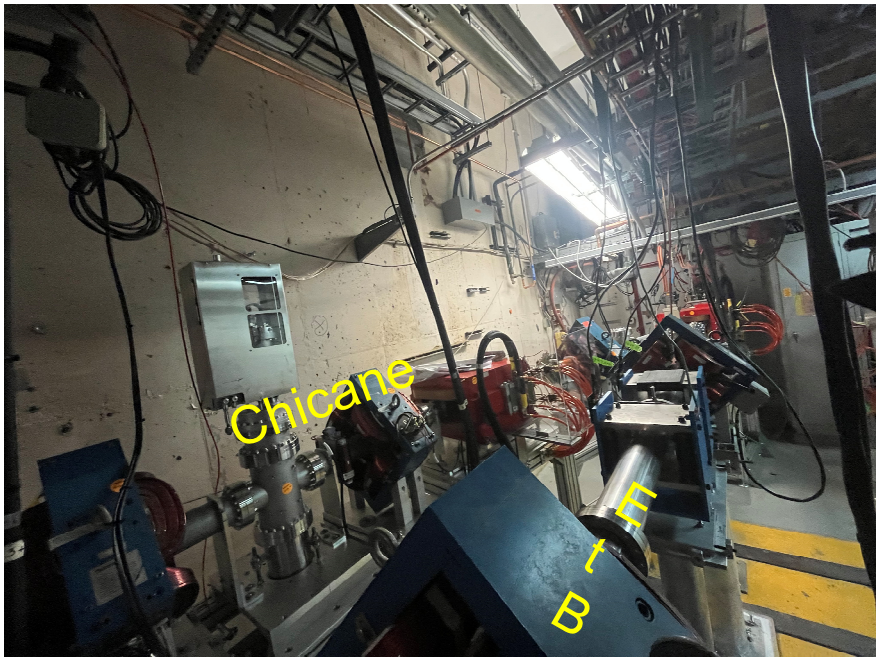


Spin Rotator -Chicane



Start of Chicane

End of Chicane

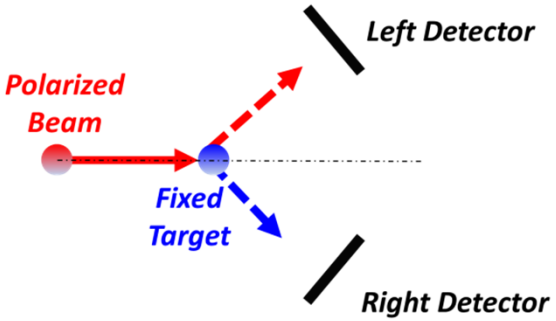


^{3}He-^{4}He scattering polarimeter at 5.4 MeV beam energy

By a measuring, the spin correlated asymmetry of ^{3}He (beam ions) scattering on the ^{4}He (gas target) to determine the polarization of ^{3}He beam.

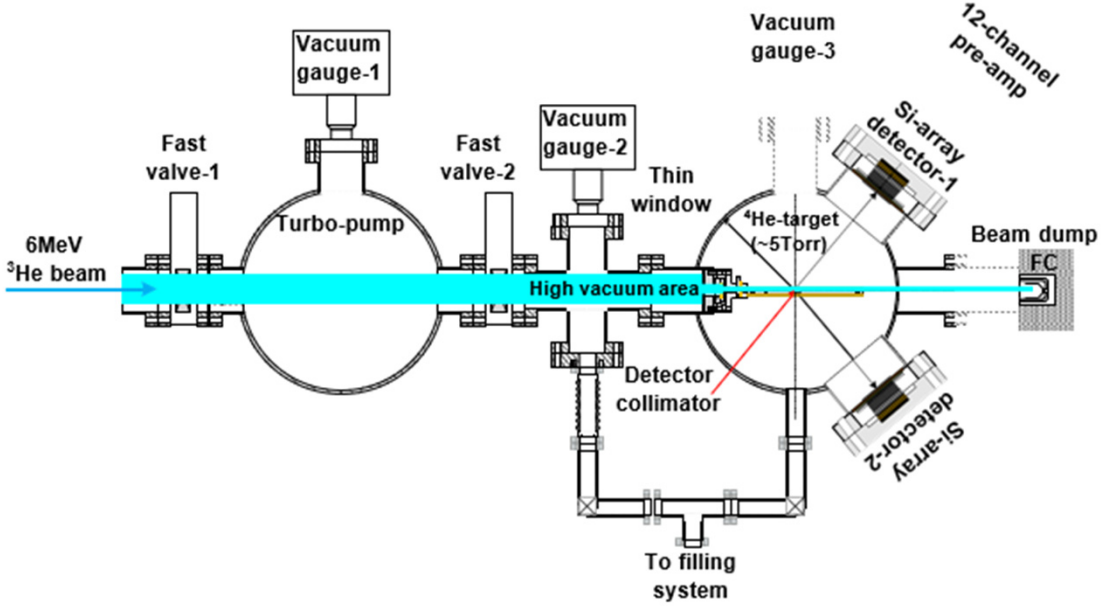
The asymmetry a could be found from the number of detected scattered particles $N_{LR}^{\uparrow\downarrow}$ in left/right (L/R) detectors depending on the beam spin (↑↓):

$$a = A_N P = \frac{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} - \sqrt{N_R^{\downarrow} N_L^{\uparrow}}}{\sqrt{N_R^{\uparrow} N_L^{\downarrow}} + \sqrt{N_R^{\downarrow} N_L^{\uparrow}}} \quad \text{and} \quad \sigma_a = \sqrt{\frac{1-a^2}{N_R^{\uparrow} + N_R^{\downarrow} + N_L^{\uparrow} + N_L^{\downarrow}}} = \sqrt{\frac{1-a^2}{N_{tot}}},$$



where P is the beam polarization, A_N - analyzing power and σ_a - statistical accuracy.

Analyzing power in 3He-4He elastic scattering at 5.4 MeV beam energy and 79° - angle is close to 100%.



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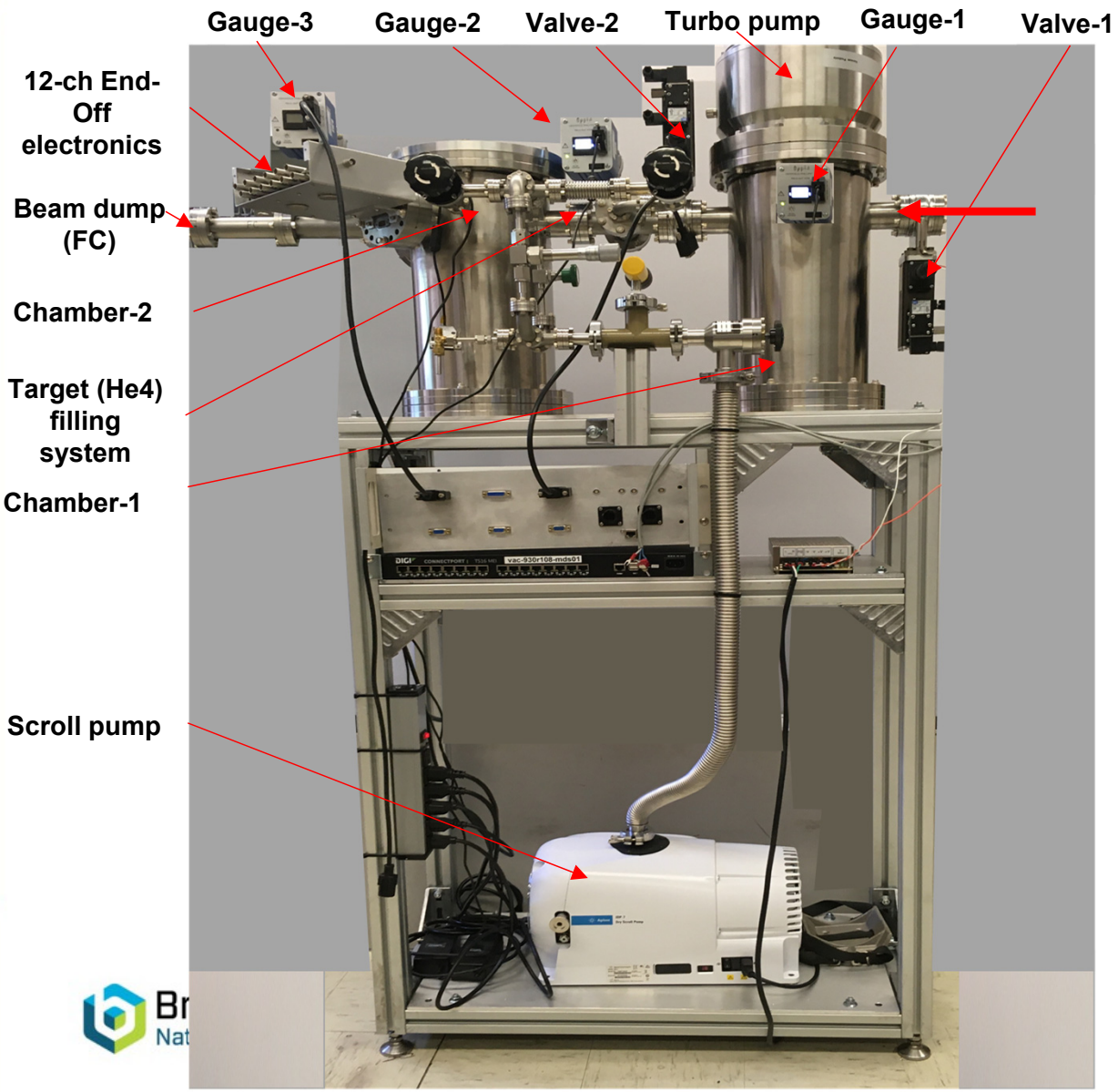
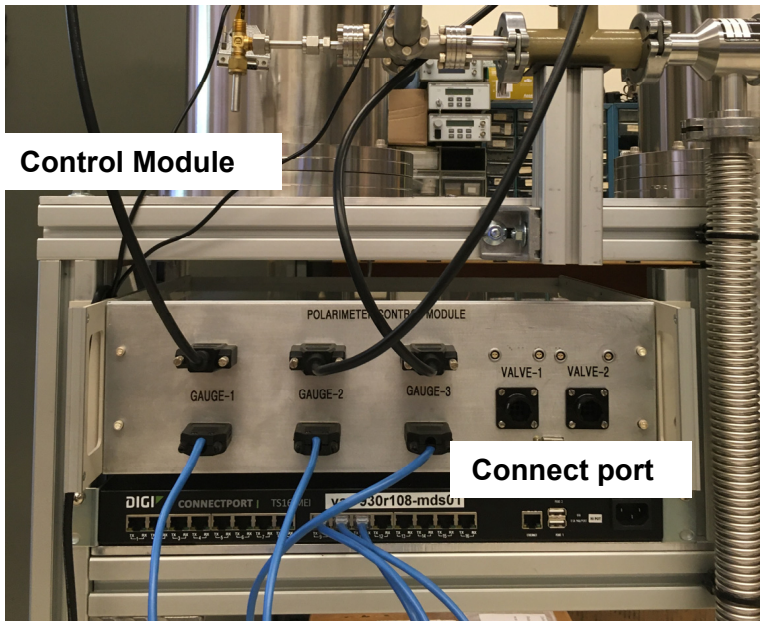
Setup of 6 MeV polarimeter

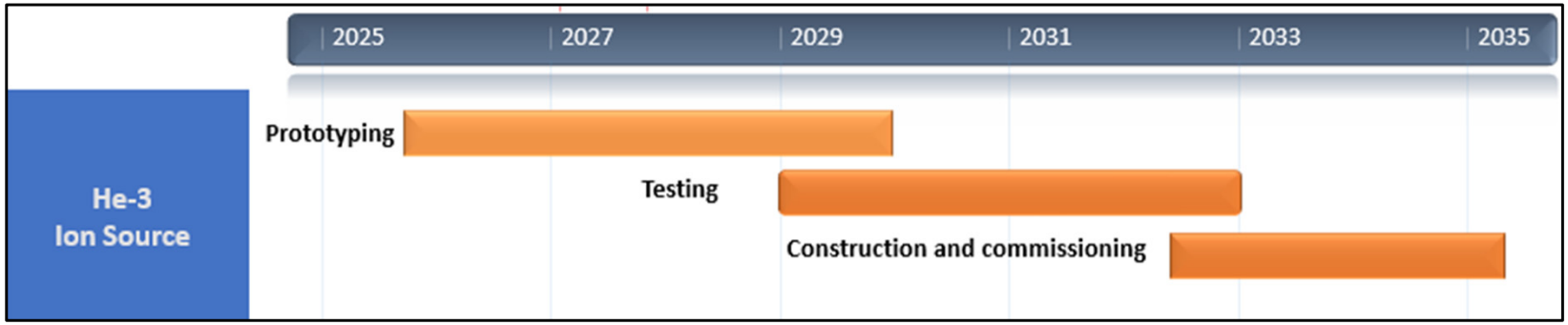
Polarimeter assembled and installed in beamline



Polarimeter Control Module

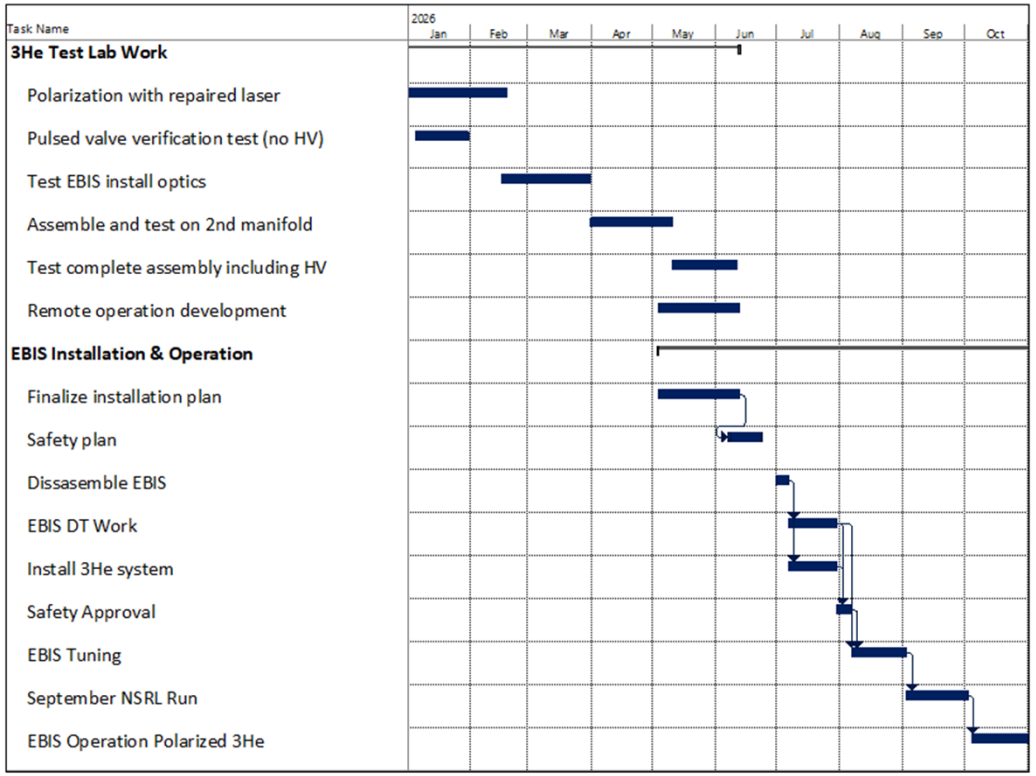


Schedule



- Complete assembly and testing prototype EBIS ^{3}He system
- Install ^{3}He polarizer during July & August shutdown
- October $^{3}He^{++}$ beam to booster

2026 Protype Schedule



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Summary

- It is essential for EIC physics to have a reliable polarized ^{3}He ion source along with developed polarimetry and beam transport.
- Updated EBIS operational.
- Developed and tested ^{3}He purification system and pulsed electromagnetic injection valve.
- Established a ^{3}He test laboratory, achieved 60% polarization in open cell with compact optics.
- Spin rotator beamline and polarimeter installed.
- Prototype system is scheduled for EBIS installation summer 2026.
- The proposed polarized ^{3}He ion source will deliver orders of magnitude higher intensities than previous generations of polarized ^{3}He sources.
- For perspective, the OPPIS source required 40 – 50 years of continuous development to reach its present performance level.
- As the first polarized ^{3}He ion source based on MEOP, it is realistically expected to require approximately a decade of sustained effort to reach full performance.
- At present, only a small number of world experts are actively working on this development; any interruption in the ^{3}He source R&D will be severely detrimental, as stopping or significantly slowing the effort would likely lead to loss of expertise and momentum, making future revival more time consuming, costly and uncertain.