PSTP 2024
20TH INTERNATIONAL WORKSHOP ON POLARIZED SOURCES, TARGETS, AND POLARIMETRY
SEPT. 22-27 | JEFFERSON LAB, NEWPORT NEWS, VA

Argonne NATIONAL LABORATORY

Development of Polarized Lithium Sources for EIC

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09/23/2024

U.S. DEPARTMENT OF ENERGY
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Overview – Why Polarized Lithium?

Electron Ion Collider

Science Goals for Polarized Beams

3D structure of nucleons and nuclei

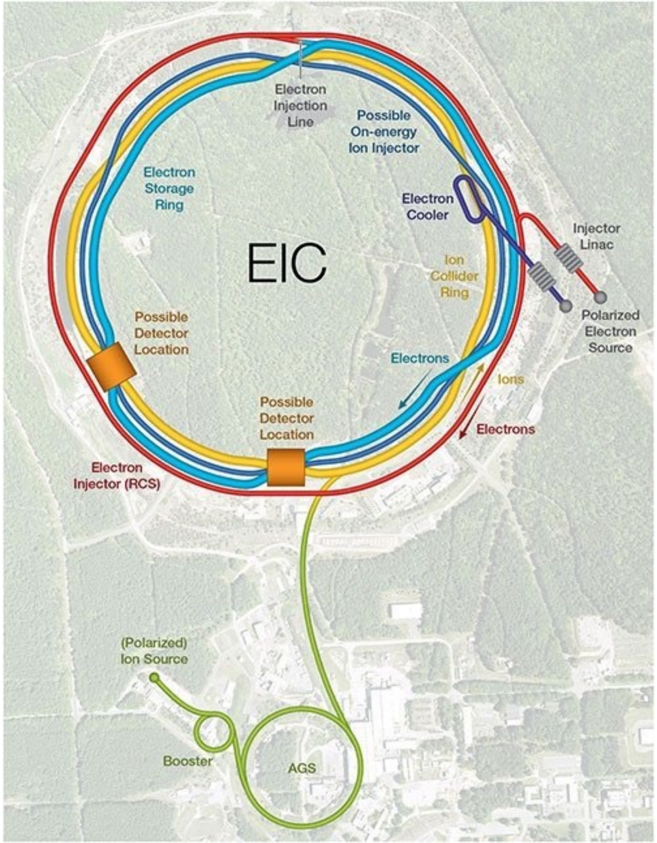
Proton spin puzzle

Quarks and gluons in nuclear matter

Quark gluon confinement

Color glass condensate

Clearly require the polarization degree of freedom for proton and nuclei!



Extends the Scientific Reach of EIC

Polarized ion sources beyond A = 3

- Included in the project: polarized H, D, ^{3}He
- Polarized ion beams beyond A = 3
  - Polarized ^{6}Li and ^{7}Li
  - Extends science programs for nuclear physics at EIC

- Polarized Lithium-6 (spin-1)
  - Nuclear b structure functions
  - Gluon Sivers function with tensor polarization
  - Reference study for the EMC effect of the deuteron in a nuclear medium

P. Hoodbhoy, R.L. Jaffe, and A. Manohar, Nucl. Phys. B, 312 (3), 571-588 (1989)

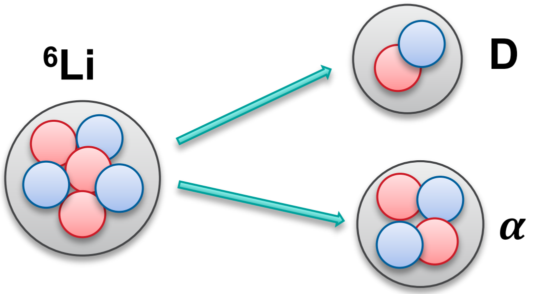
R.L. Jaffe and A. Manohar, Phys. Lett. B, 223 (2), 218-224 (1989)

- Polarized Lithium-7 (spin-3/2)
  - Polarized EMC effect

I.C. Cloët, W. Bentz, A.W. Thomas, **Phys. Lett. B 642, 210-217 (2006)**

Polarized Lithium-6 Source

Tensor Polarization of a Spin-1 Nucleus



- Richer spin structure from the spin-1 nucleus
  - Additional structure function from inclusive DIS: $\boldsymbol{b_1}, \boldsymbol{b_2}, b_3$, and b_4

    Leading twist, Callan-Gross-like relation

  - Reference study to polarized Deuteron measurements

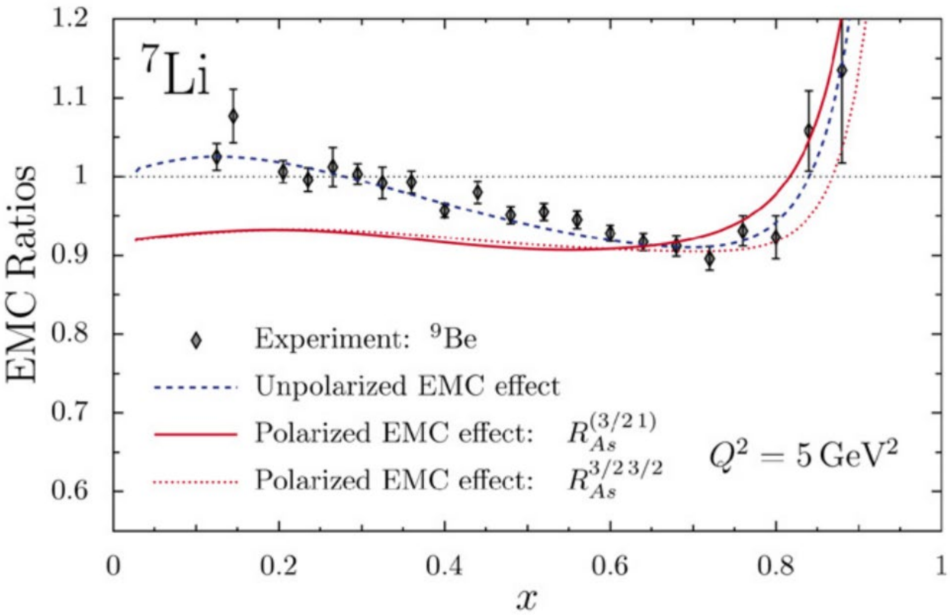
    HERMES, JLab E12-13-011 (approved), and future EIC with polarized D source

- Tensor-polarized gluon distribution
  - Vector/tensor asymmetries measurements
  - Access gluon helicity PDFs and gluon Sivers functions

Polarized EMC Effects

Test the Theoretical Prediction with Polarized ^{7}Li

- Large polarized EMC effects predicted at small x from models
  - ^{7}Li, ^{11}B, ^{15}N, and ^{27}Al
  - Significant medium modification to the spin structure function
  - Awaits for experimental inputs with polarized light nuclei target/source
  - JLab Proposal PR12-14-001
  - Ongoing study with EIC kinematics

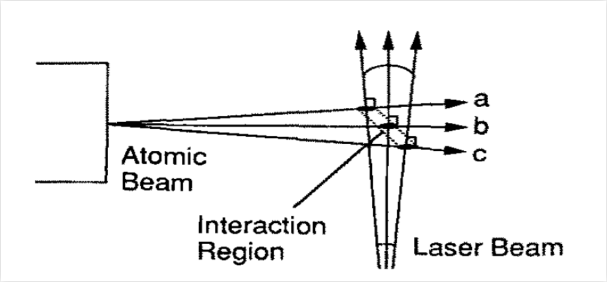


I.C. Cloët, W. Bentz, A.W. Thomas, Phys. Lett. B 642, 210-217 (2006)

Techniques to Produce Polarized Lithium Beams

Previous Polarized Lithium Ion Sources

Polarized ^{6}Li and ^{7}Li Sources at 80s/90s



- The idea was realized in 80s/90s
  - University of Wisconsin, Madison

G.S. Masson, T. Wise, P.A. Quin, W. Haeberli, NIM A242, 196-200 (1986)

  - Florida State University (OPPLIS)

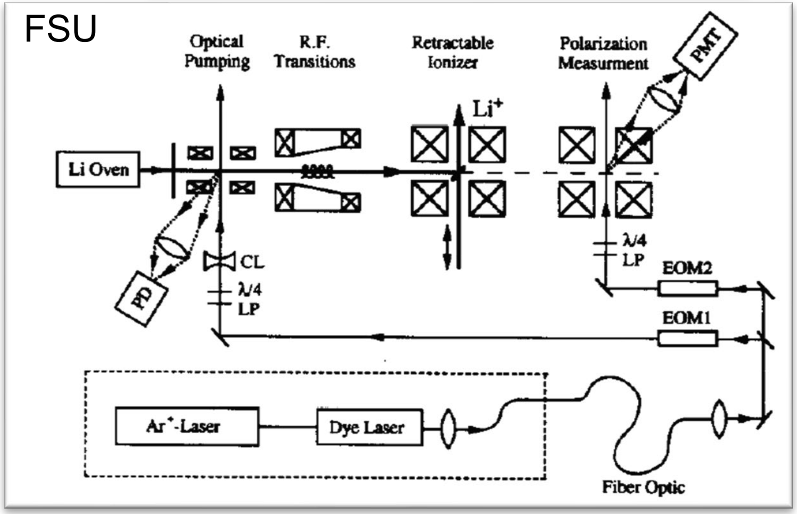
E.G. Myers, A.J. Mendez, B.G. Schmidt, K.W. Kemper, P.L. Kerr, E.L. Reber, NIM B79, 701-704 (1993)

  - HD-MPI (Heidelberg MP tandem)

D. Krämer et al., Nuclear Instruments and Methods in Physics Research 220 (1984) 123-132.

H. Jänsch et al., Nuclear Instruments and Methods in Physics Research A254 (1987) 7-12.

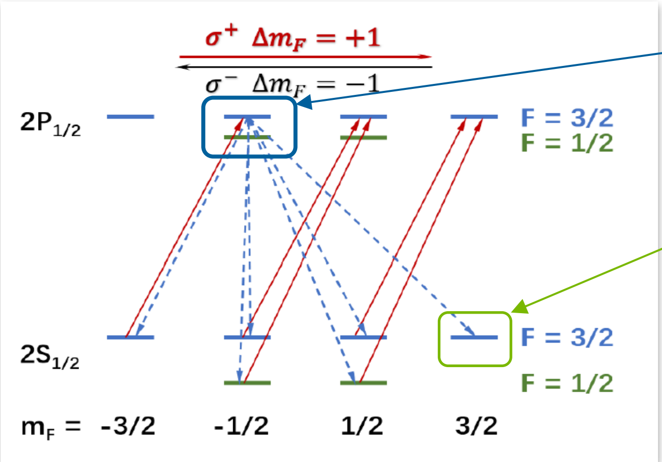
- Polarization techniques
  - Stern-Gerlach system
  - Optical pumping



Optical Pumping of Lithium

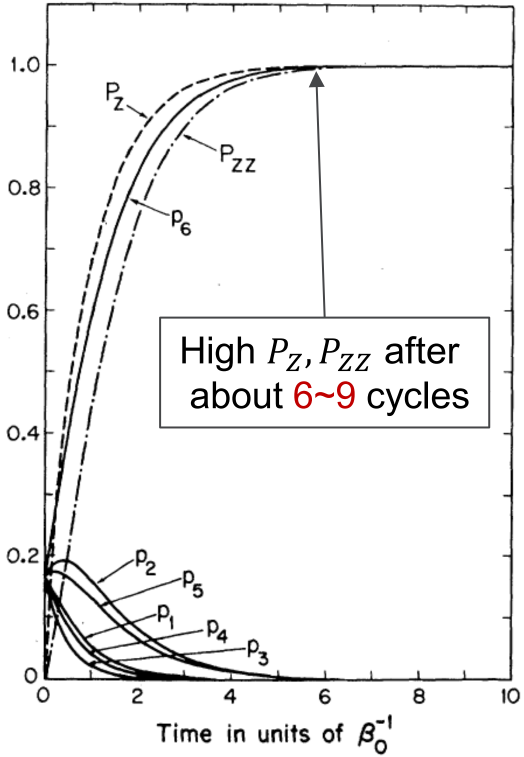
Nuclear vector pol.: $P_Z = N_1 - N_{-1}$
Nuclear tensor pol.: $P_{ZZ} = 1 - 3N_0$

- Polarize lithium atom beam
  - With laser at ≈671 nm
  - High polarization achieved with the laser power of about 30~35 mW



For simplicity, only showing decays from this state

Survived state after many cycles

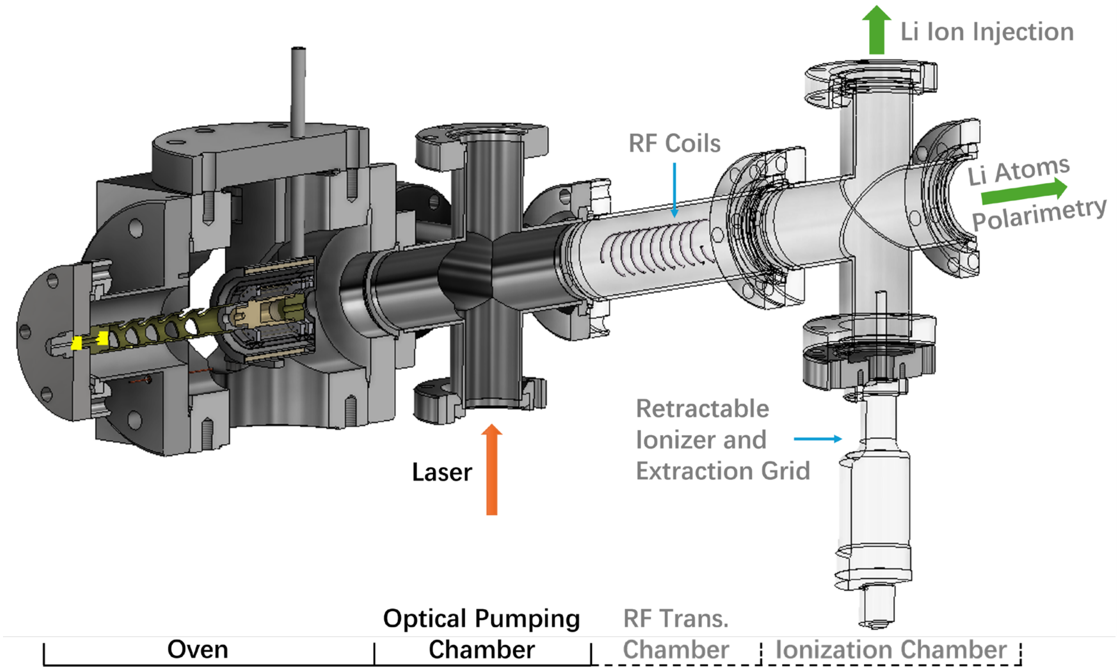


High P_Z, P_{ZZ} after about 6~9 cycles

L.W. Anderson, G.A. Nimmo, **Phys. Rev. Lett. 42, 1520 (1979)**

Proposed Polarized Lithium Sources for EIC

- Development of polarized ^{6}Li and ^{7}Li sources at Argonne
  - Optical pumping using modern solid-state lasers



Development of Polarized Lithium Sources at Argonne

Collobaration between ANL and UKY

A Growing Collaboration

- Collaboration since 2022/09
- Supported by Argonne LDRD, future support from DOE EPSCoR

Argonne National Laboratory

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Wolfgang Korsch
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Upcoming Graduate Student

Project Goals and Milestones

- **GOAL (Phase 1)**: Produce polarized Lithium-ion beam and precisely determine its polarization
- **MILESTONES:**

Done ✓ Build the system and produce Lithium vapor beam
Vaporizing oven, convergence-divergence nozzle, and vacuum system were built in this summer

Prog. ➢ Study and optimize the beam profile with benchmarked simulation
Two sets of hot-wire beam profile measurements were implemented, profile measurement data were taken and being studied with simulation

Plan ☐ Polarize Lithium vapor beam and implement the Breit-Rabbi Polarimeter
Acquired a single-frequency tunable laser at 671 nm (25 mW) + future booster
Polarimeter design optimized by simulations

- **Phase 2:** Study the injection into the EBIS

Current Experimental Setup

RGA

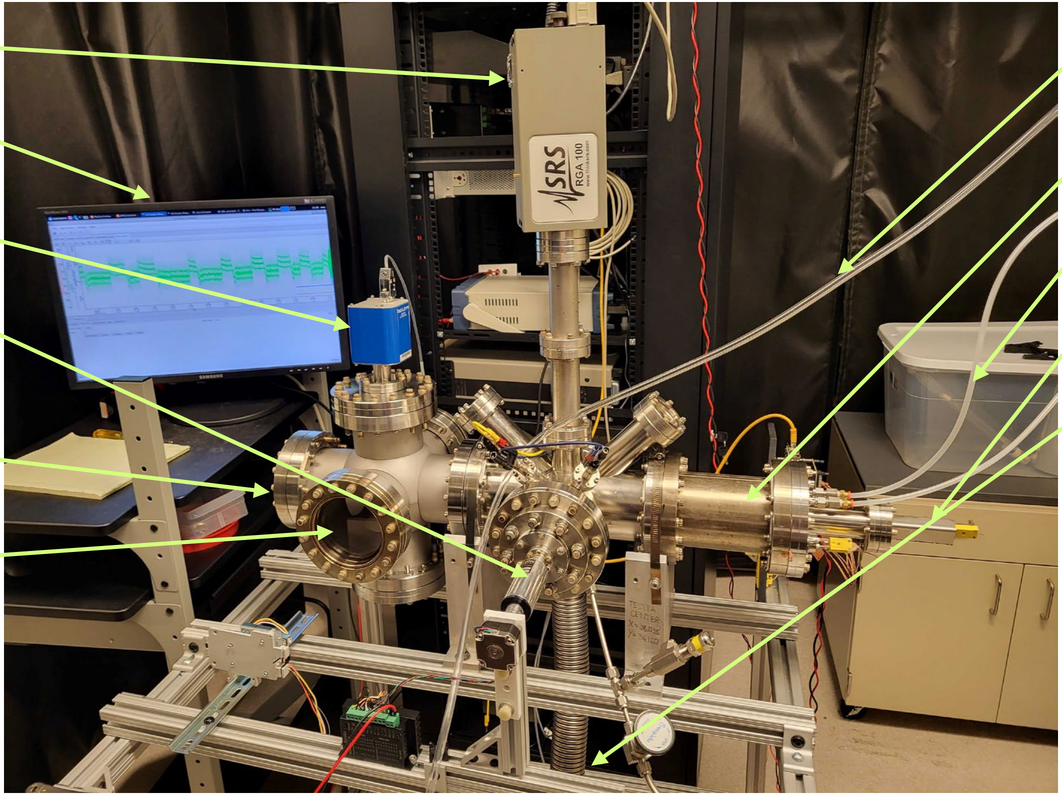
Controlling computer (with EPICS)

Vacuum gauge

1st wire-scanner

End viewport (visual measurement)

2nd wire-scanner (will be installed)



CO_2 Gas line (flushing chamber)

Oven and nozzle

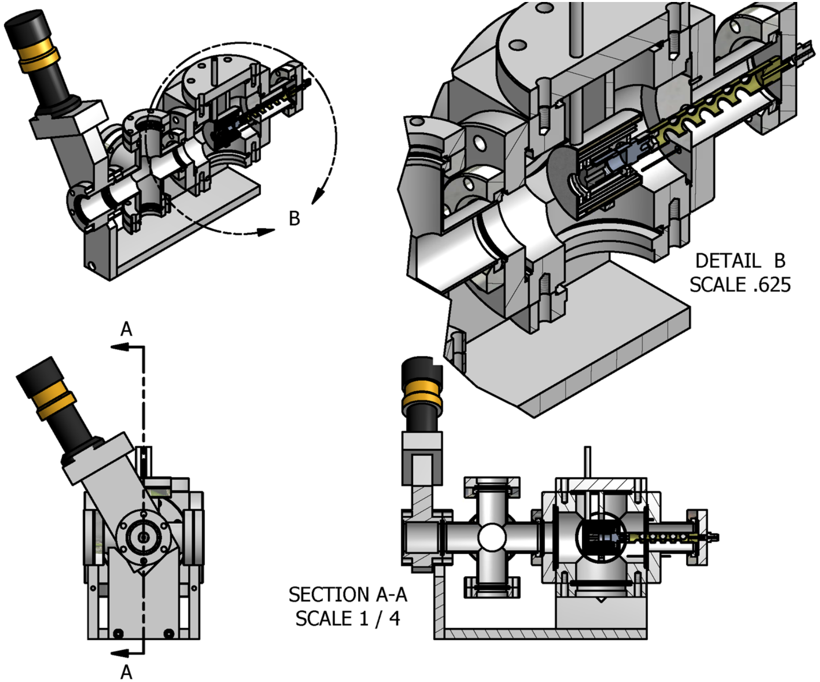
Water lines

Temperature sensor

Vacuum pump

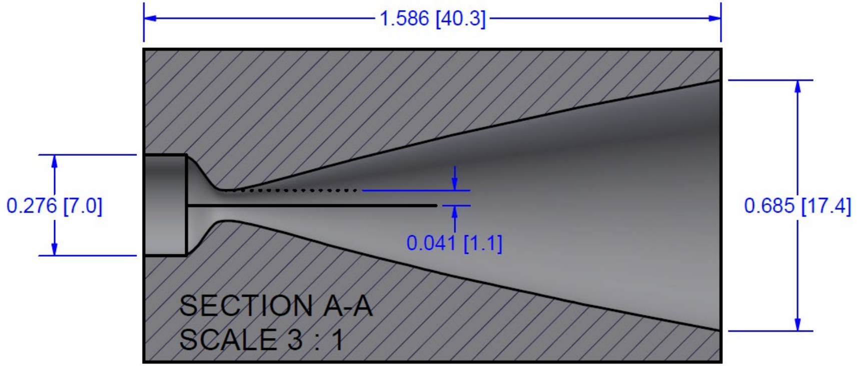
Vaporizing Oven Design

- Oven operates at around 850℃
  - ^{6}Li vapor pressure ~7.6 mbar
  - Expected ^{6}Li ion current $> 0.2\ \mu A$, $\sim 10^{12}$ ions/sec
- Isolated crucible with a water-cooling shell
  - Crucible volume: ~2 cm^3
  - Currently testing with Lithium Hydride (LiH)
  - Planned for replacement with pure Lithium
- Refilling feed-through

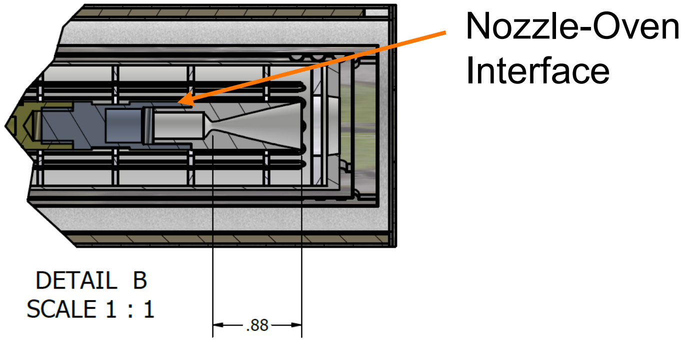


Convergence-Divergence Nozzle

- De Laval Nozzle
  - Replaceable
  - Fully contained in the heating filaments (prevent for clogging)
  - Convert the Lithium vapor into a non-divergent beam

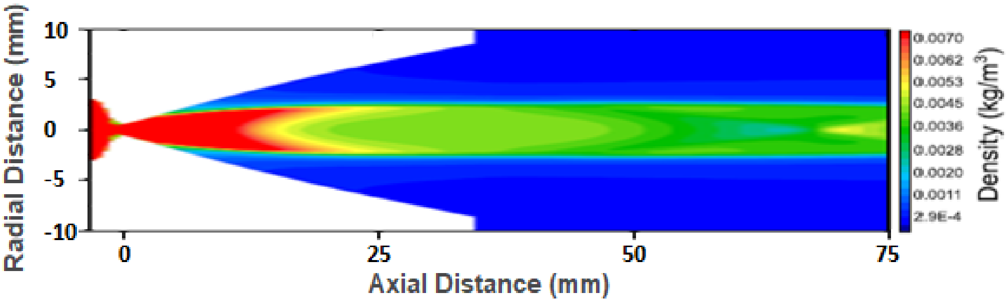


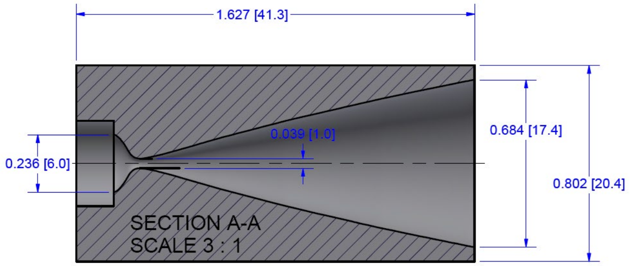
- Inner contour design
  - 2-mm-diameter throat
  - Initial design from Computational Fluid Dynamics (CFD) simulation
  - Will be further optimized after benchmarking simulation with real profile measurements

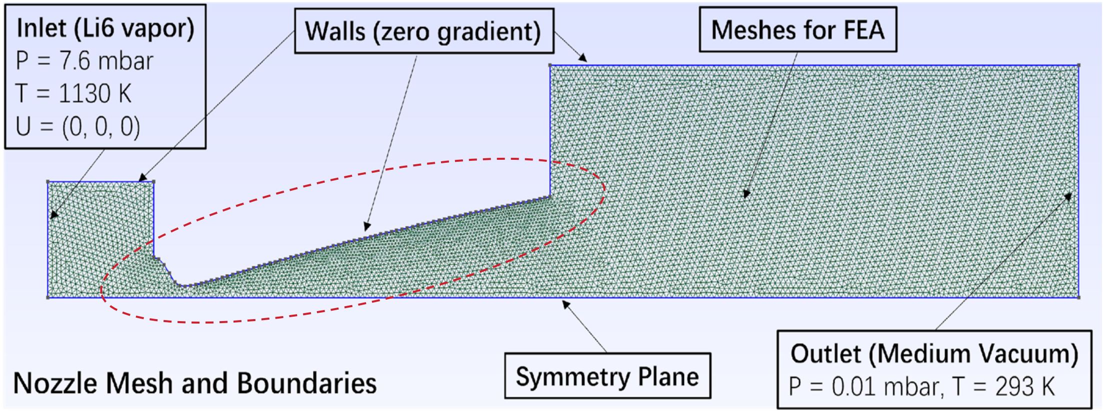


CFD Simulation for Nozzles

- Need a Non-divergent beam
  - Initial design with CFD simulation
  - benchmarking with real data
  - Plan to re-optimize the design





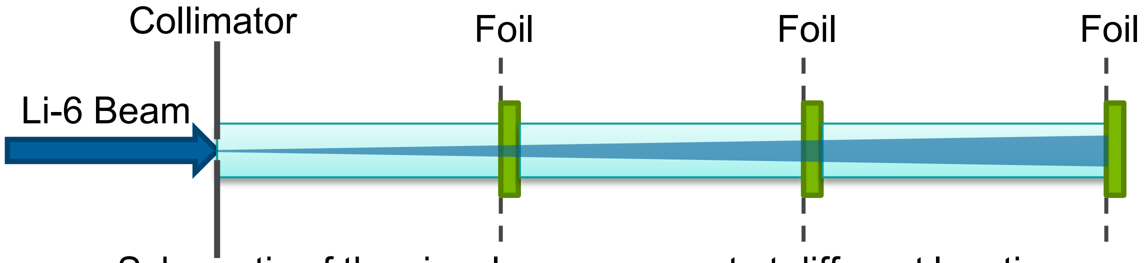


Beam Profile Measurement

- Benchmark the simulation
- Design and preparation for the measurements
  - Visual measurement: transverse deposit of Li-6 beam
  - Wire scan measurement
    - Ionizer-wire scan (thermal ionization)
    - Laser-wire scan

Appl. Opt. 49, 6816-6823 (2010)

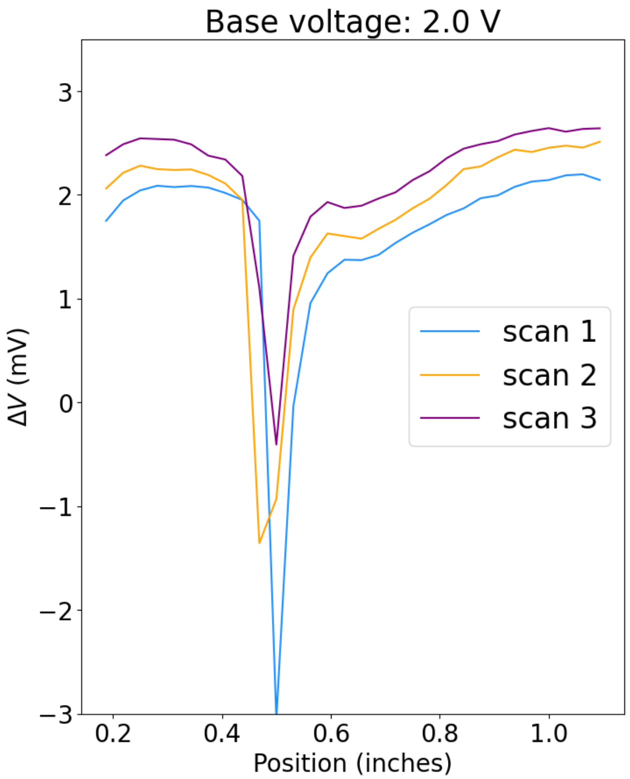
Nuclear Instruments and Methods in Physics Research A242 (1986) 196-200



Schematic of the visual measurement at different locations

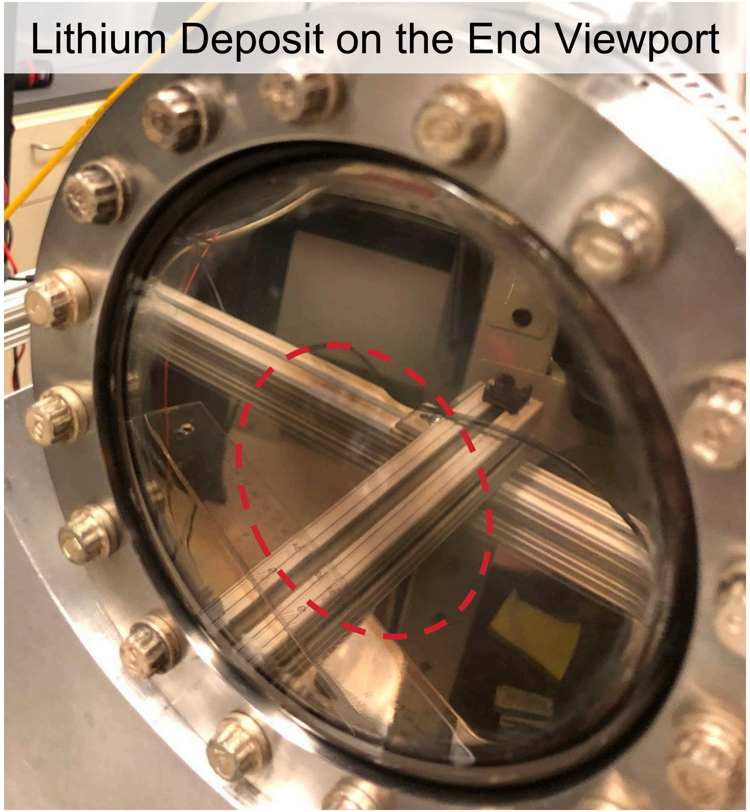
Rhenium wire used in the measurement

Beam Profile Measurement



Wire-scan measurement

Visual measurement



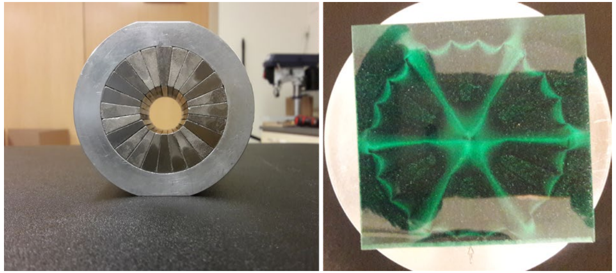
Progress of the Development

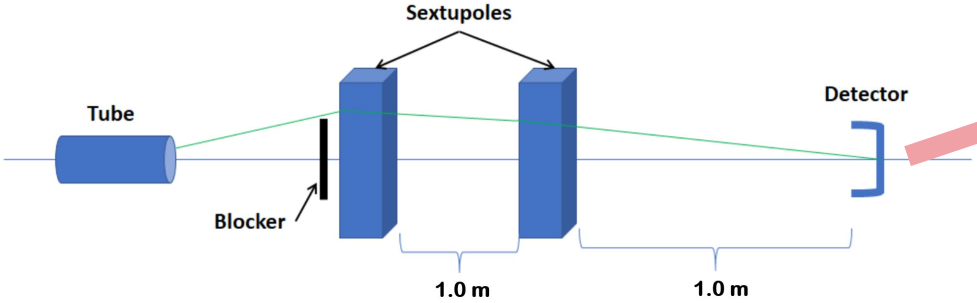
- Vacuum system, oven, and nozzle were built
  - ✓ Dull nozzle (straight hole) + De Laval nozzle
  - ✓ Stable oven operation at 850℃
  - ✓ System operates at around $10^{-5} - 10^{-6}$ torr
  - ✓ Lithium observed at RGA
  - ✓ Lithium deposit observed at the end viewport

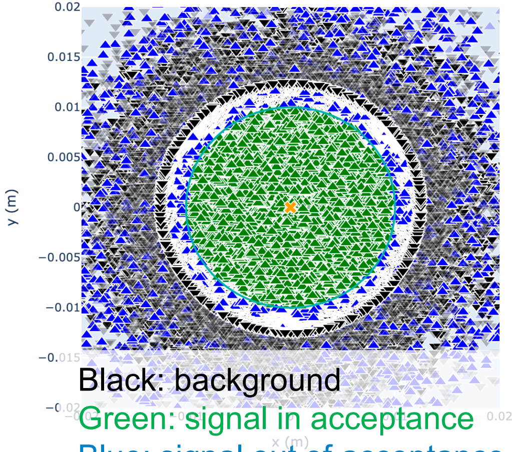
- Hot-wire scan measurement
  - ✓ First set of measurement close to the nozzle exit
  - ✓ The second set will be at about 6 inches downstream
  - ✓ Test measurements (empty or with Lithium) of the first set
  - ➢ Analyzing the data and benchmarking simulations

Future: Polarization, Ionization, and Polarimetry

- Polarization: optical pumping
- Ionization: hot oxygenated Tungsten surface
- Breit-Rabbi polarimeter
  - Precision polarization measurement
  - Simulation package (Pytomic) developed from ANL LDRD







Black: background
Green: signal in acceptance
Blue: signal out of acceptance

Summary

- We are developing polarized ^{6}Li and ^{7}Li sources for EIC
  - Collaborated work between ANL and UKY (may grow in the future)
  - Rich physics program with the new polarized ions beyond A=3
  - Revival of old techniques with modern technologies

- Current status of the development
  - Major parts of the system were constructed and assembled
  - Lithium vapor beam produced
  - Beam profile measurements conducted
  - Simulation is being benchmarked and further optimization is expected
  - Plan to start the optical pumping(solid-state laser at 671 nm acquired)

THANK YOU!

This work is supported by the ANL LDRD Project 2023-0157 and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357. Future support from DOE EPSCoR (Award Number: DE-SC0025511).

Lithium 6 Vapor Pressure

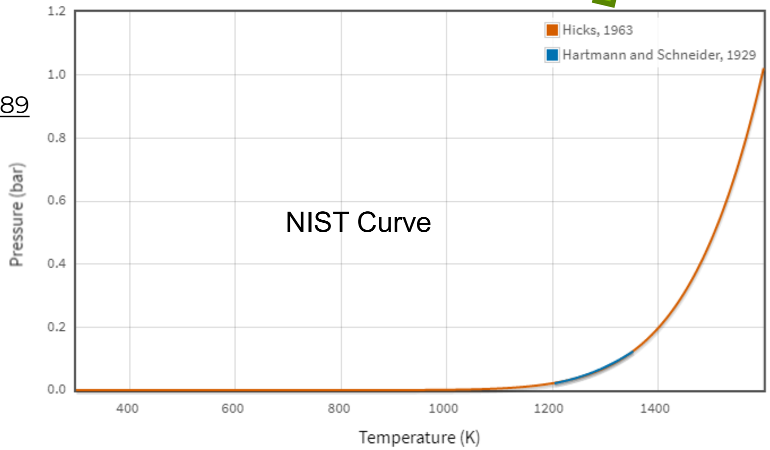
- A gram of Lithium-6 should be more than enough
  - Semi-confined in the oven volume ~0.9 cubic cm
  - Assumed **ideal gas law**, **1100 K** and **1 bar -> 0.06 mg** of Li-6
  - Of course we are continuously sending out Li-6 through the nozzle
  - Fluid dynamics -> values of P, T, N are difficult to estimate

Two extreme cases

- Lithium vapor pressure

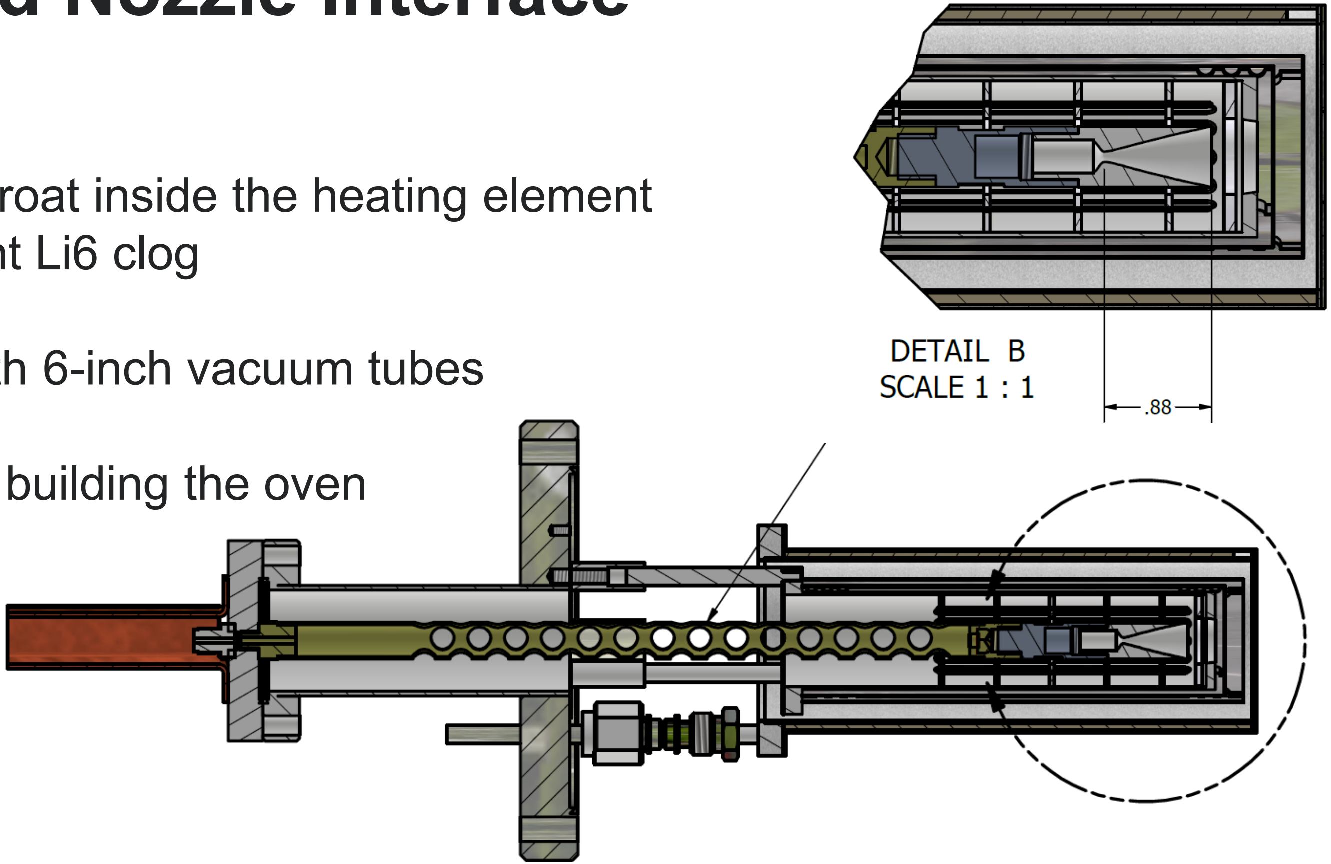
  J. Chem. Phys. **38**, 1873 (1963); https://doi.org/10.1063/1.1733889

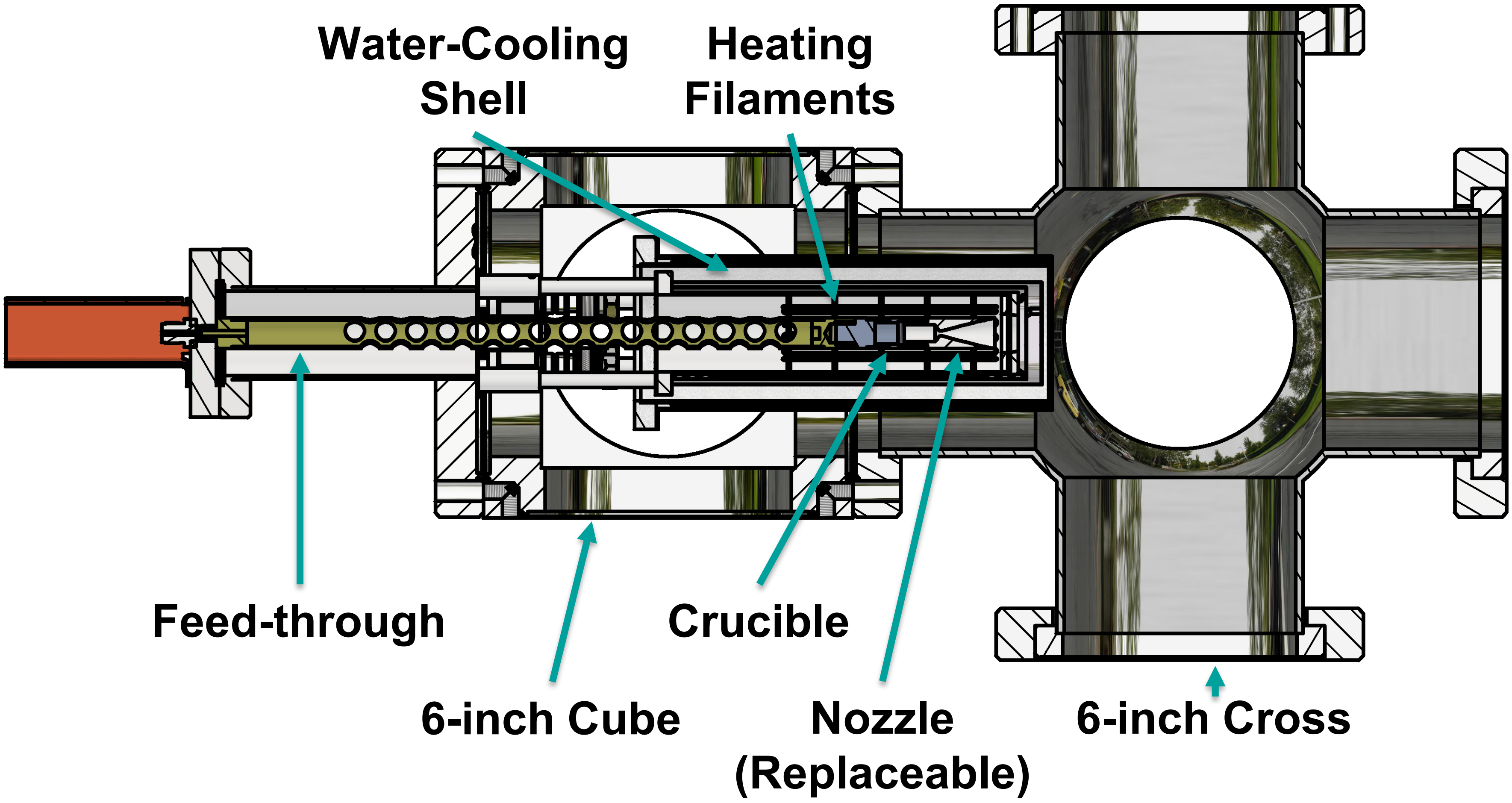
  - **Isothermal expansion**
  - 800℃ (1073 K) – 3.5 mbar
  - 850℃ (1123 K) – 7.6 mbar
  - 1174℃ (1447 K) – 302 mbar
  - 1324℃ (1597 K) – 1 bar



Oven and Nozzle Interface

- Nozzle throat inside the heating element
  - Prevent Li6 clog
- Mount with 6-inch vacuum tubes
- Currently building the oven




Water-Cooling Shell
Heating Filaments
Feed-through
Crucible
6-inch Cube
Nozzle (Replaceable)
6-inch Cross