

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

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Outline

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

Schedule

Summary

^3He Source at BNL

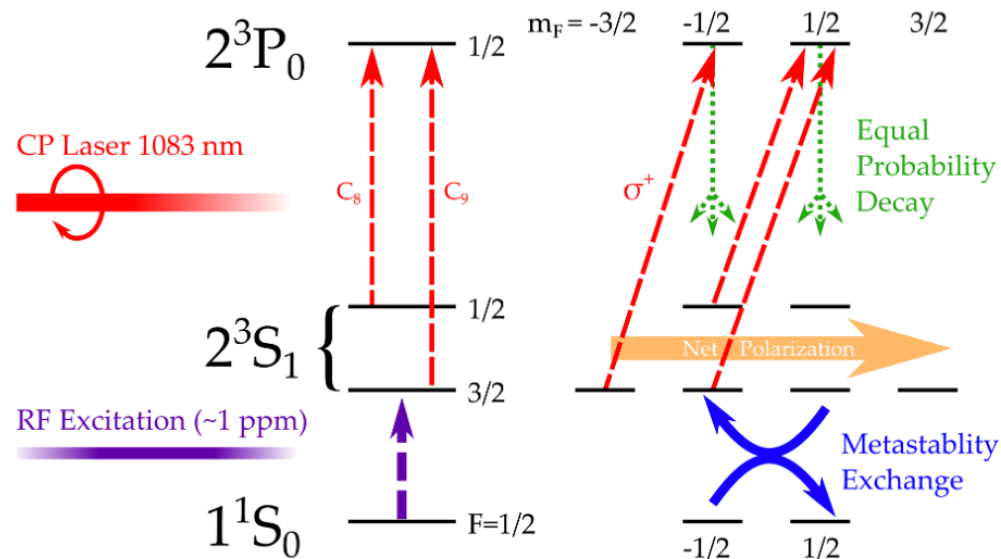
- Originally proposed by A. Zelenski and J. Alessi in ICFA Newsletter in 2003.
(A. Zelenski, J. Alessi, “**Proposal of production of polarized $^3\text{He}^{++}$ beam in EBIS**” , ICFA Beam Dynamics Newsletter 30, p.39, (2003)
- Identified as High Priority R&D for EIC by EICAC review in 2009, continued 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 ^3He ion source is a BNL MIT collaboration that began in 2013.

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

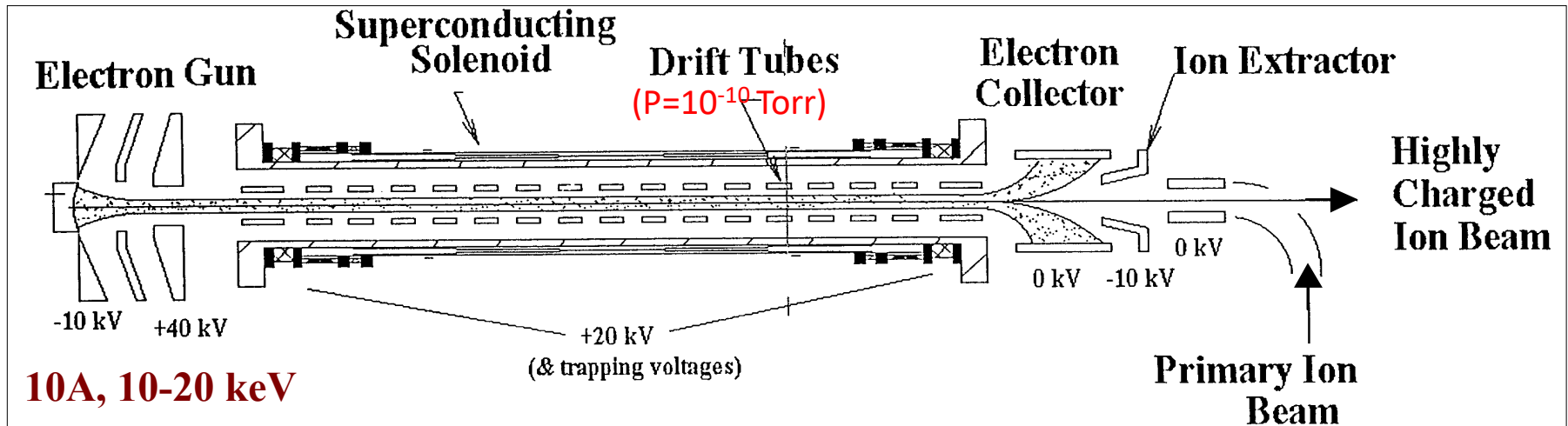
- Intensity $\sim 2.5 \cdot 10^{11}$ $^3\text{He}^{++}$ ions in 20 us pulse ~ 4 mA-peak current
- Polarization $> 80\%$
- Compatibility with the operational EBIS for heavy ion physics and other programs.
- Spin flip every source pulse in the beam transport line for spin measurements.

Metastability Exchange Optical Pumping MEOP

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



Principle of EBIS Operation



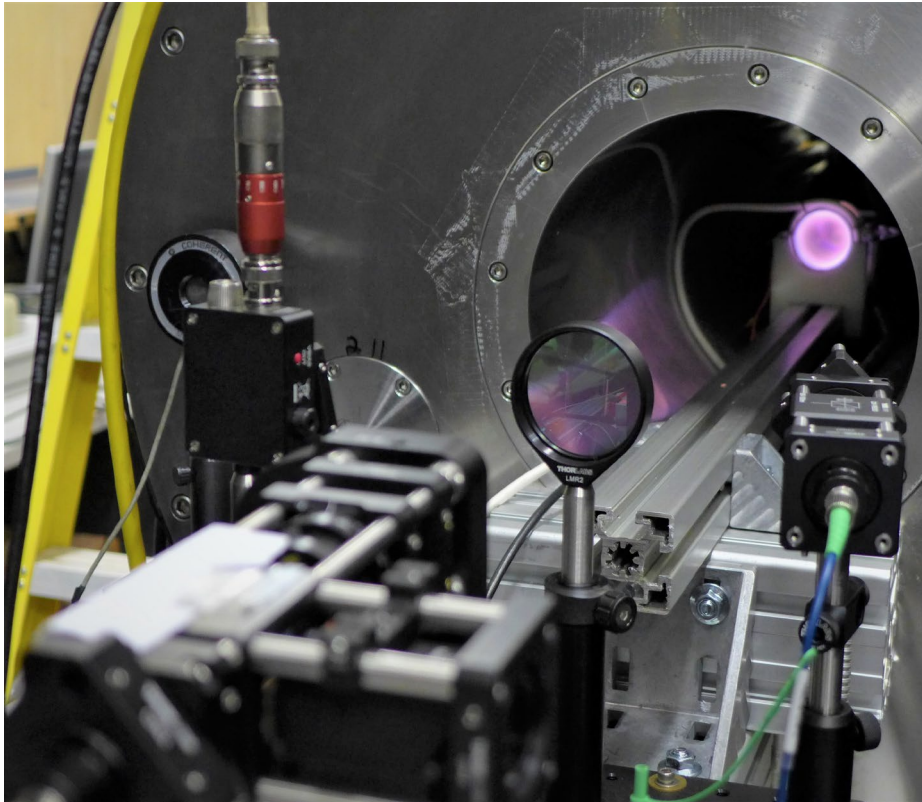
*Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.*

- 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!*

Production of Polarized $^3\text{He}^{++}$ in EBIS

- ^3He polarization by optical pumping and metastability-exchange (MEOP) technique inside the EBIS in high (5.0T) magnetic field.
- EBIS is used for efficient ionization and accumulation of polarized $^3\text{He}^{++}$ ions to the full capacity of about $(2.5) \cdot 10^{11}$, $^3\text{He}^{++}$ ions.
- The upgraded EBIS has a pulsed gas injection that allows for production of ion beams.
- The ^3He system will allow for injection of both polarized and unpolarized from separate pulsed valves.

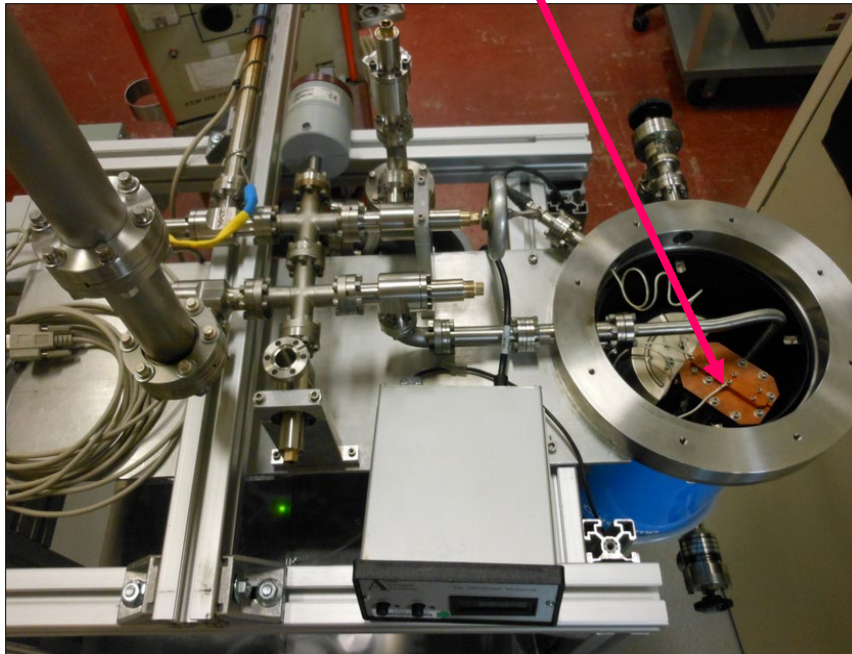
Previous BNL MEOP results



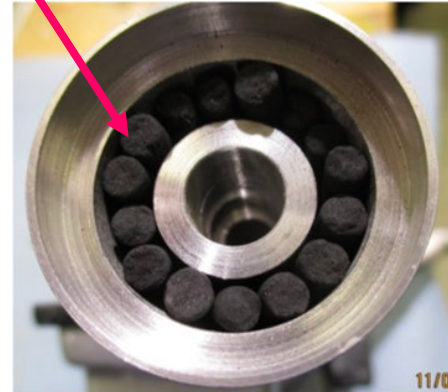
- 89% polarization with sealed cell at 3T
Maxwell & Zelenski - 2016

^3He -gas purification and filling system

Modified Cryo-pump for ^3He purification and storage



Vessel filled with activated charcoal granules



The activated charcoal cryopumps ^3He gas.

The adsorbed gas is released by cartridge heater vessel heating $\sim 20\text{K}$.

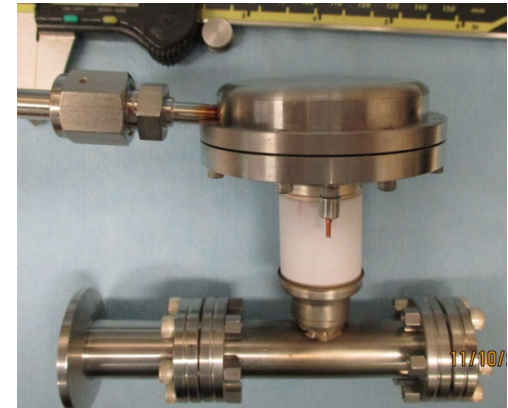
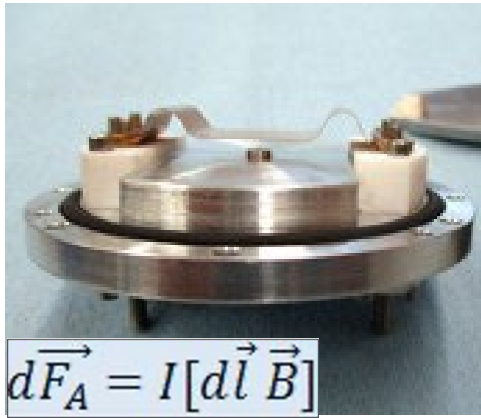
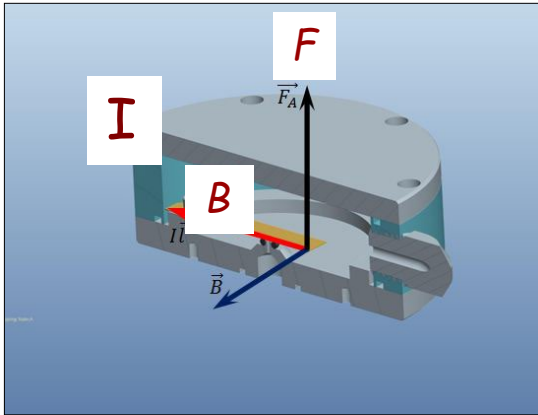
This system provides gas storage and supply for ^3He -cell operation at the optimal pressure value (3-5 Torr).



Fast Pulsed Gas Injection Valve

“Electro-magnetic”, $[I \times B]$ 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.

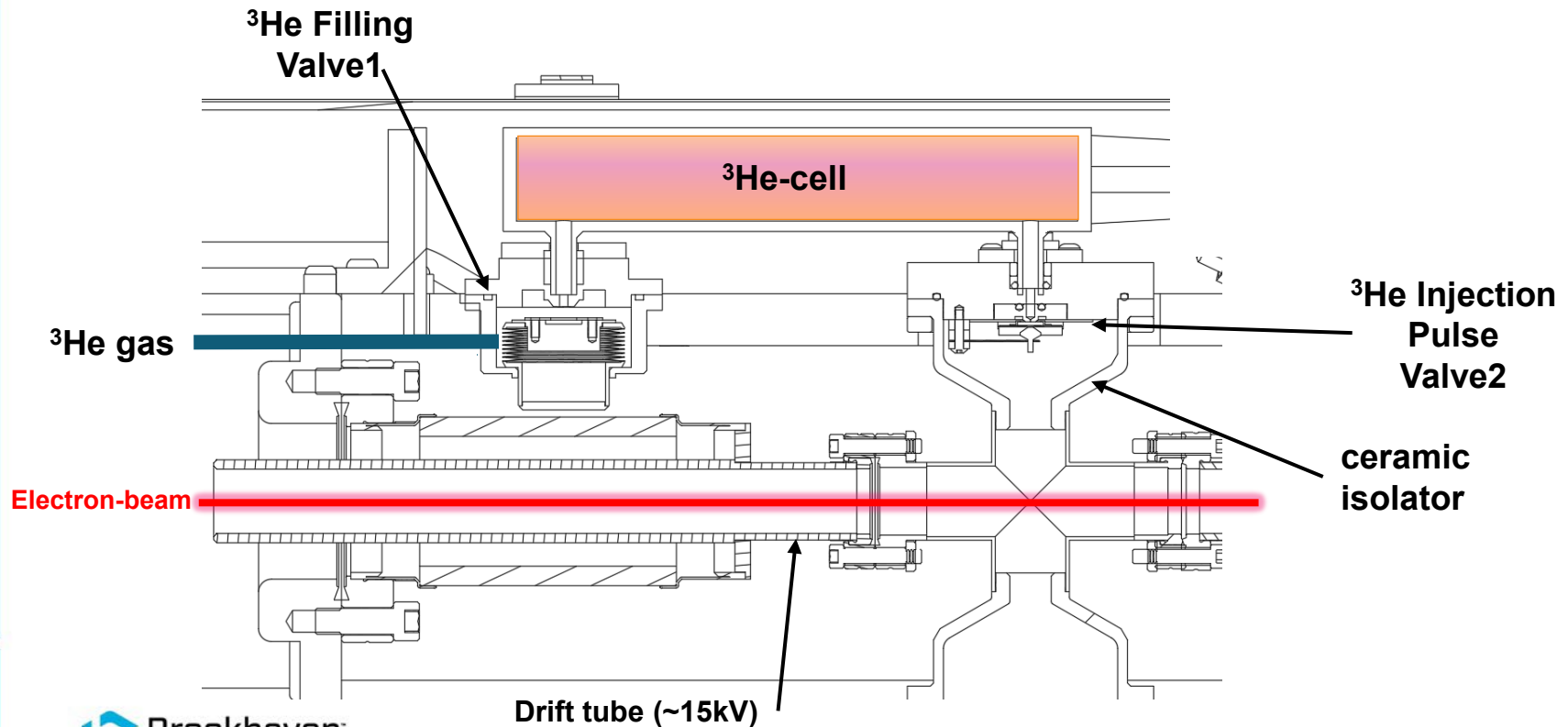


Pulsed valve for
Un-polarized gas
Injection to the EBIS

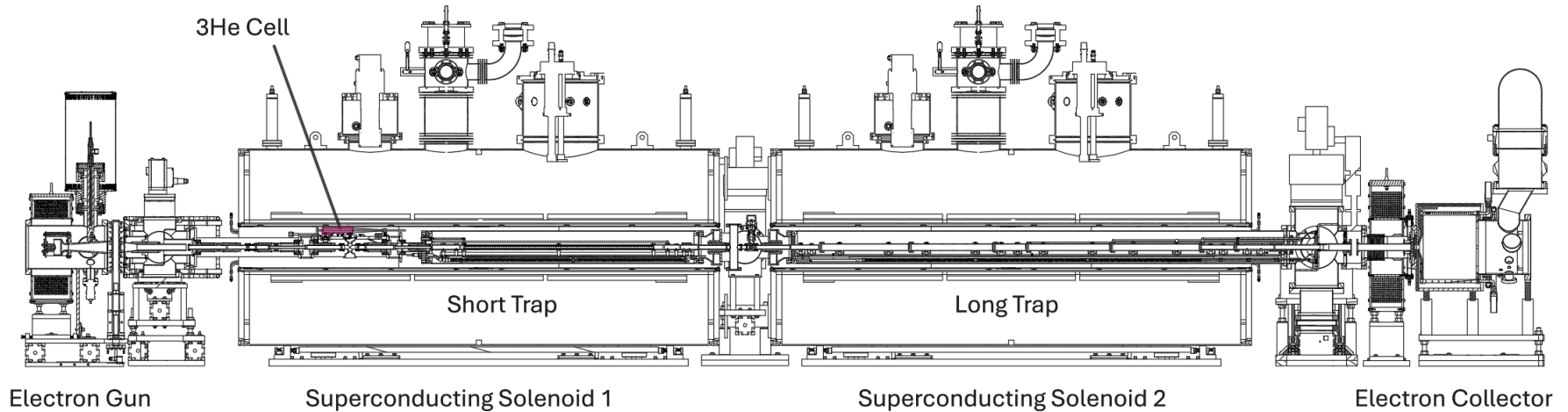
^3He Polarizing Cell inside EBIS

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

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



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

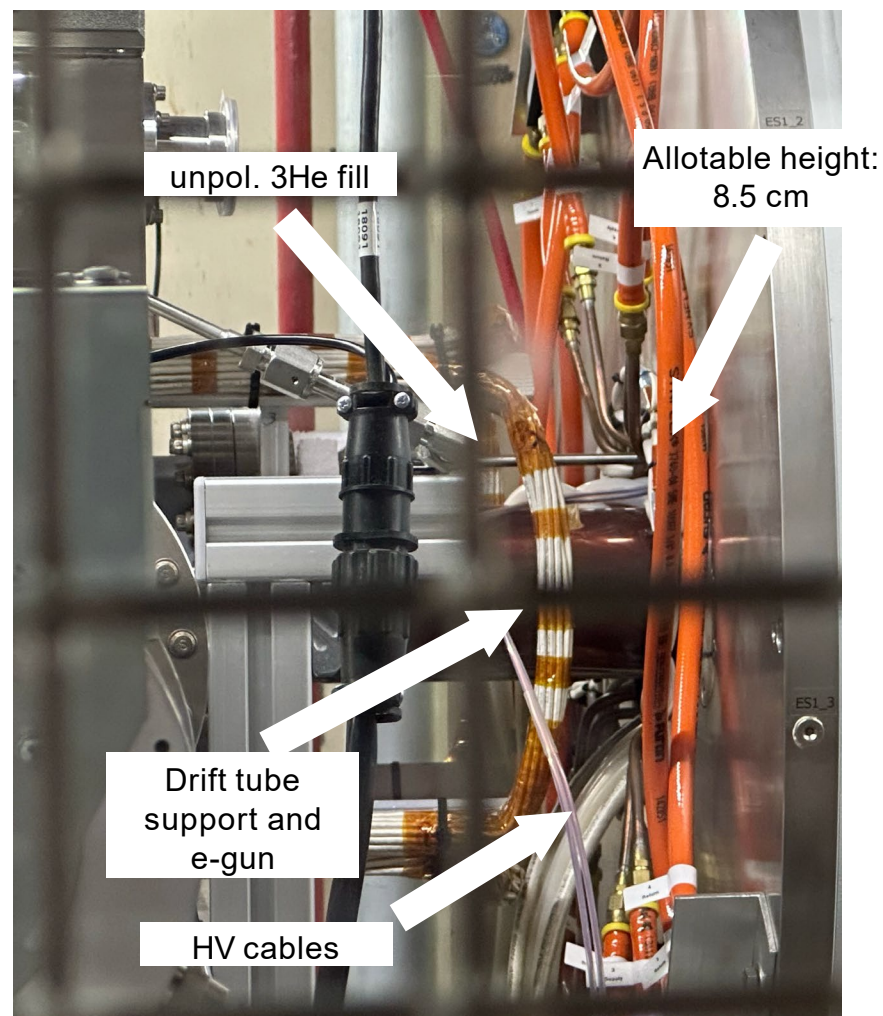


The polarized ^3He ion source will be installed inside Solenoid 1.

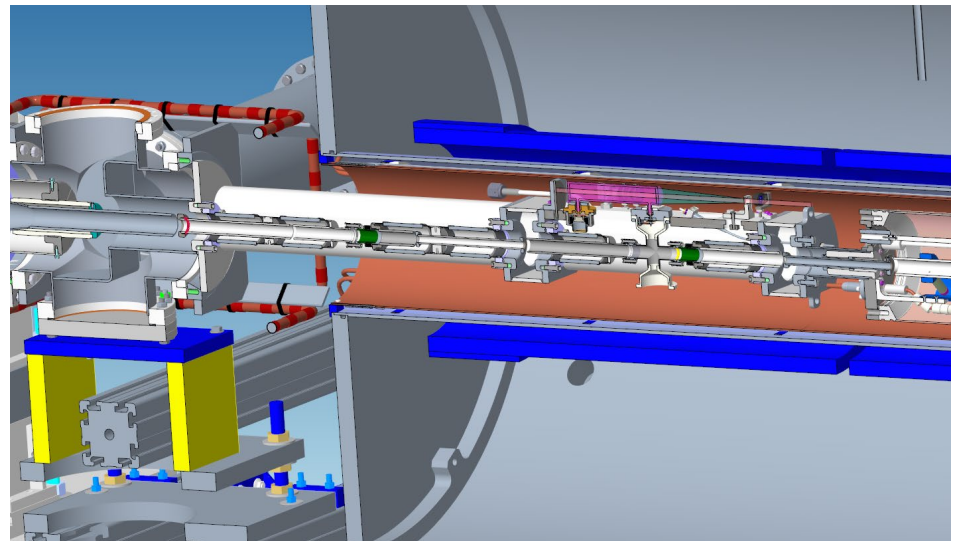
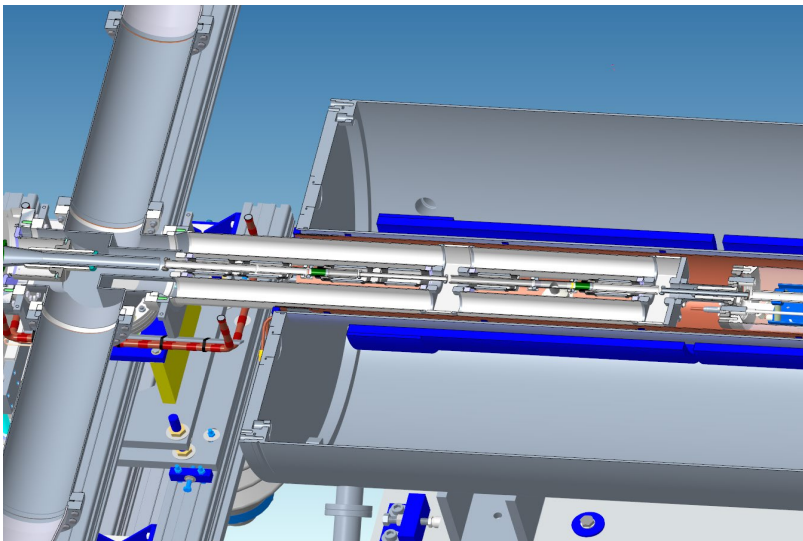
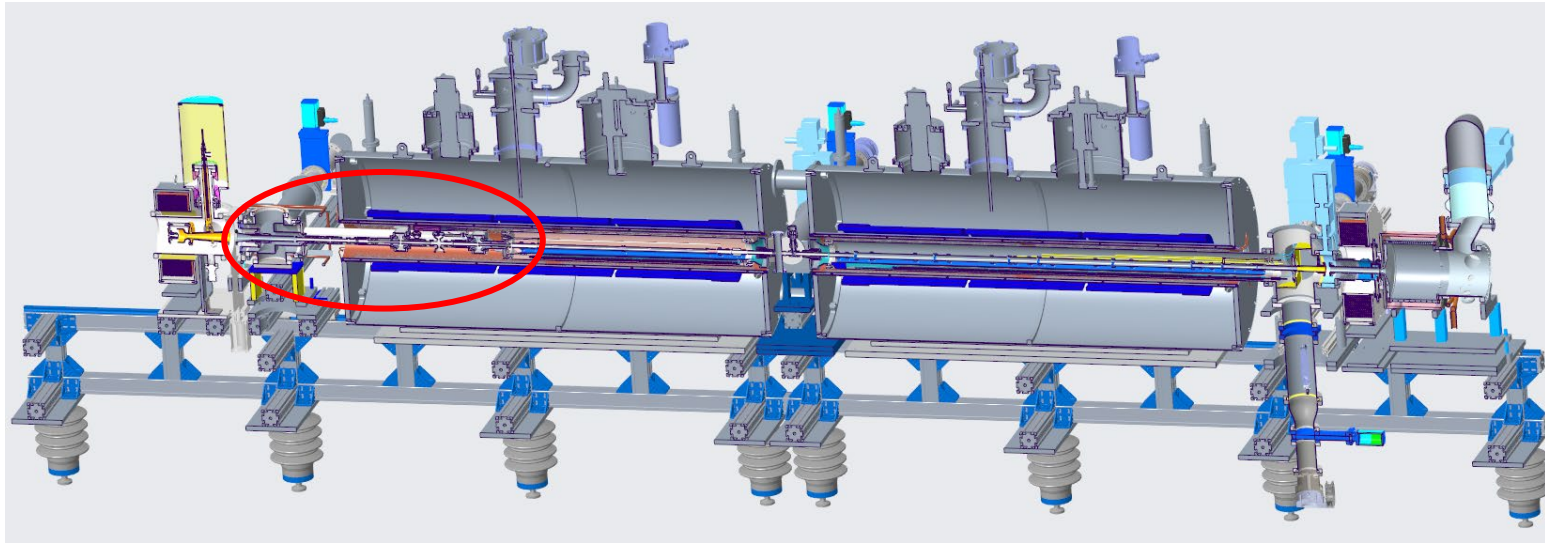
- The atoms of the ^3He gas will be polarized by MEOP technique
- The fast pulse valve will inject the polarized gas into the ion trap region of the EBIS.
- Inside trap the ^3He ions will be stripped of electrons to the $^3\text{He}^{++}$ state.
- The trap barrier is lowered and beam sent to Booster.

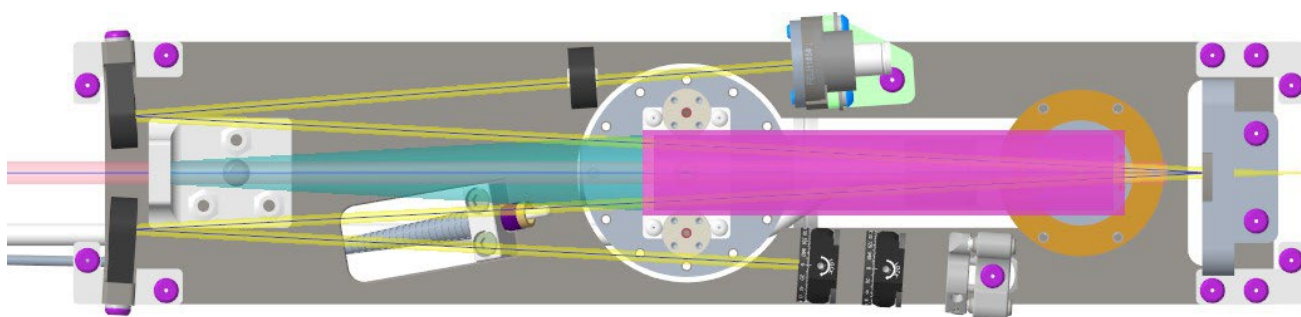
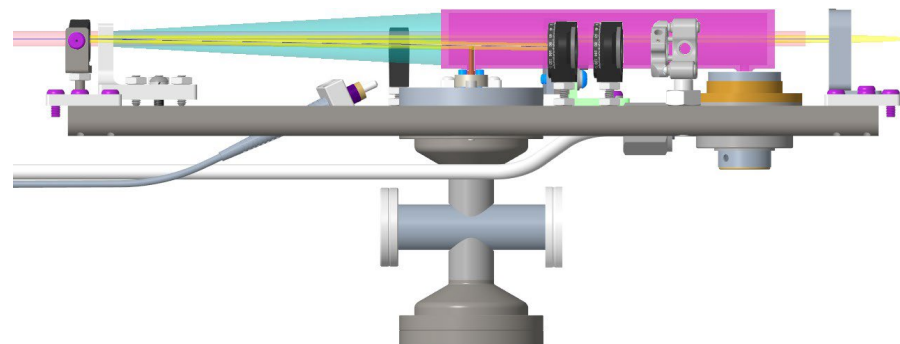
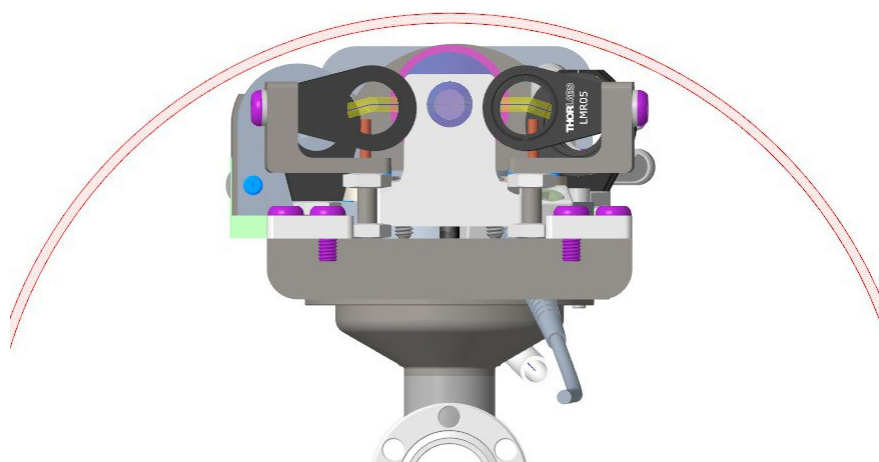
Challenges in EBIS

- In EBIS limited space in bore.
- Allowable cross section for in situ polarization cell and optics is just 8.5 cm height x 18.5 cm width.
- During installation possibility of sensitive fiber optics being caught on other objects, optic misalignment could damage cabling.
- Inhomogeneity in magnetic field depolarizes 3He cell and causes challenges for steering the e-beam, requiring non-magnetic materials.

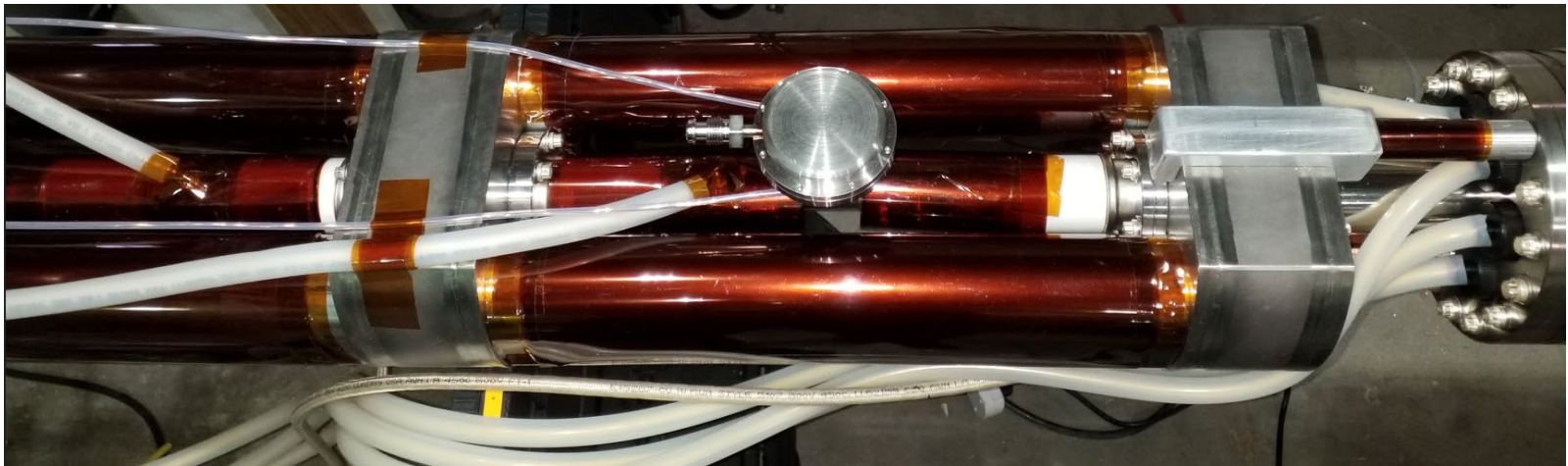


EBIS





Vacuum manifold with drift tubes



RHICEBIS in the test lab



RHICEBIS moving
to test lab Nov 2023

RHICEBIS inside Test Lab

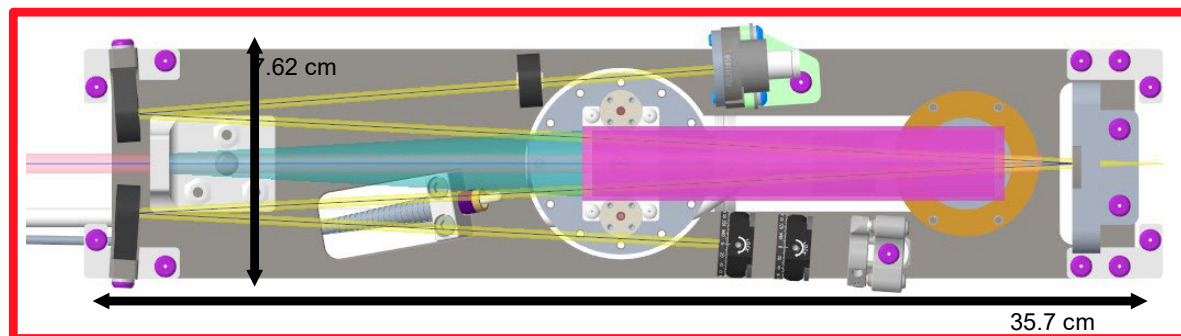
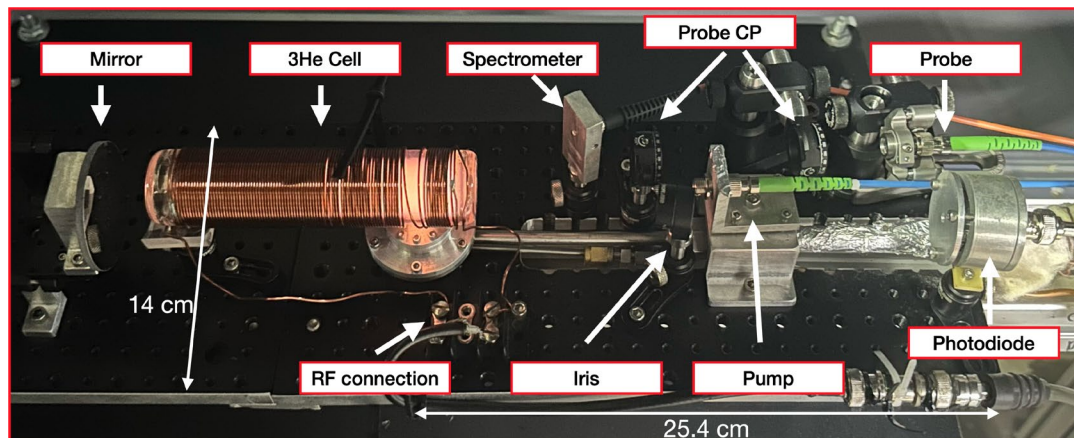


^3He Test Lab Developments

- Since mid 2023 Noah Wuerfel (MIT) has led the polarized ^3He 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.

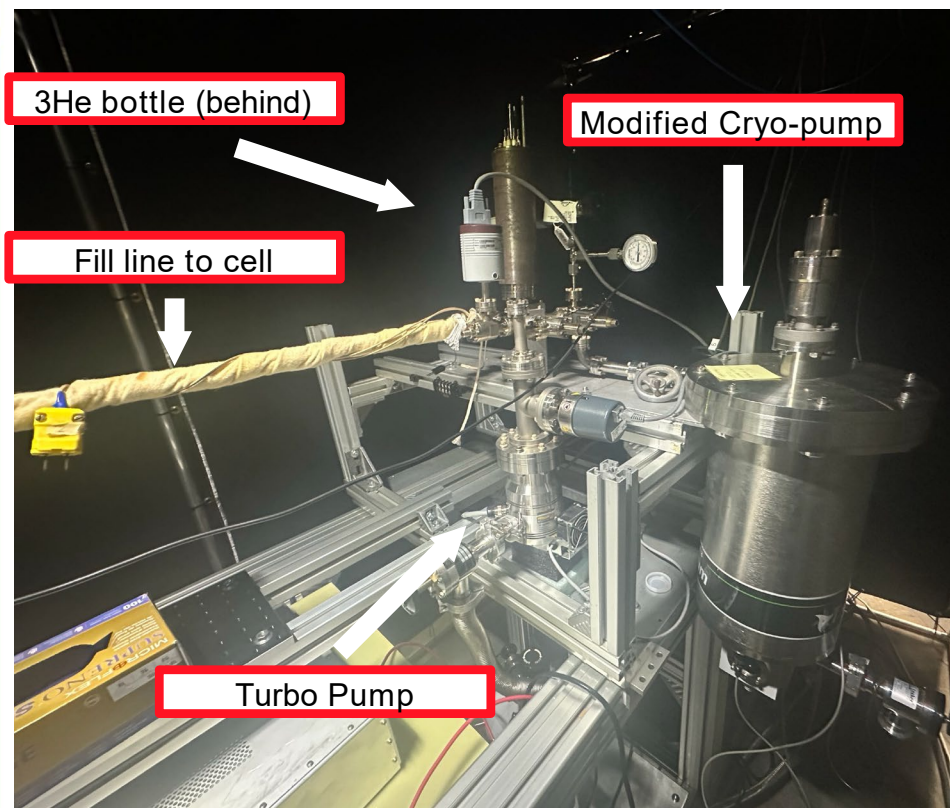


Reduced optical Footprint

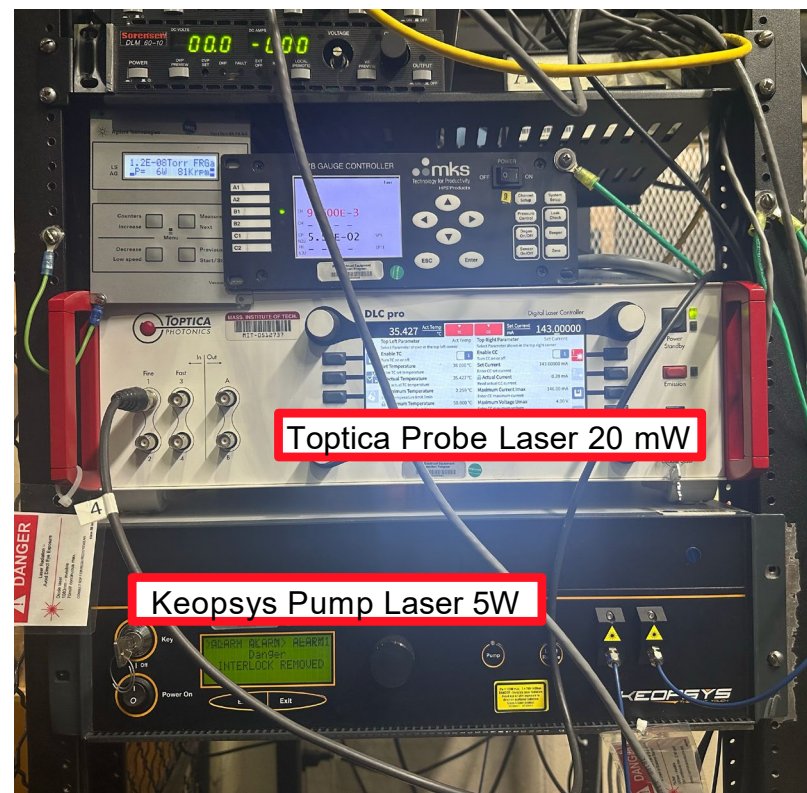


Final layout designed to meet space constraints in EBIS.

3He work in Test Lab



Cryogenic gas purification system

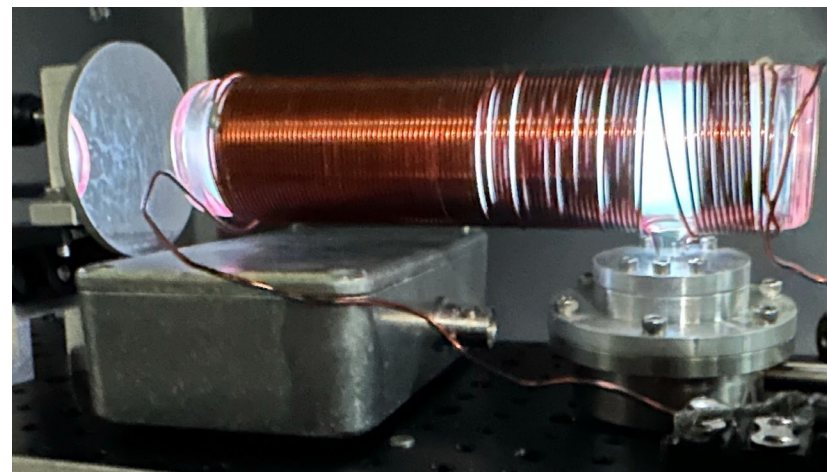
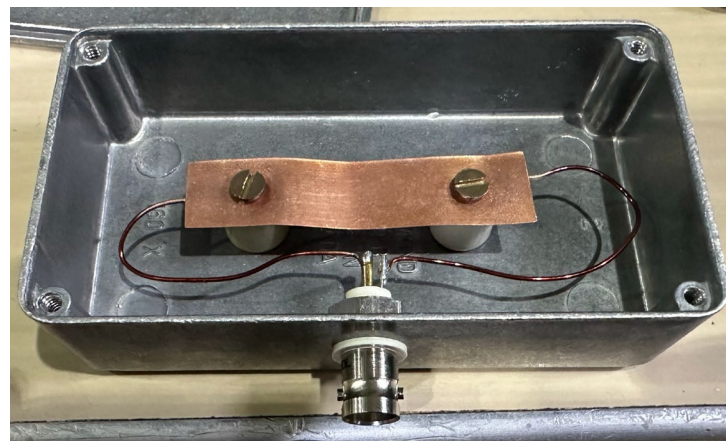


Controls rack with pump and probe 17

Mock Pulse Valve

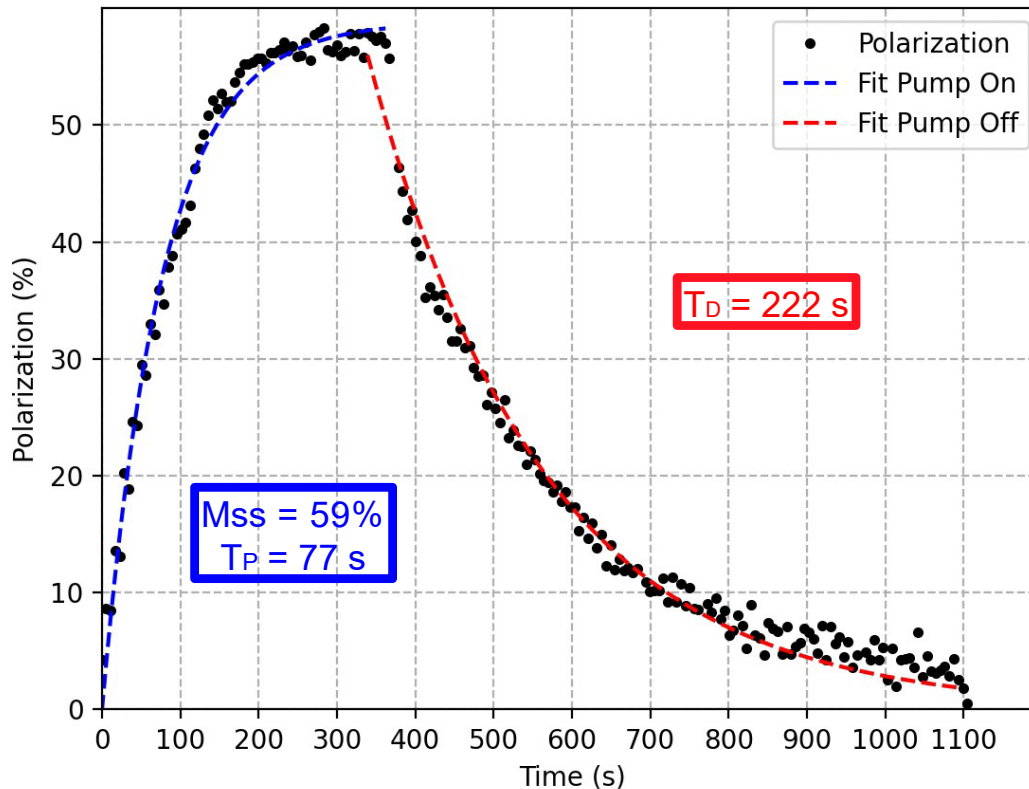


- Constructed a mock pulse valve to test effect of 10 A current on the cell polarization.
- Aluminum case with copper strip of roughly the same dimensions as pulse valve.
- No measurable effect on cell polarization at 10A at 1hz and 1Khz.



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.

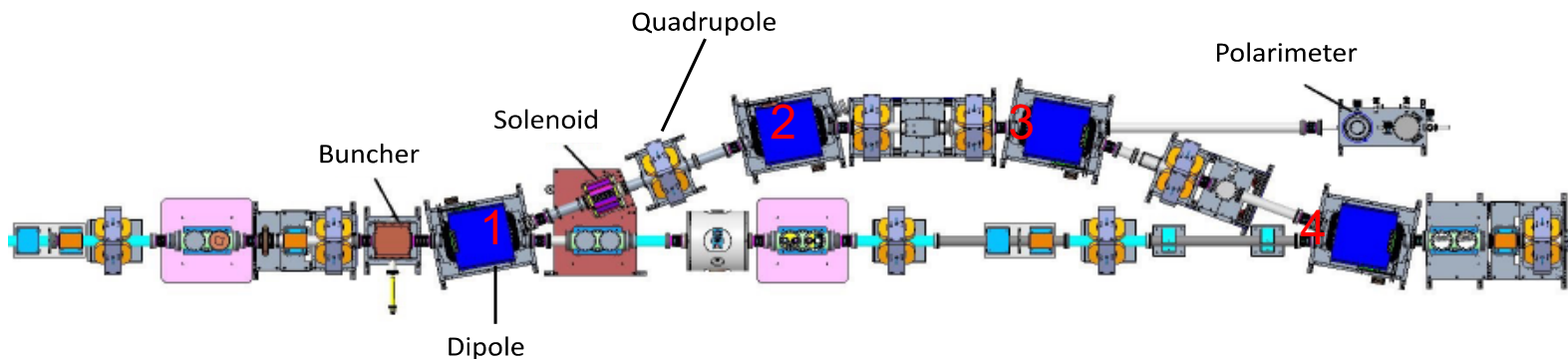


$^3\text{He}^{++}$ Spin-Rotator in the at 6.0 MeV Beam Energy

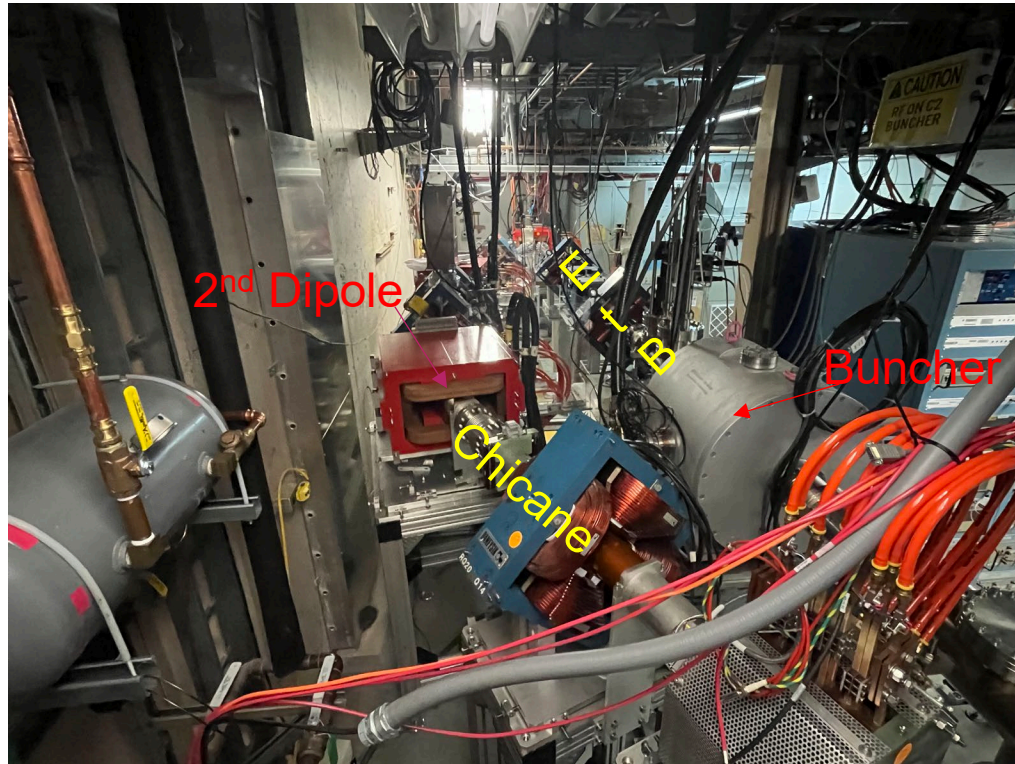
After acceleration by EBIS LINAC, the polarized $^3\text{He}^{++}$ beam will have an energy of 6MeV with a longitudinal spin direction.

- 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).

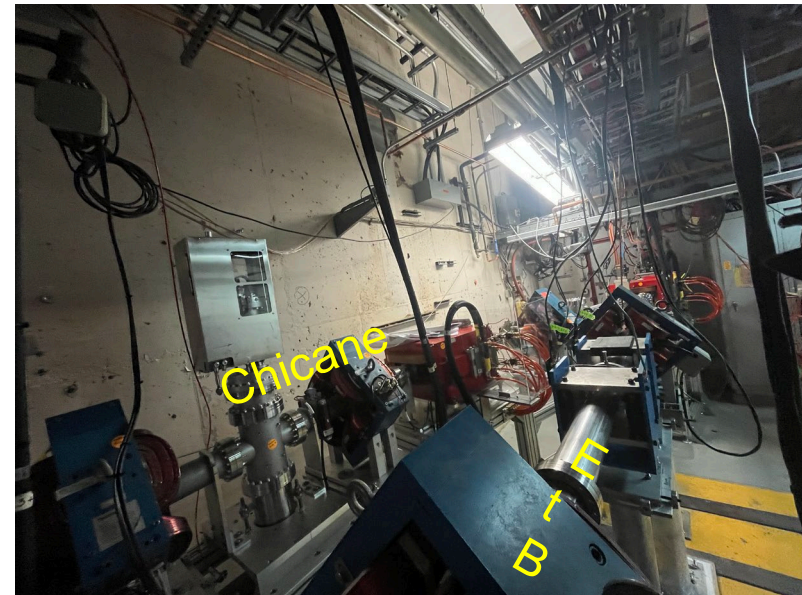


Spin Rotator -Chicane



Start of Chicane

End of Chicane



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

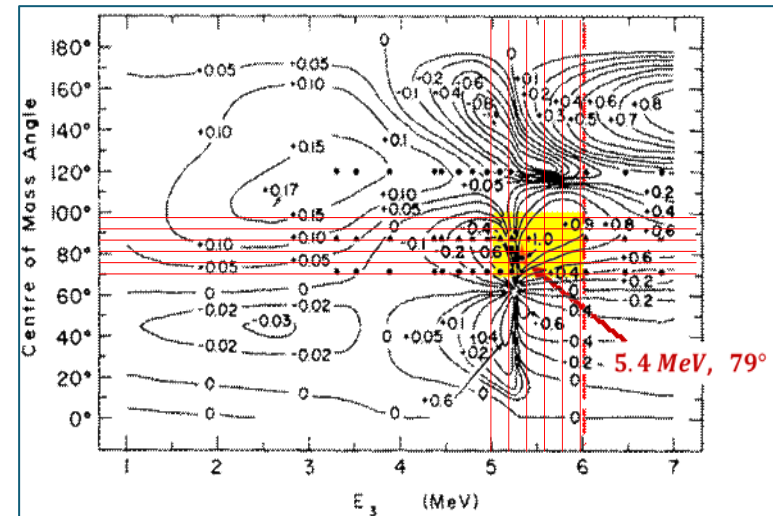
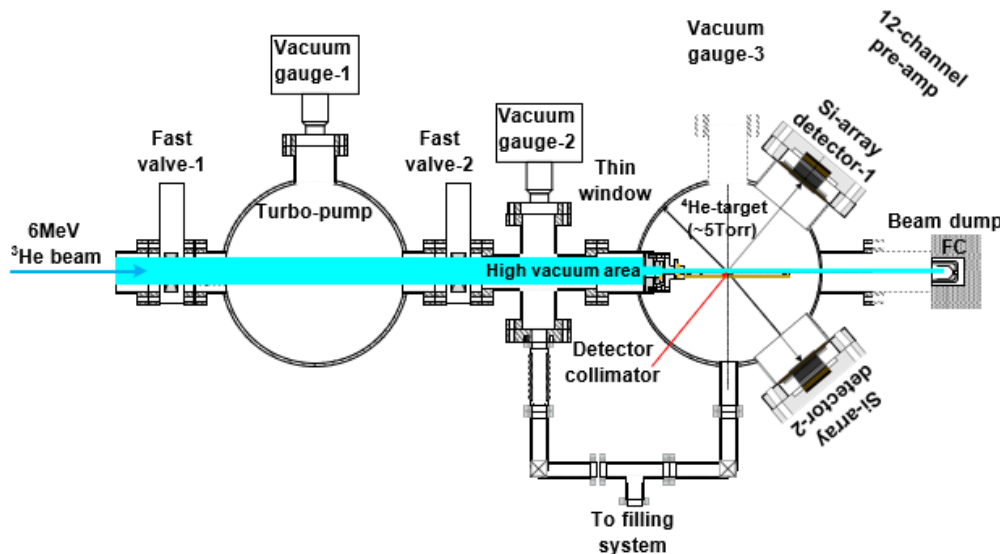
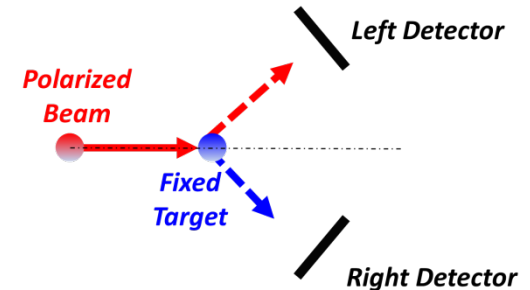
By a measuring, the spin correlated asymmetry of ^3He (beam ions) scattering on the ^4He (gas target) to determine the polarization of ^3He beam.

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 ($\uparrow\downarrow$):

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

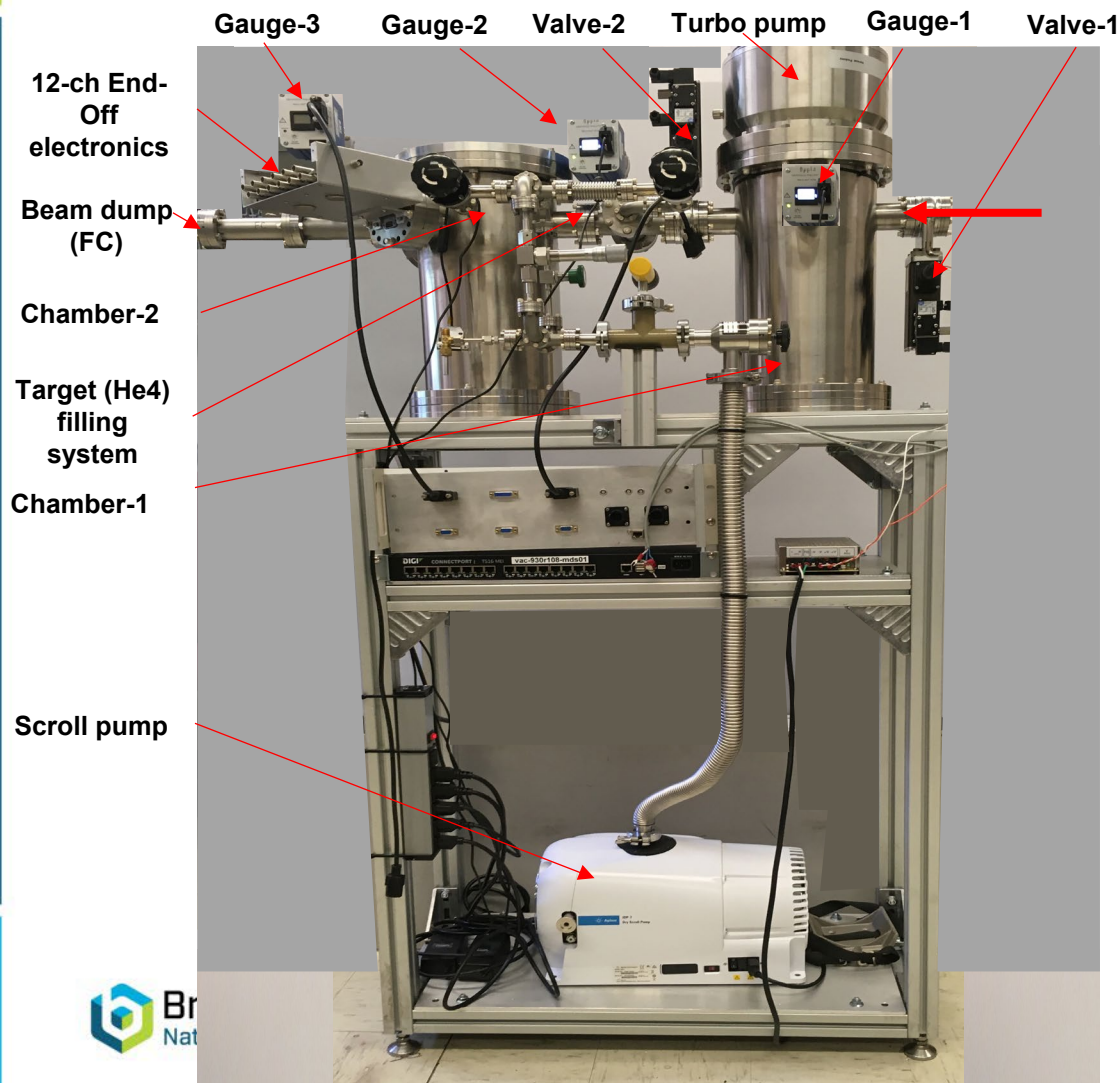
where P is the beam polarization, A_N - analyzing power and σ_a - statistical accuracy.

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

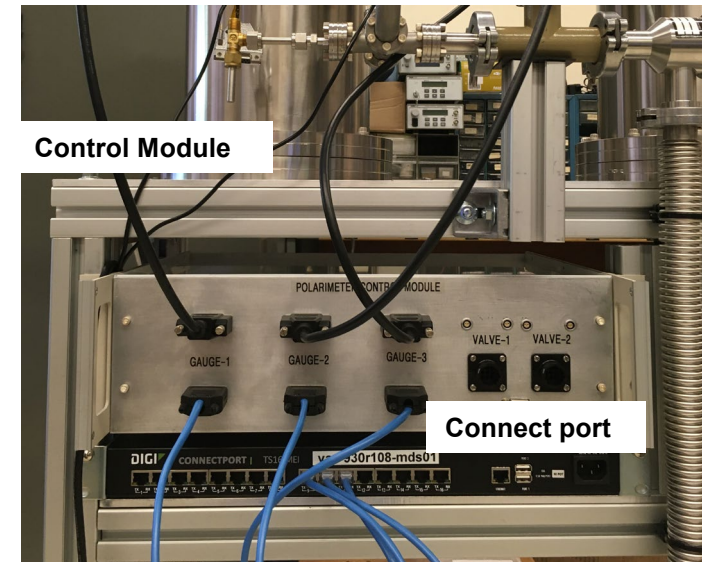


Setup of 6 MeV polarimeter

Detector completed with the required geometry, the energy range and is being installed in the EBIS beam line.



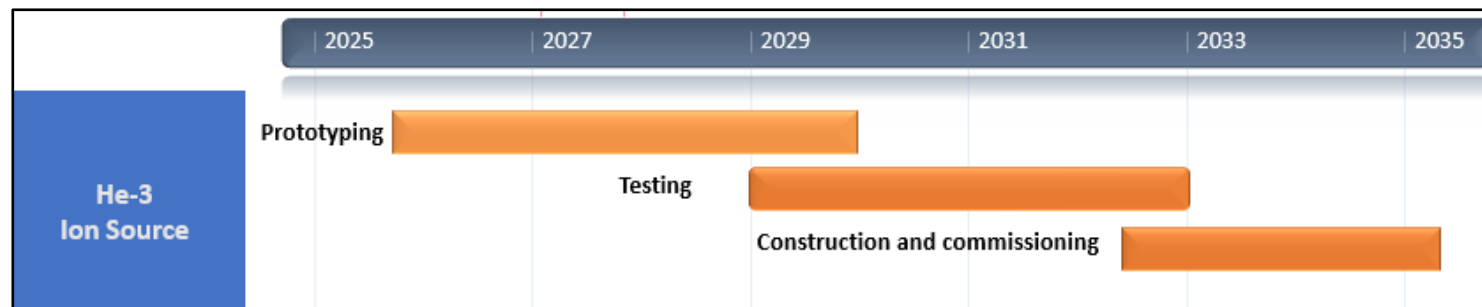
Polarimeter Control Module



With the beam we plan to study:

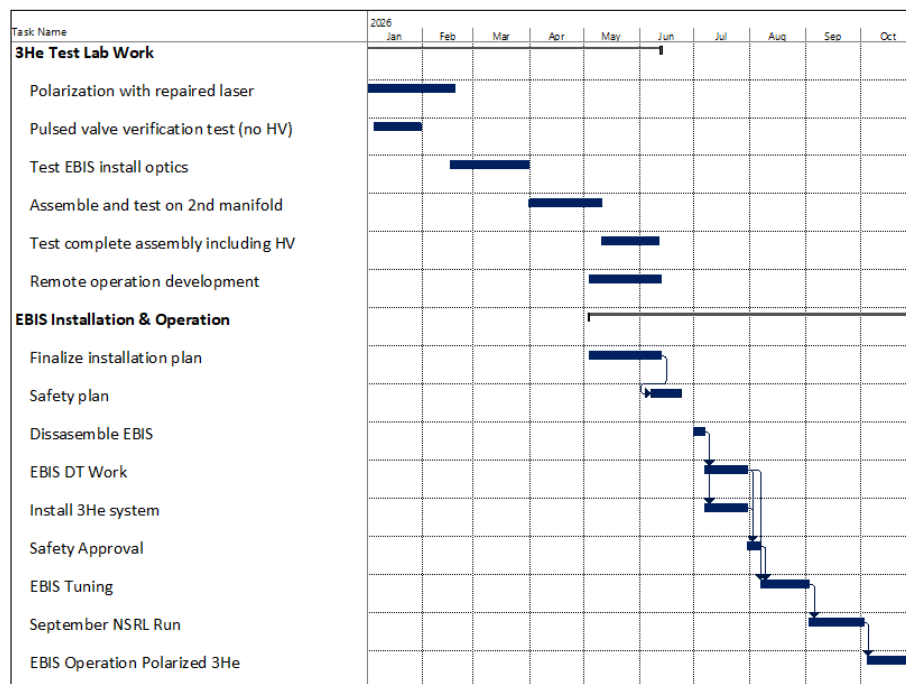
- Kinematics of elastic ^3He - ^4He scattering;
- Energy distribution of the ^3He - ^4He pair;
- Energy and time resolution;
- Electronics and DAQ;
- Data collection and analysis of events;
- Controlling and monitoring the detectors;
- Vacuum control system;
- Communication system;
- ...

Schedule



2026 Prototype Schedule

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



Summary

- It is essential for EIC physics to have a reliable ^3He polarized ion source along with developed polarimetry and beam transport.
- Achieved high ^3He polarization in open cell under high magnetic field.
- Developed and implemented a ^3He purification and supply system using cryo-pumping, successfully meeting the requirements for high polarization.
- Designed and tested a pulsed electromagnetic injection valve for delivering ^3He into the drift tube; this valve type is already proven in EBIS operations.
- Established a dedicated ^3He test laboratory.
- Installed and tested the spin-rotation line. The polarimeter will be tested with ^3He beam.
- Active research includes optimization of polarization in compact configuration, assembly of updated injection valve, and further integration of polarization controls.

Summary

- The proposed polarized ^3He ion source will deliver orders of magnitude higher intensities than previous generations of polarized ^3He sources.
- For perspective, the OPPIS source required 40 – 50 years of continuous development to reach its present performance level.
- As the first polarized ^3He ion source based on MEOP, it is realistically expected to require approximately a decade of sustained effort to reach full performance.
- At present, a small number of world experts are actively working on this development; any interruption in the ^3He source R&D will be severely detrimental to the project.
- If development is stopped or significantly slowed, reviving the effort later would likely take much longer and be substantially more expensive, with no guarantee of recovering the same expertise or momentum.