Polarized ^{3}He in High Magnetic Fields

李夏卿
山东大学（青岛）

第一届介子束流物理研讨会
兰州大学
2024年12月27-30日

Outline

- Polarized ^3He and nucleon spin structures
- Optical pumping techniques for polarized ^3He gas
  - Spin exchange optical pumping (SEOP)
  - Metastability exchange optical pumping (MEOP)
- Polarized ^3He in high magnetic fields using MEOP
  - BNL-MIT for EIC polarized $^3He^{++}$ beam
  - JLab-MIT for CLAS12 polarized ^3He target
- Summary

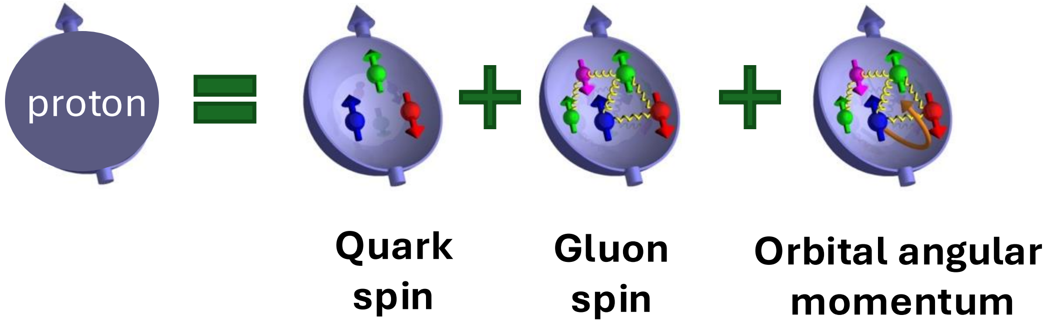
The Spin of the Nucleon Remains Puzzling

- Proton spin crisis since the EMC experiment in 1980's
- One of the major tasks of hadronic physics studies is to understand the nucleon spin structures

Leading twist TMDs

Nucleon Polarization \ Quark Polarization	U	L	T
U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity (worm-gear)
T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity; $h_{1T}^\perp$ pretzelosity

Spin decomposition



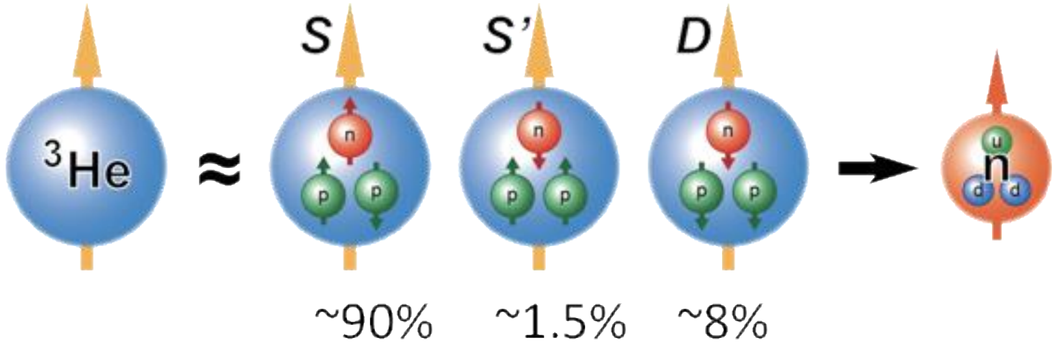
$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

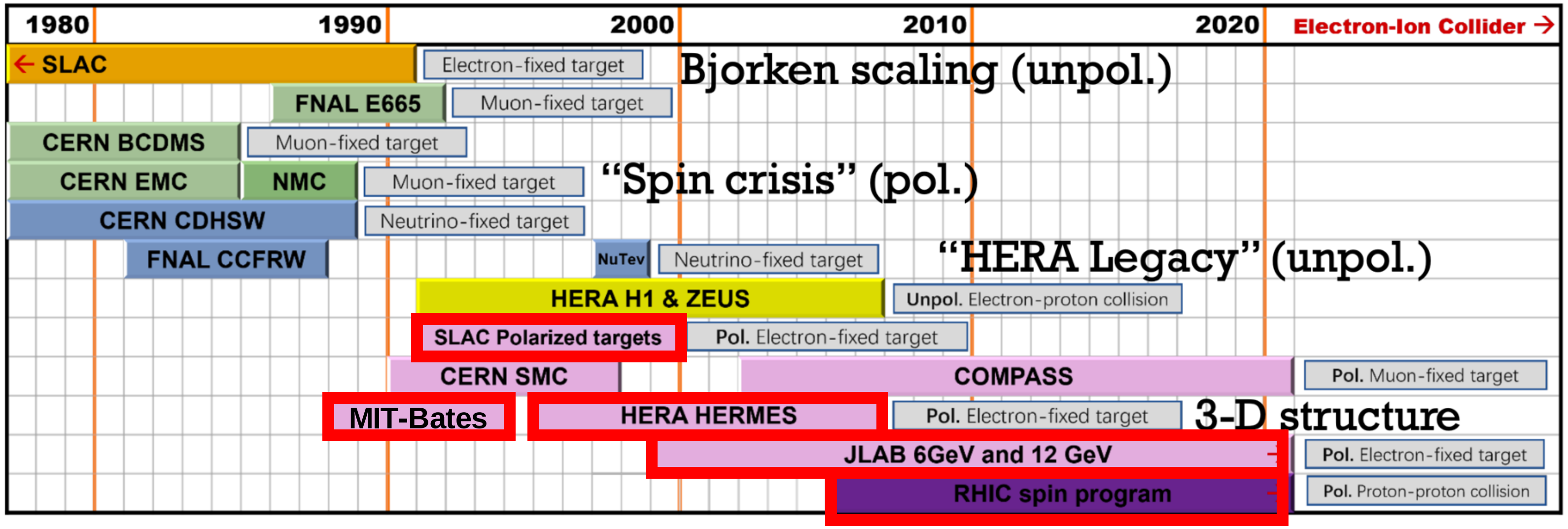
- Requires polarized nucleon targets/beams
  - Polarized proton: H, NH_3
  - Polarized neutron: ^3He, ND_3, ...

Polarized ^{3}He: Effective Polarized Neutron

- ^{3}He nucleus: *S* state ~90%
  - 2 proton spins anti-parallel
  - nucleus spin carried by the neutron



- Polarized ^{3}He for lepton scattering experiments



Two **optical pumping** techniques to polarize ^{3}He

- **Spin exchange**
  - SLAC
  - JLab
  - TUNL
- **Metastability exchange**
  - MIT-Bates
  - HERMES
  - MAMI
  - (JLab)
  - (RHIC)

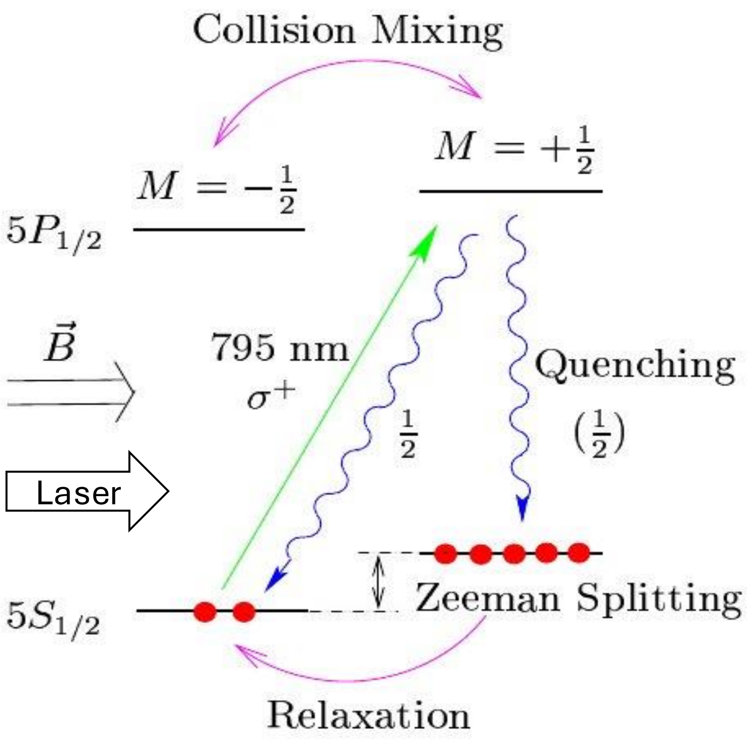
Spin Exchange Optical Pumping (SEOP)

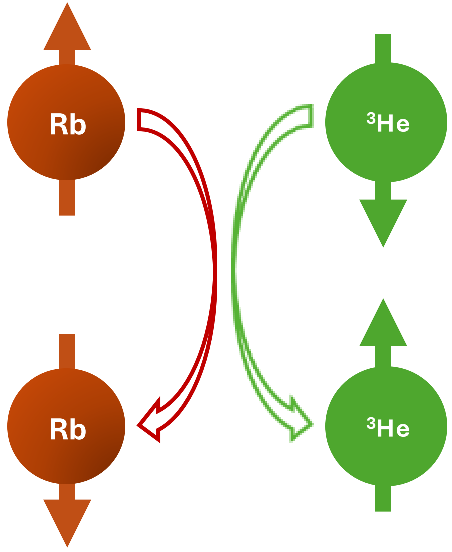
- Optically pump alkali-metal atoms in ^{3}He gas mixture
- Spin exchange between alkali electrons and ^{3}He nuclei
- Need oven (~475 K)
- Pro: large pressure range (1 to 13 bar)
- Con: low pumping rate

Application:

✓ **MIT-Bates**
✓ **TRIUMF**
✓ **SLAC**
✓ **TUNL**
✓ **JLab Hall A/C**
  - 13 experiments for 6 GeV
  - 7 experiments approved for 12 GeV

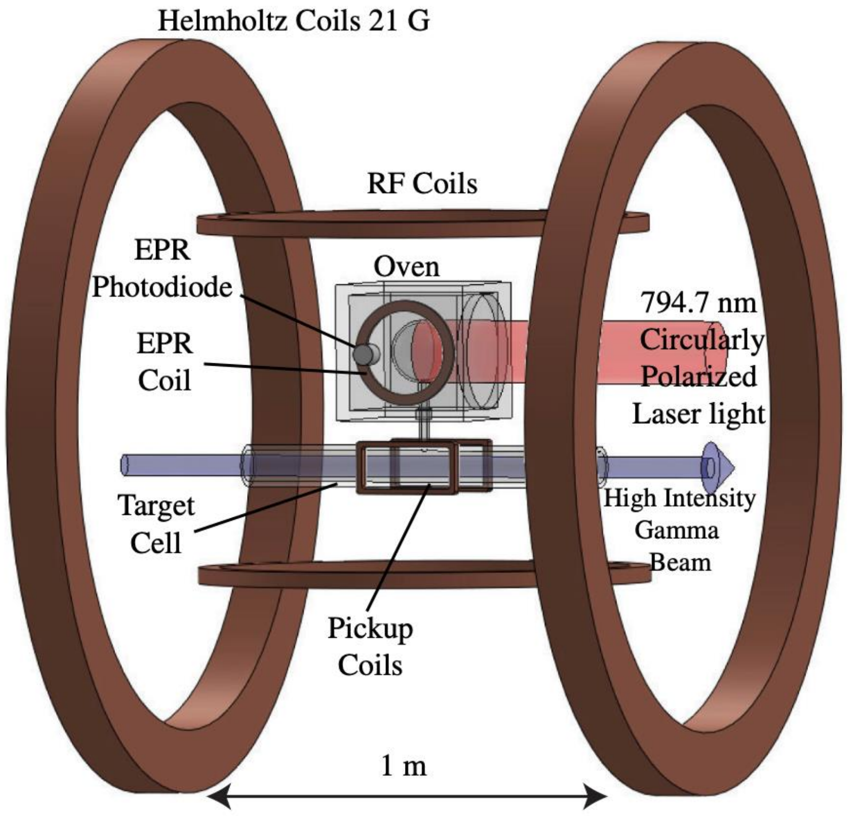
Bouchiat, Carver, and Varnum, PRL 5, 373 (1960)





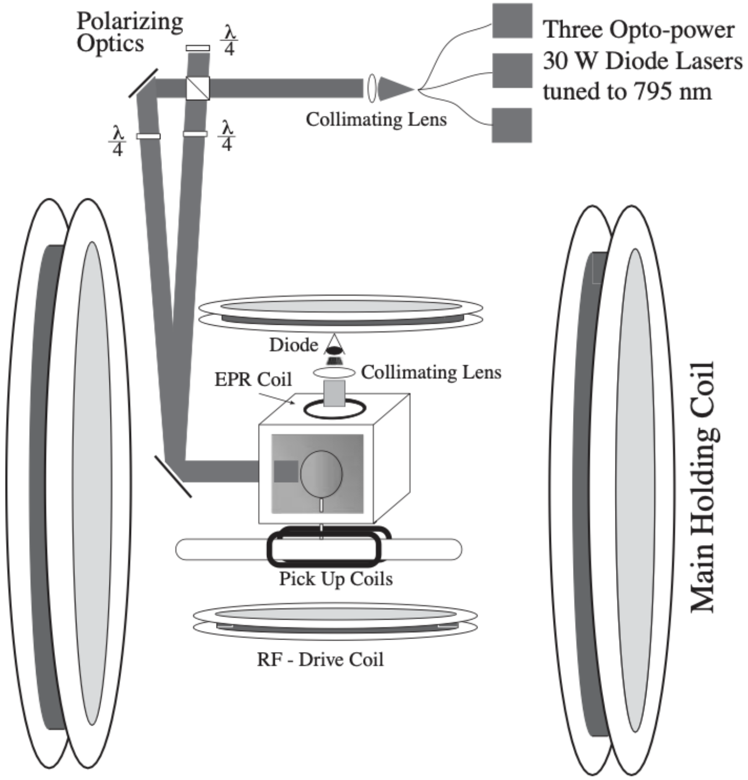
Polarimetry Methods for SEOP

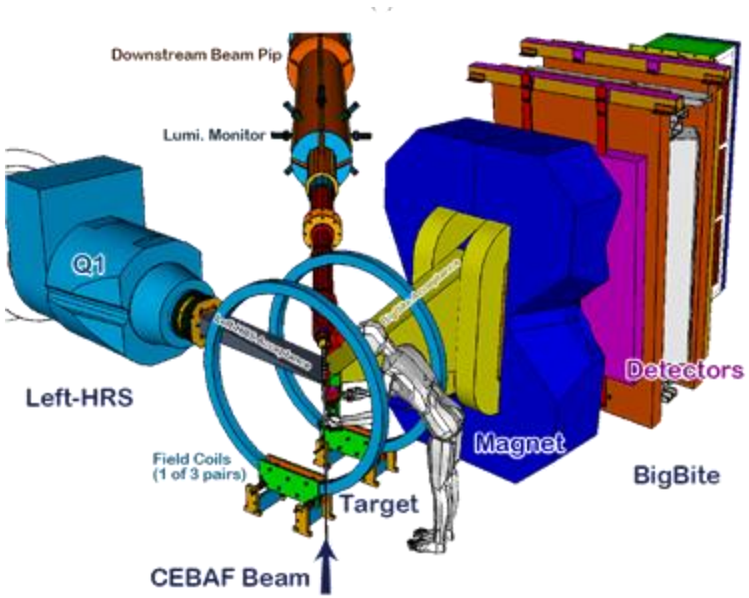
- Nuclear Magnetic Resonance
  - ➢Adiabatic fast passage
    - transverse RF signal with swept frequency
    - ^{3}He spin flipped at Larmar frequency
    - pick up the spin precessing signal
  - ➢Free induction decay
    - transverse RF pulse at Larmar frequency
    - ^{3}He spin tilted by a small angle
    - measure the transverse relaxation time of FID
- Electron Paramagnetic Resonance

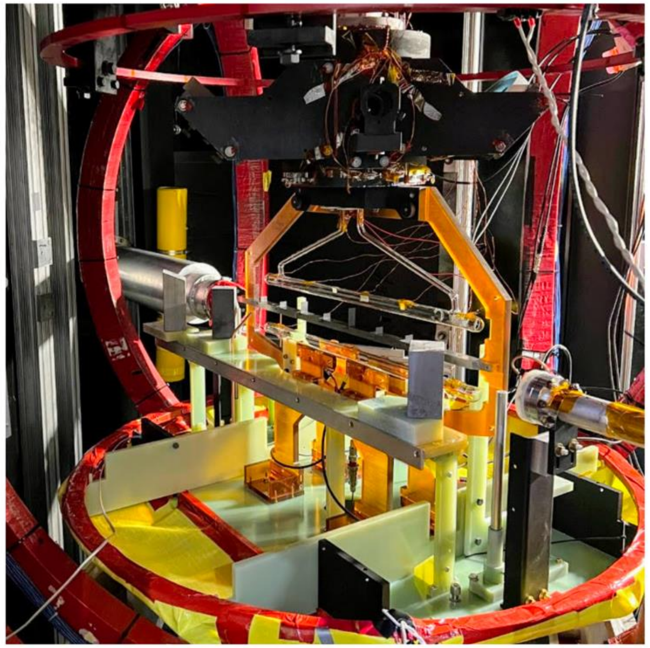


T.R. Gentile *et al.*, Rev. Modern Phys. **89**, 045004 (2017)

Polarized ^{3}He Targets at JLab Hall A

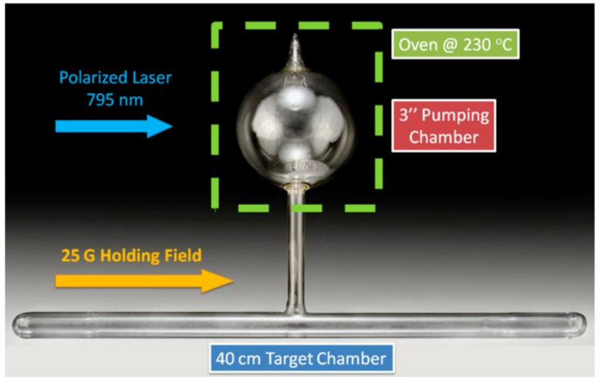


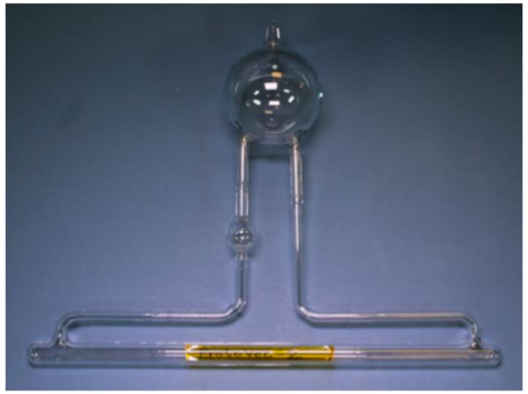




^{3}He nuclear polarization: 40-50%

J. Alcorn et al., Nucl. Instr. and Meth. A 522, 294 (2004)

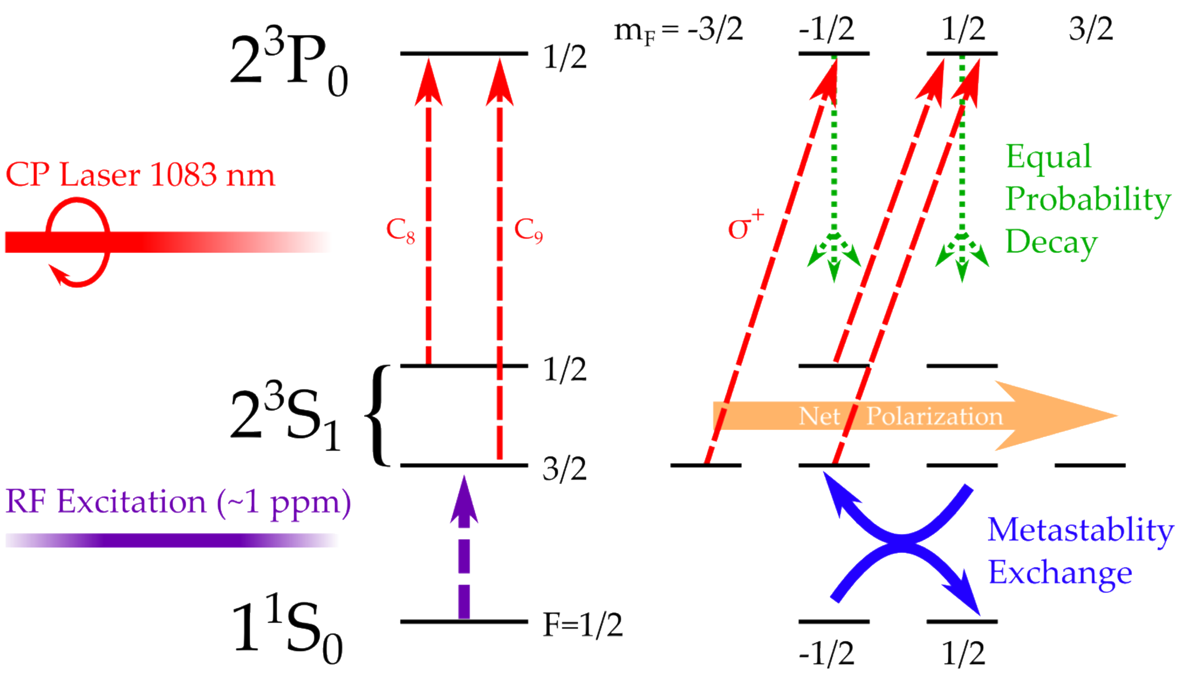




Metastability Exchange Optical Pumping (MEOP)

- Optical pumping of metastable-state (2^3S_1) ^3He
- Spin transferred to ground-state ^3He nuclei via metastability exchange collision and hyperfine coupling
- Room temperature
- Pro: high pumping rate
- Con: limited pressure range (~1 mbar)

Colegrove, Schearer, Walters, PRL 132, 2561 (1963)

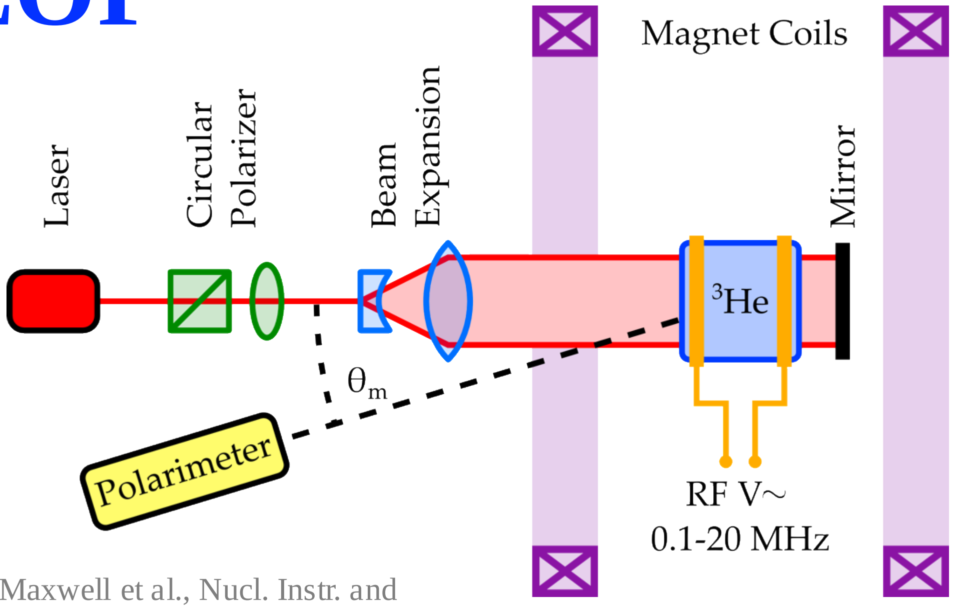


Applications:

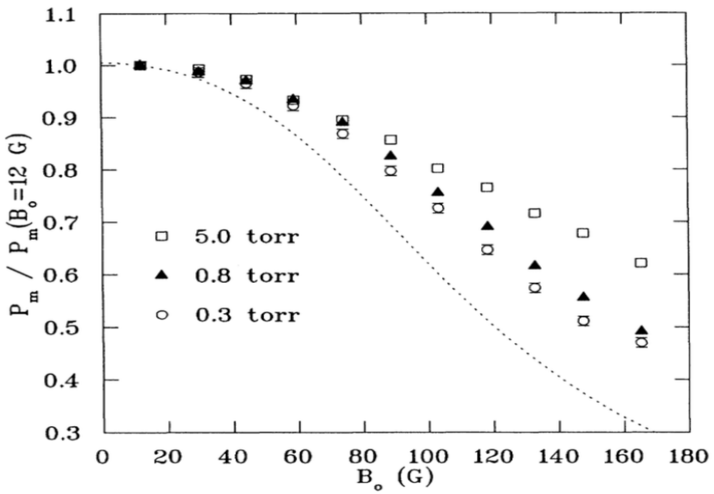
✓ **MIT-Bates** (external target, cryogenic target cell)
✓ **HERMES** (internal target, cryogenic storage cell)
✓ **MAMI** (external target, piston compression)
❑ **JLab CLAS12** (external target in high field, cryogenic, under development)
❑ **RHIC EIC** (polarized ion source in high field, under development)

Polarimetry Method for MEOP

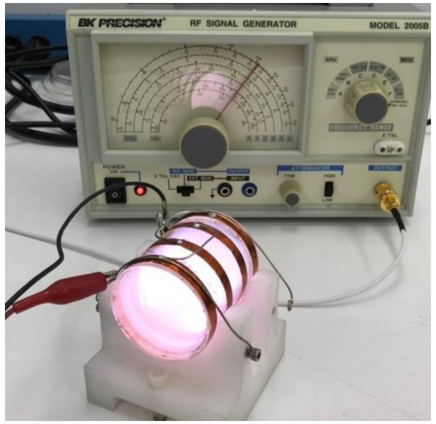
- Measure the degree of circular polarization of the 668 nm discharge light emitted by the metastable-state ^{3}He atoms
- Obtain the electron polarization *P*
- Nuclear polarization P_n determined by applying NMR calibration
- Only work well in low magnetic field



J.D. Maxwell et al., Nucl. Instr. and Meth. A **764,** 215 (2014)



W. Lorenzon et al., Phys. Rev. A 47 (1993) 468-479



Polarized ^{3}He for MIT-Bates 88-02 Experiment

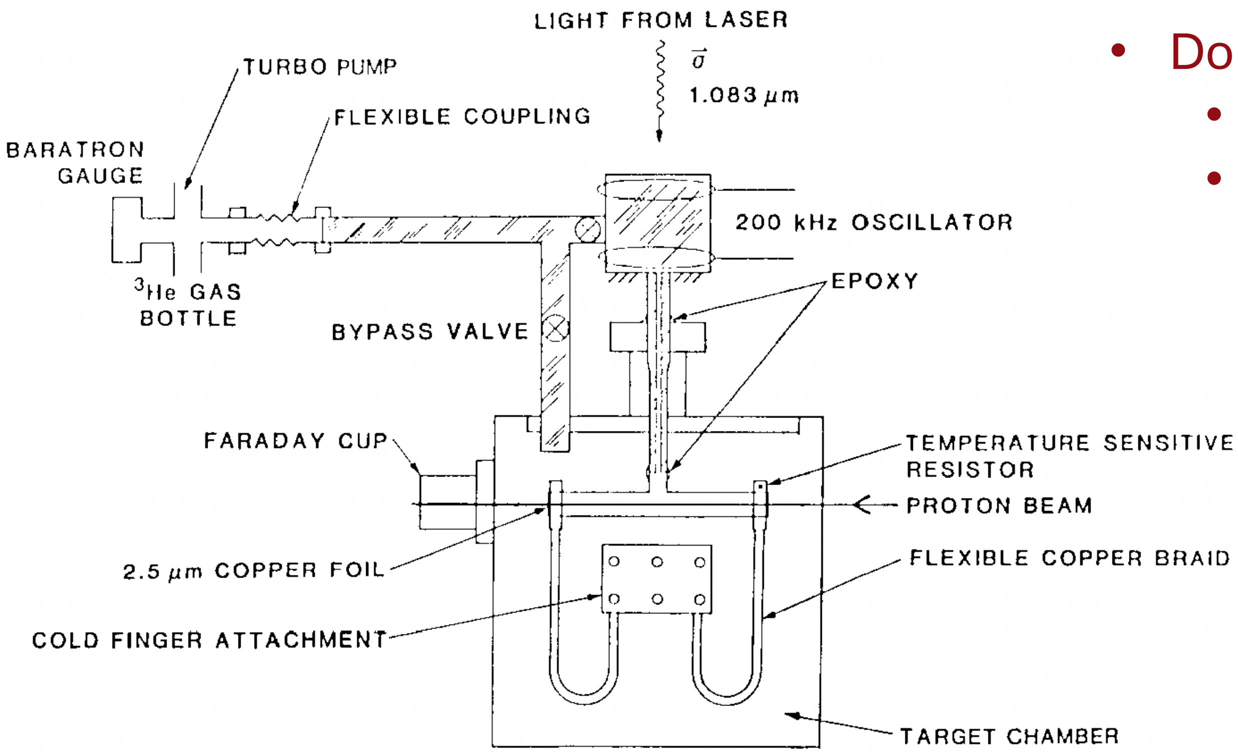
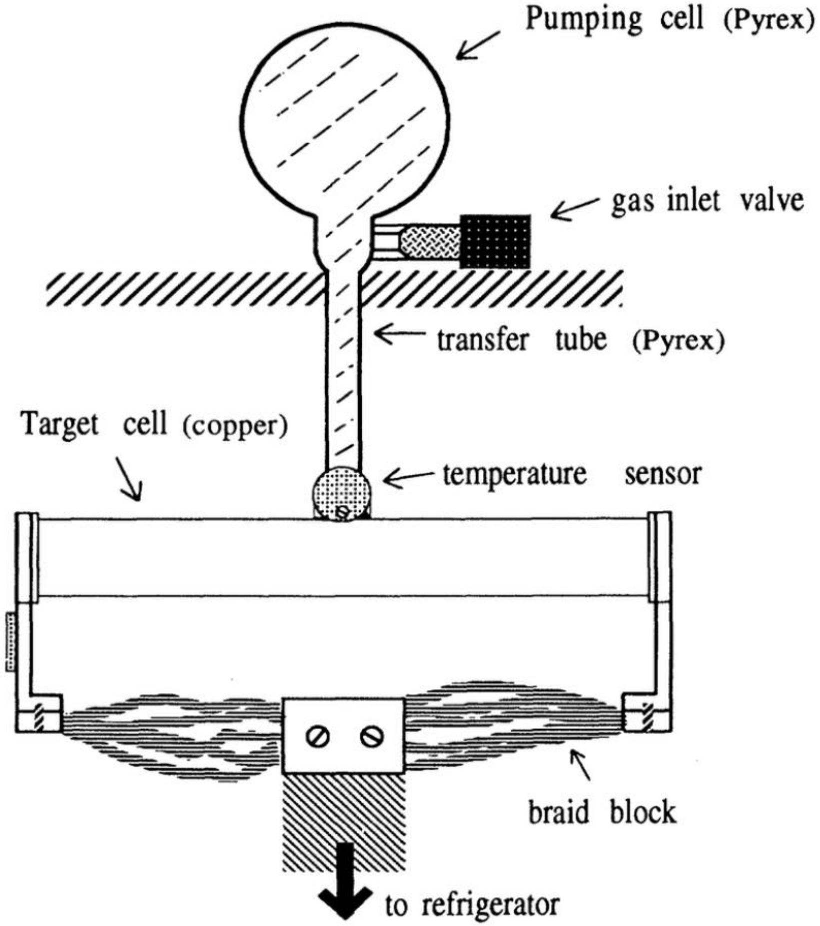


Fig. 3. The target apparatus of the double cell prototype.

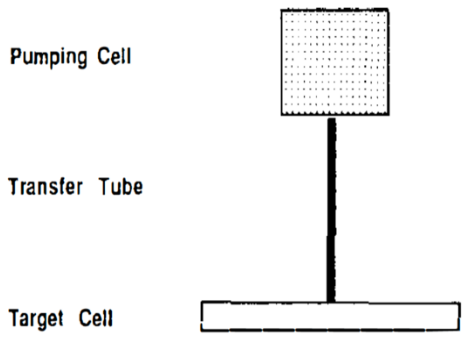
R.G. Milner et al., Nucl. Instr. and Meth. A **274,** 56 (1989)

- Double-cell design
  - Pumping cell: room temperature, 2 mbar
  - Target cell: 17 K, 2 mbar

Polarized ^{3}He for MIT-Bates 88-02 Experiment



- Double-cell design
  - Pumping cell: room temperature, 2 mbar
  - Target cell: 17 K, 2 mbar
- Polarimetry of ^{3}He
  - Polarization measured from pumping cell
  - Well inferred for target cell



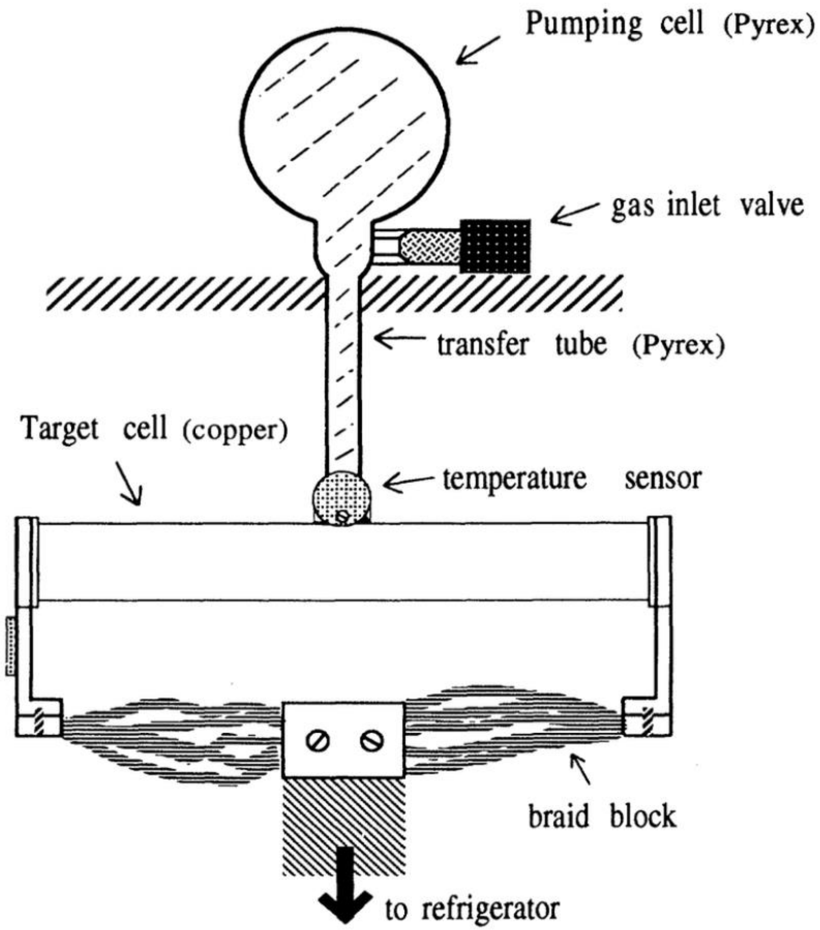
$$\frac{dP_p(t)}{dt} = -\frac{P_p(t)}{\tau_p} + \frac{P_t(t) - P_p(t)}{t_p}$$

$$\frac{dP_t(t)}{dt} = -\frac{P_t(t)}{\tau_t} + \frac{P_p(t) - P_t(t)}{t_t}$$

$$P_p(t) = a_s e^{-t/\tau_s} + a_l e^{-t/\tau_l}$$

C.E. Jones et al., Phys. Rev. C 47 (1993) 110–130

Polarized ^{3}He for MIT-Bates 88-02 Experiment

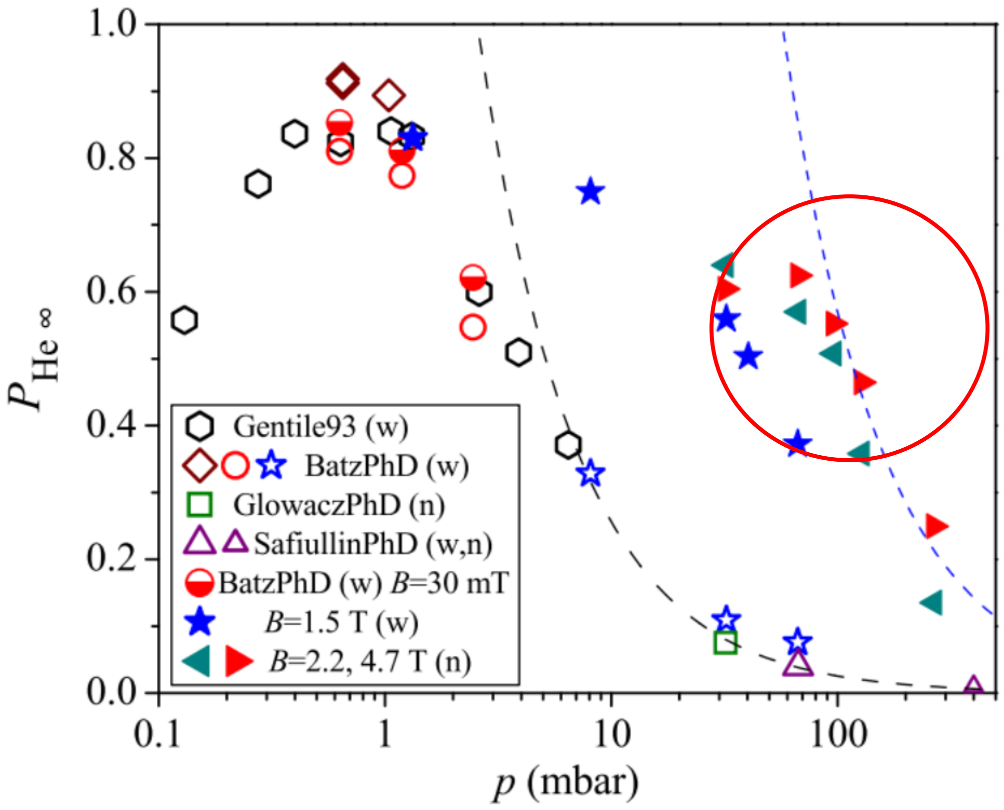


- Double-cell design
  - Pumping cell: room temperature, 2 mbar
  - Target cell: 17 K, 2 mbar
- Polarimetry of ^{3}He
  - Polarization measured from pumping cell
  - Well inferred for target cell
- Target performance:
  - Up to ~40% in-beam polarization
  - 10^2 to 1×10^3 seconds relaxation time

C.E. Jones et al., Phys. Rev. C 47 (1993) 110–130

Path to Polarized ^{3}He in High Magnetic Field

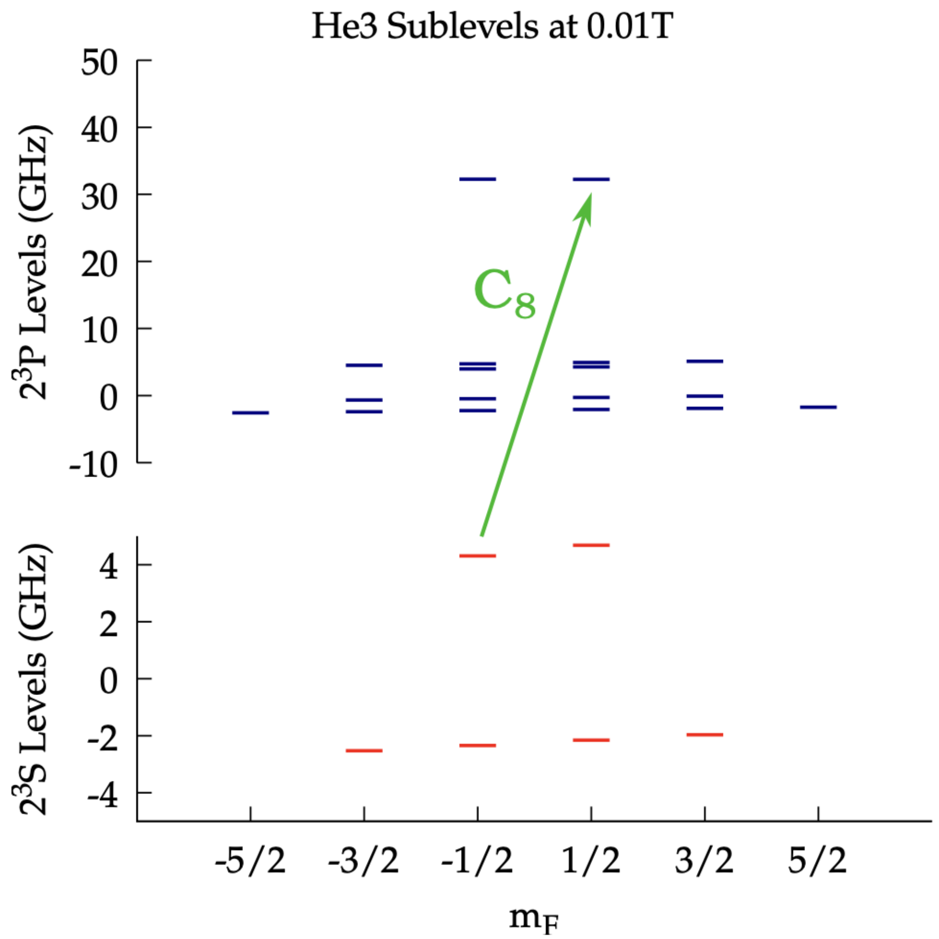
- Historically, ^{3}He could not be polarized in high field…
  - SEOP: increasing wall relaxation
  - MEOP: weak hyperfine coupling
- Until recent high-field MEOP development
  - Motivated by NMR medical imaging demand (Kastler Brossel Lab, Paris)
  - Found MEOP effective at higher pressures
  - Successfully produced nearly 60% polarization at 100 mbar and 4.7 T

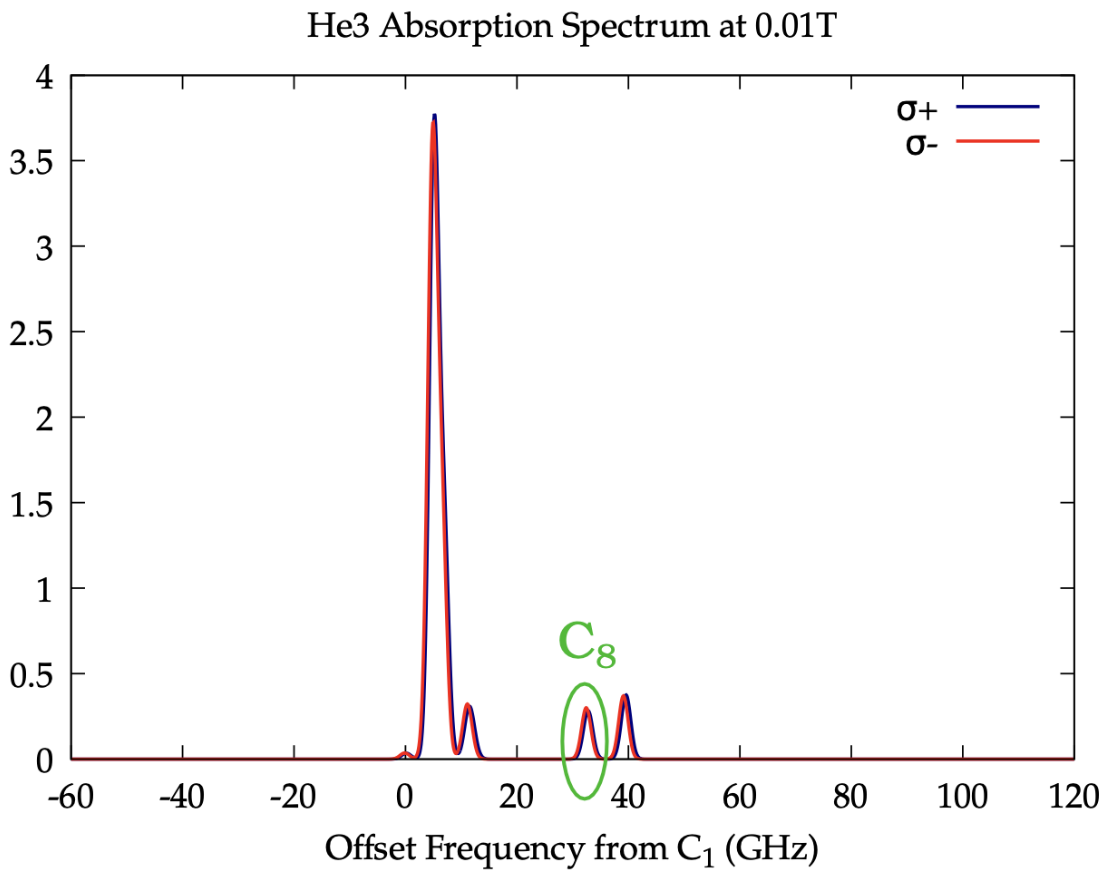


Nikiel-Osuchowska *et al.*, Eur. Phys. J. D **67**, 200 (2013)
T.R. Gentile *et al.*, Rev. Modern Phys. **89**, 045004 (2017)

- ○ Open symbols: low field (1 – 3 mT)
- ▪ Filled symbols: high field (1.5 – 4.7 T)

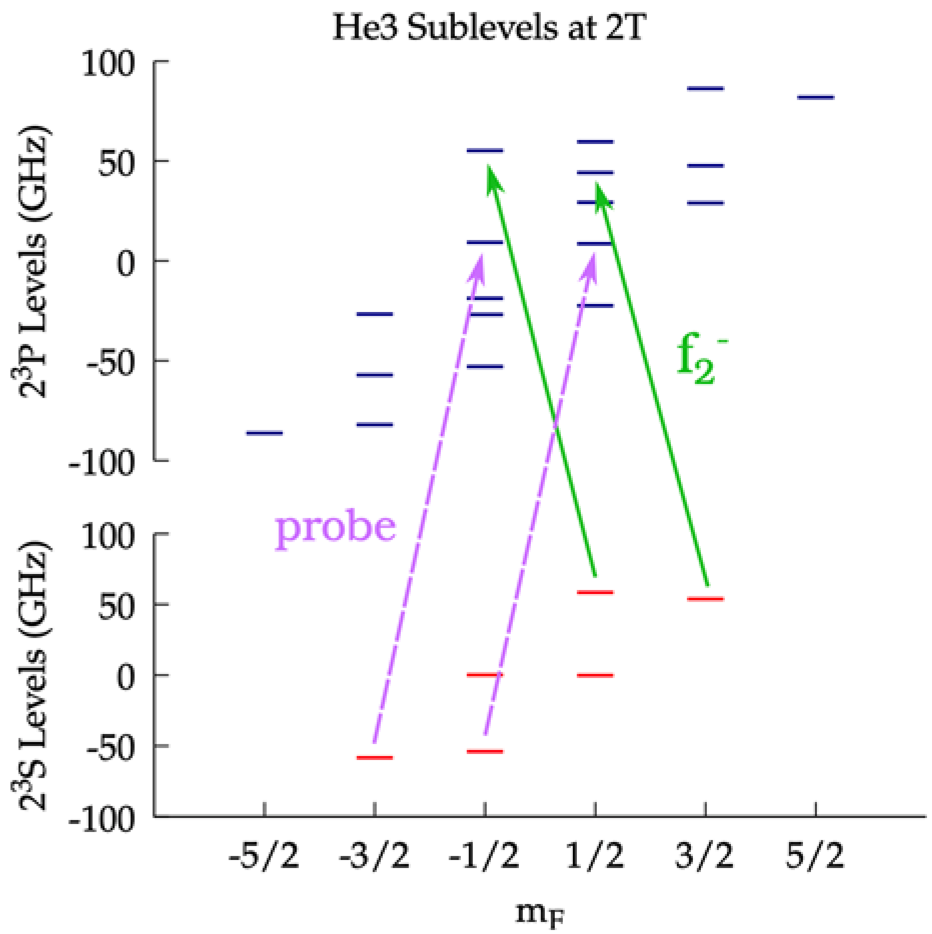
^{3}He Transitions at Low Field

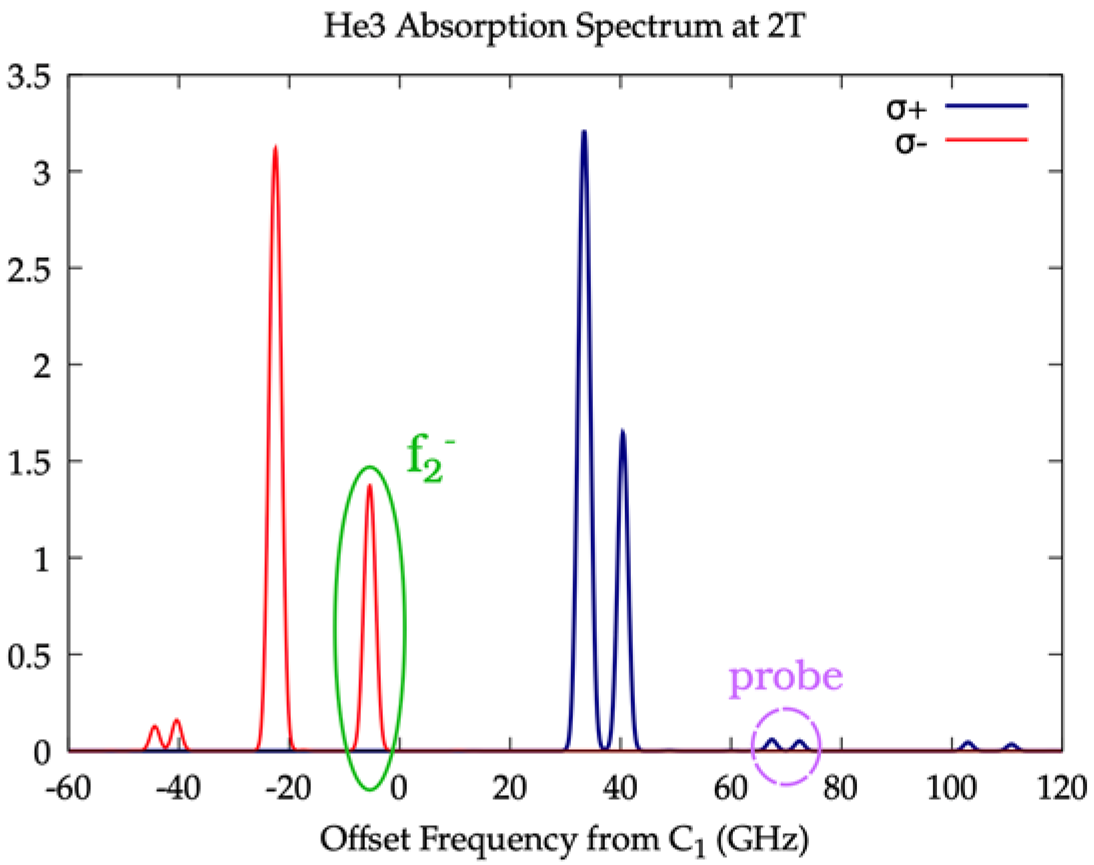




Figures based on Courtade (2002), Nikiel (2013), from calculation by Nacher. Figures made by J. Maxwell.

^{3}He Transitions at High Field

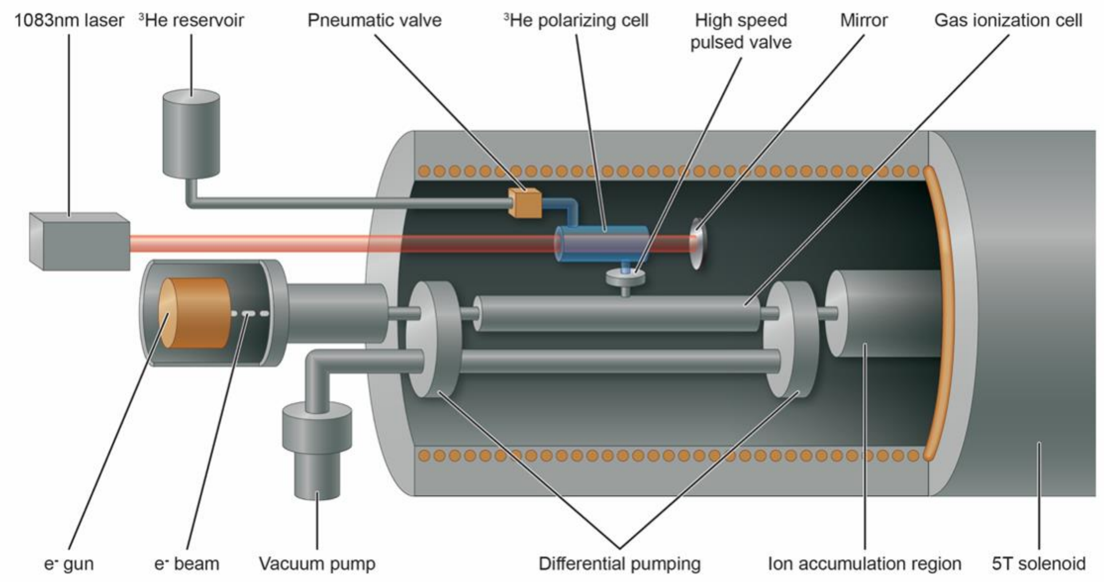


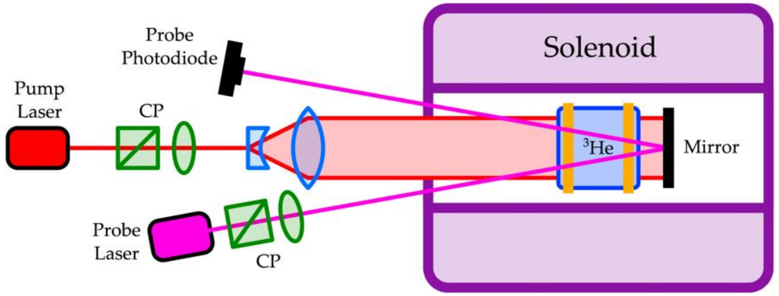


Figures based on Courtade (2002), Nikiel (2013), from calculation by Nacher. Figures made by J. Maxwell.

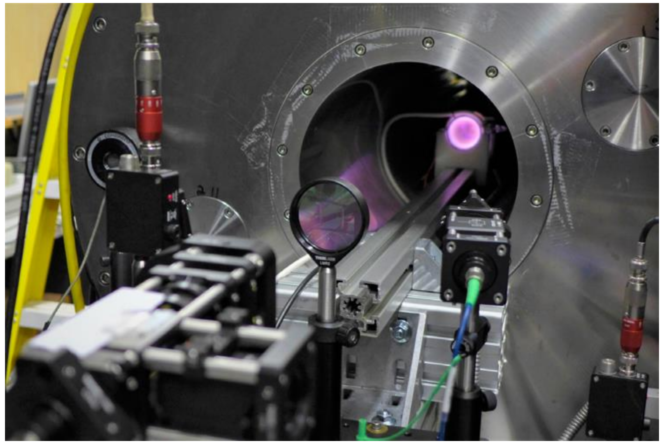
BNL-MIT Development of High Magnetic Field MEOP for the future EIC

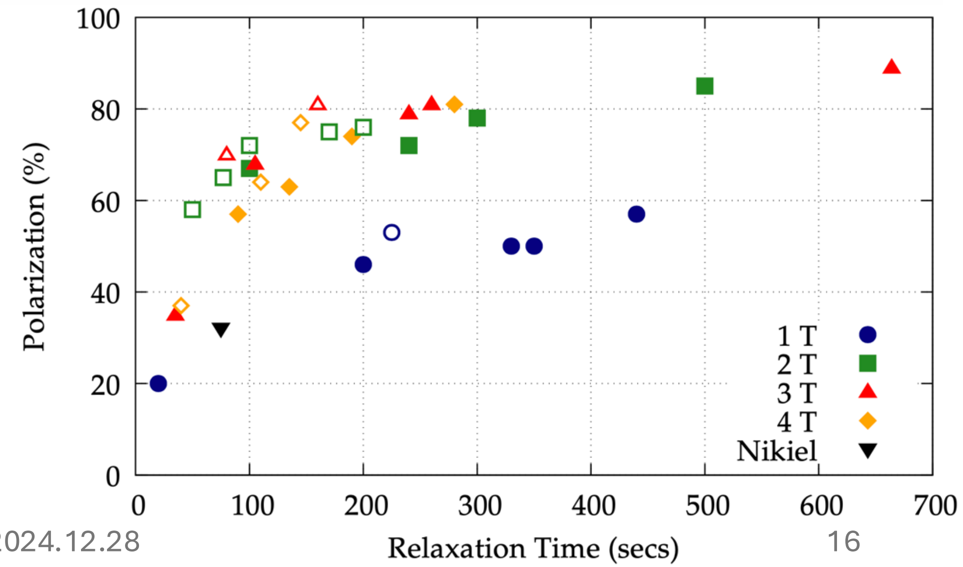
- Polarized ^{3}He ion source for the EIC at RHIC at Brookhaven National Lab
- Electron Beam Ion Source (EBIS) operates at 5 T
- MEOP within 5 T field, transfer into EBIS for ionization and extraction
- Motivated development of EBIS configuration which also benefits other ions



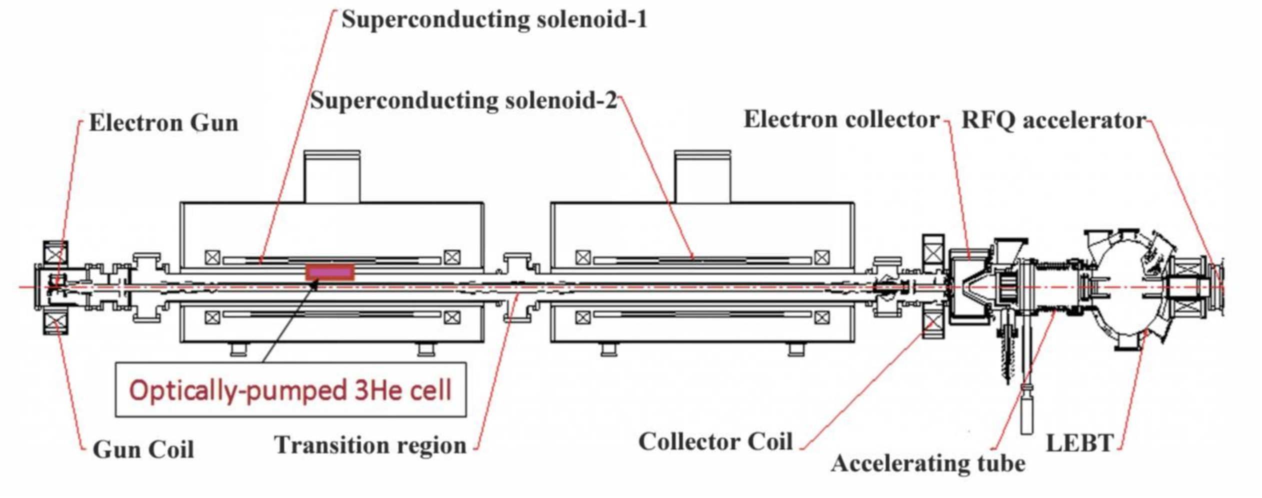


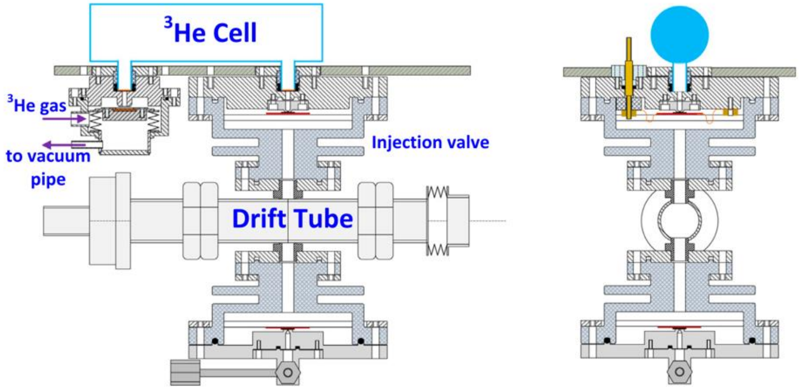
J.D. Maxwell et al., Nucl. Instr. and Meth. A 959, 161892 (2020)



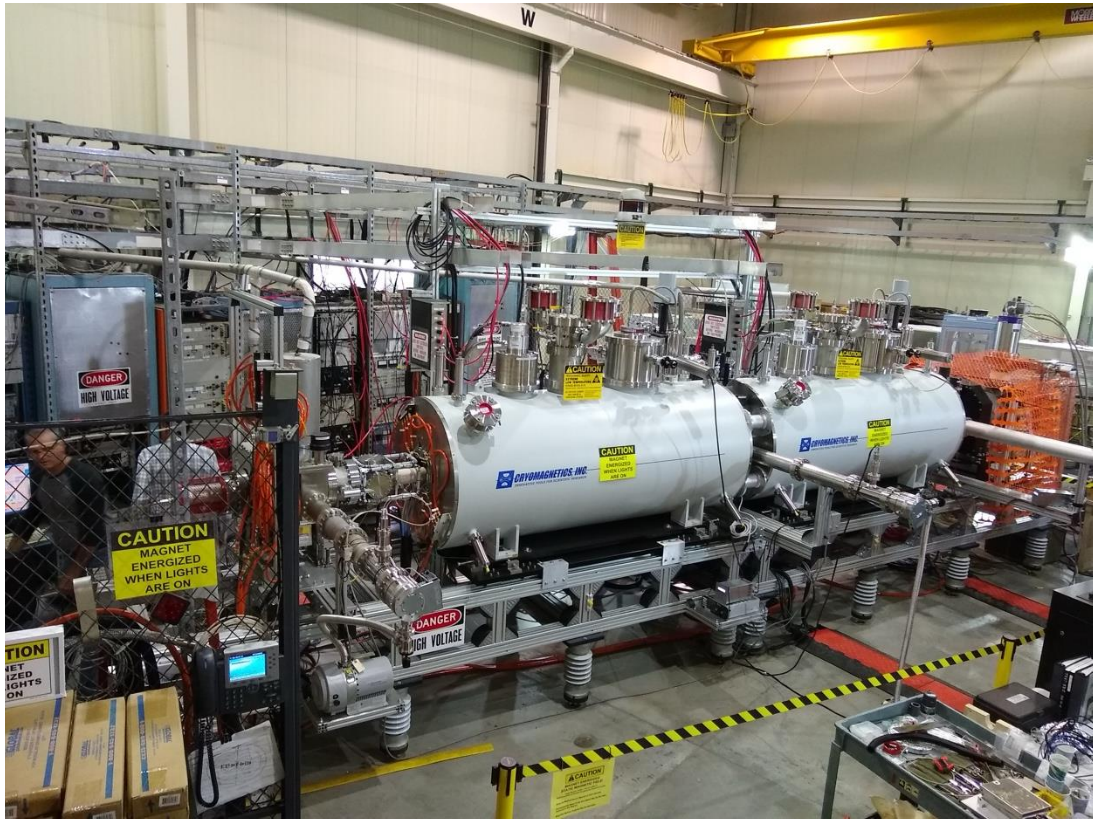


BNL-MIT Development of High Magnetic Field MEOP for the future EIC





A. Zelenski *et al.*, Nucl. Instr. and Meth. A 1055, 168494 (2023)



Extraction and measurement of ^{3}He nuclear polarization anticipated in 2025.

Courtesy of R. Milner

Proposed Experiment Using Polarized ^{3}He at CLAS12 at JLab

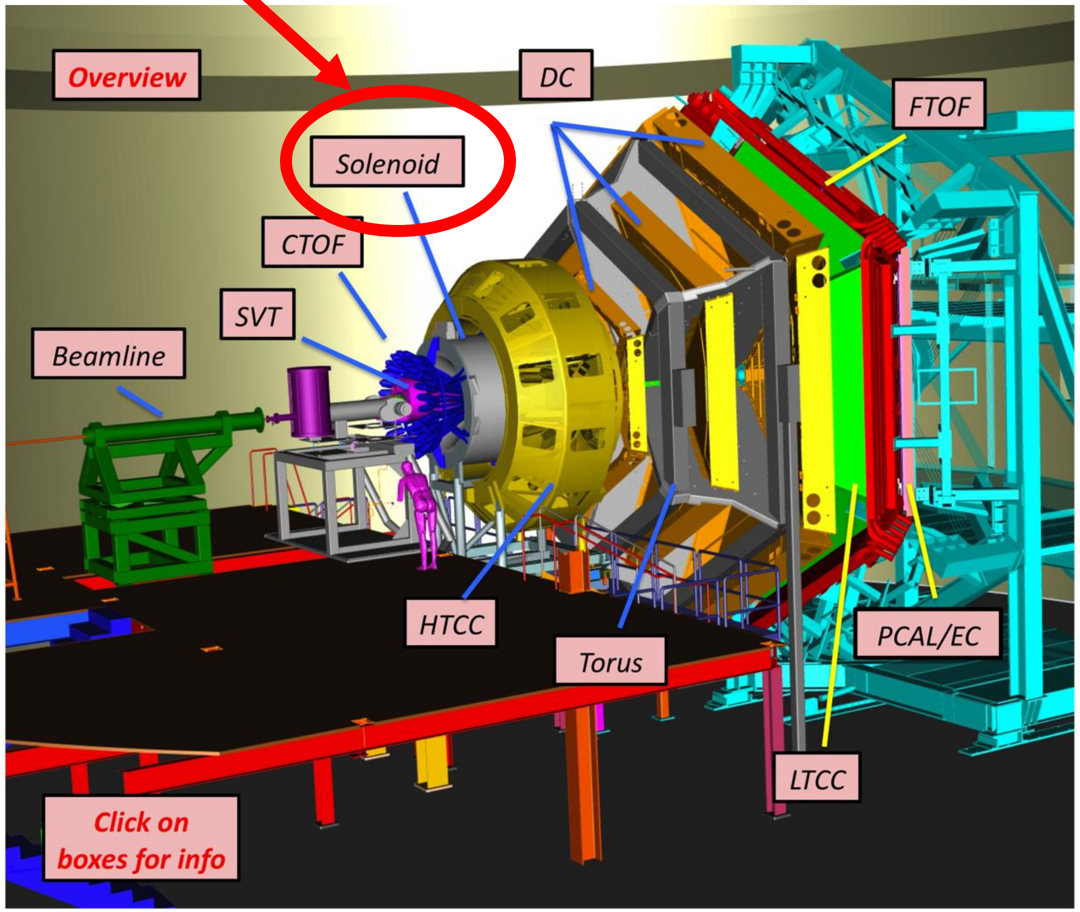
CLAS12: CEBAF Large Acceptance Spectrometer for operation at 12 GeV

- ✓ High luminosity electron scattering
- ✓ Multi-particle final-state response

C12-20-002: A program of spin-dependent electron scattering using a polarized ^{3}He target at CLAS12

- Scientific opportunities
  - ➢ **SIDIS and nucleon spin structure**
  - ➢ Tagged DIS (deuteron tagging)
  - ➢ Quasi-elastic scattering
  - ➢ Nuclear corrections to SIDIS
  - ➢ Deeply virtual exclusive processes
- 30 days of running at 10.6 GeV electron energy

5 T solenoid in interaction region



A Novel Polarized ^{3}He Target at CLAS12

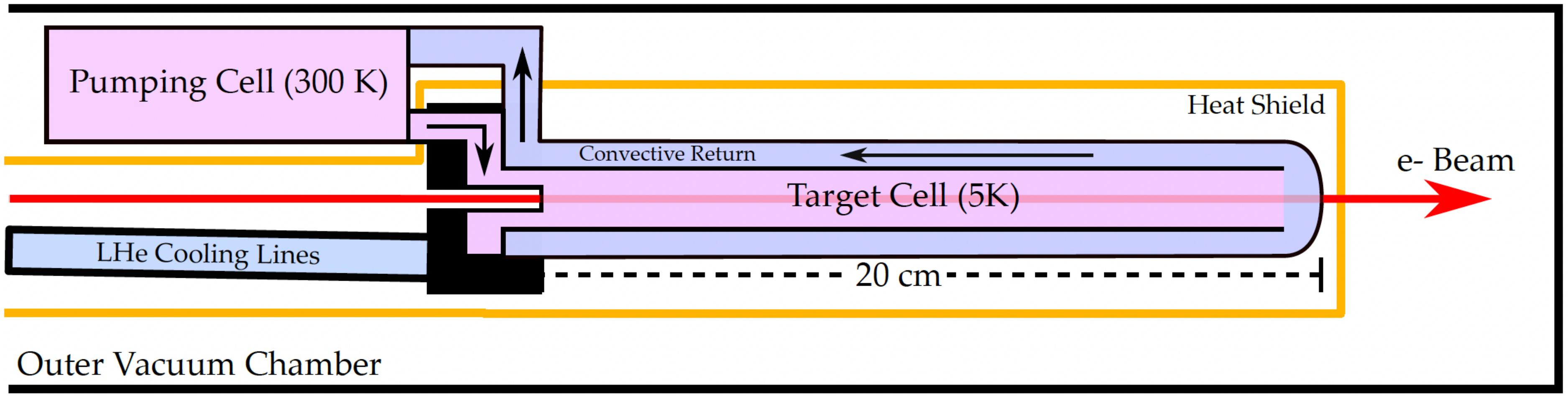
Creating a New Target for CLAS12

Double-Cell Cryo Target		High Field MEOP
• Polarize at 300 K • Transfer to 5 K target cell • Density increase 60×	+	• High Polarization (∼60%) • High magnetic fields (5 T) • Pressure increase 100×

- By combining established technologies: a new polarized target
  (Maxwell, Milner, NIM A, 2021.)
- Achieve 5.4 amg, roughly half JLab SEOP target gas density
- Polarize within 5 T solenoid: CLAS12 standard configuration

Slide from J. Maxwell

CLAS12 Polarized ^{3}He Target Conceptual Design



J.D. Maxwell and R.G. Milner, Nucl. Instr. and Meth. A **1012,** 165590 (2021)

Pumping cell (293 K)

- Borosilicate glass cell
- MEOP to 60% polarization
- Annular cylindrical volume

Target cell (5 K)

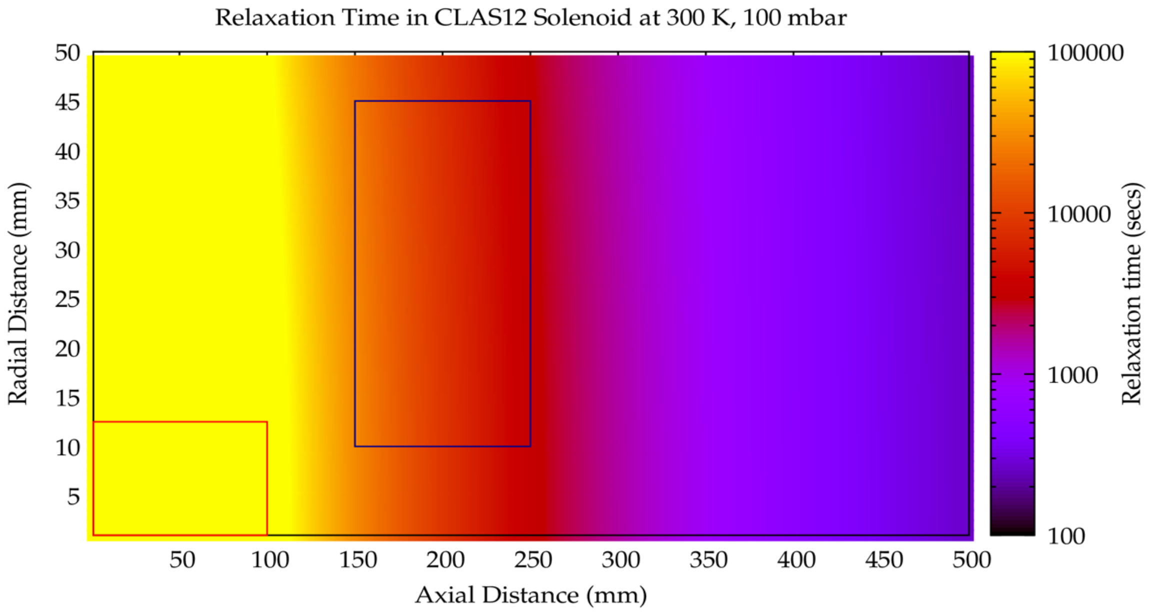
- 100 cm^3, 20-cm aluminum cell coated with cryogenic layer
- Cooled by LHe heat exchanger
- Luminosity: 2.7×10^{34} nucleons/cm^2/s at 0.5-μA beam current

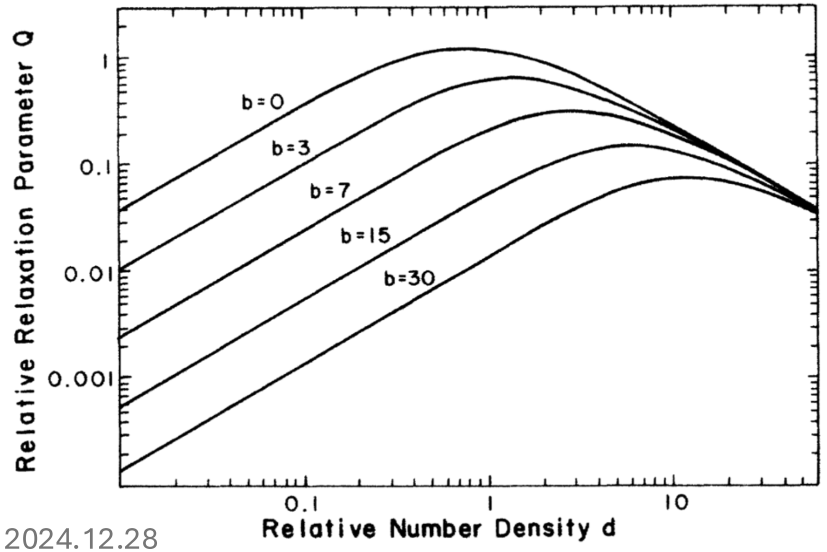
^3He depolarization mechanisms

- Wall relaxation: borosilicate glass and coating for aluminum
- Transverse B-field gradient
  - 10^4 seconds relaxation time around the pumping region

    J.D. Maxwell and R.G. Milner, Nucl. Instr. and Meth. A **1012,** 165590 (2021)
- Ionizing radiation
  - $^3He_2^+$ ions from the beam
  - suppressed with higher field

    K. Bonin *et al.*, Phys. Rev. A **37**, 3270 (1988)
  - to be validated by in beam tests



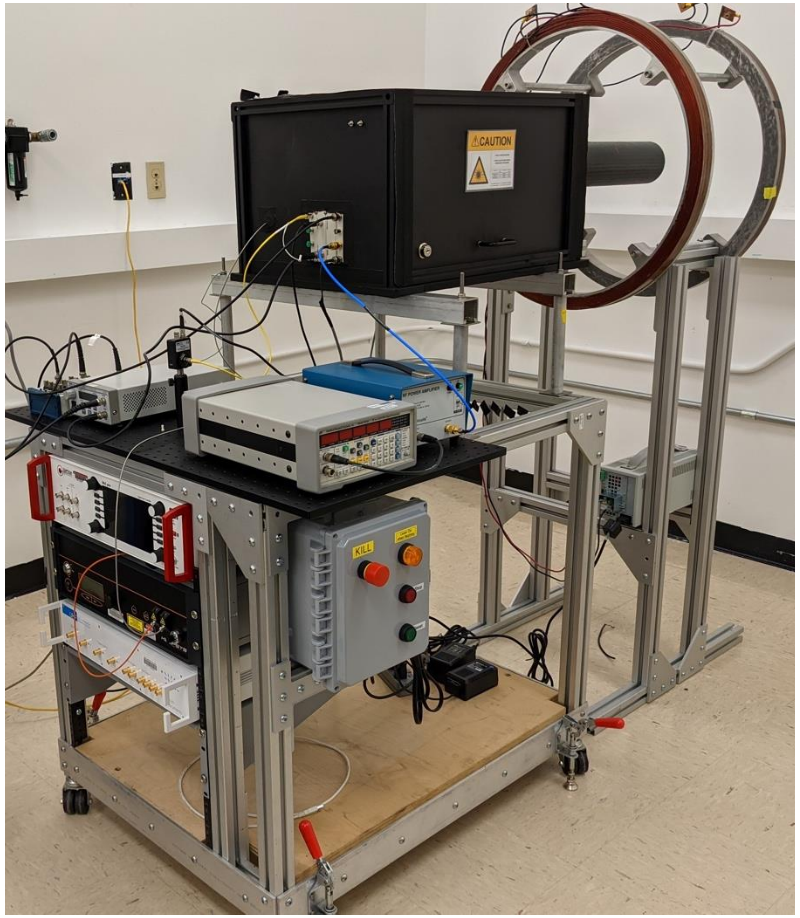


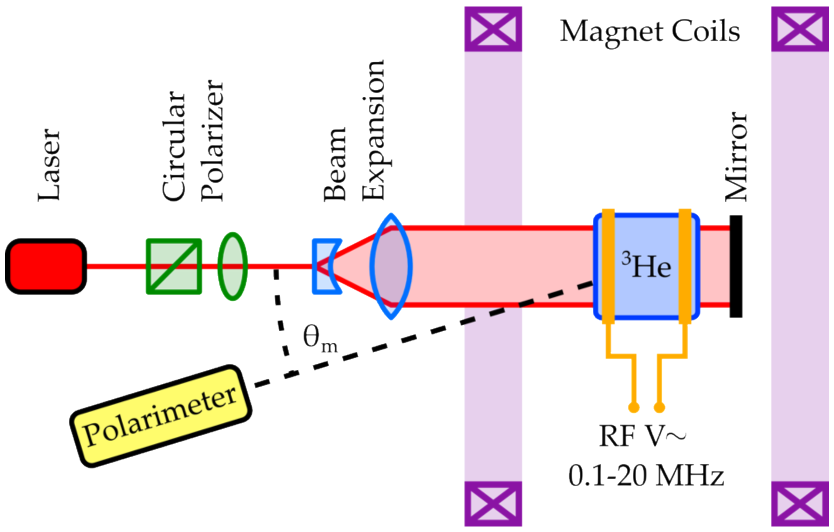
Target Development: Step 1 - Low Field Test

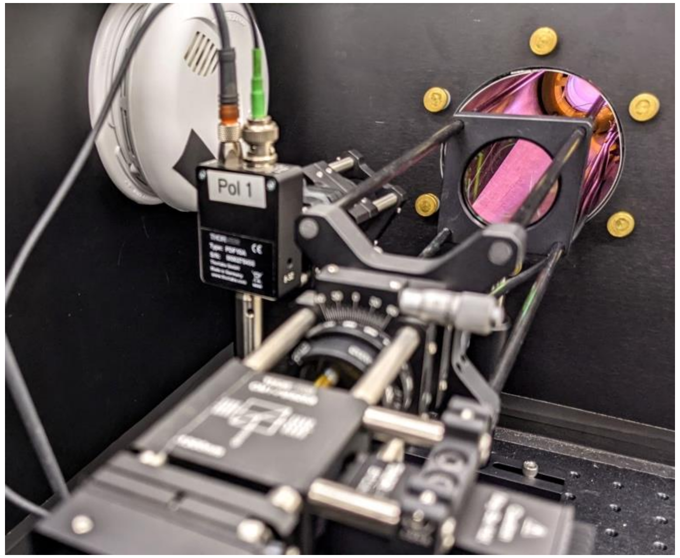
- 30-Gauss magnetic field
- 1-mbar sealed ^{3}He cell
- 70% nuclear polarization
- ~180 seconds relaxation with discharge on

First ^{3}He polarization using MEOP at JLab in low field (30 Gauss)

Polarized ^{3}He test system in 2021



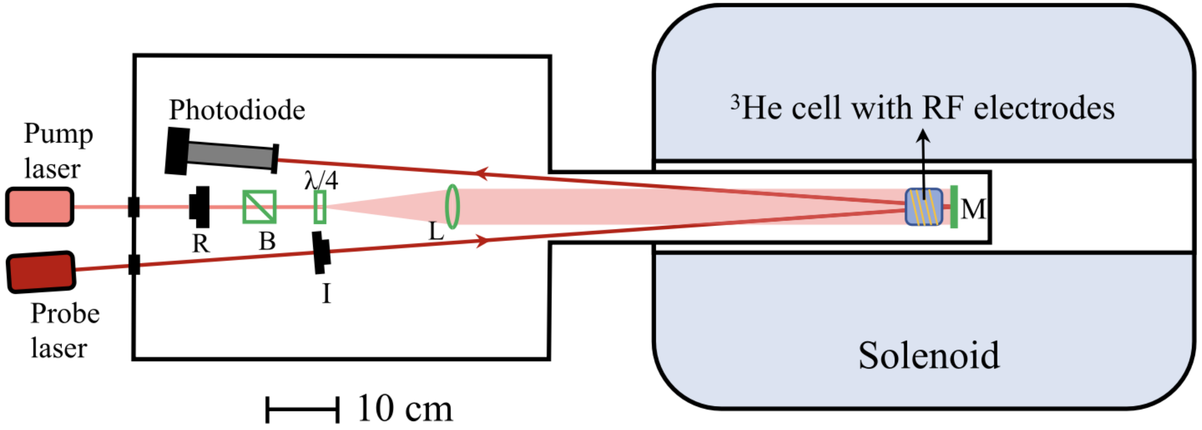




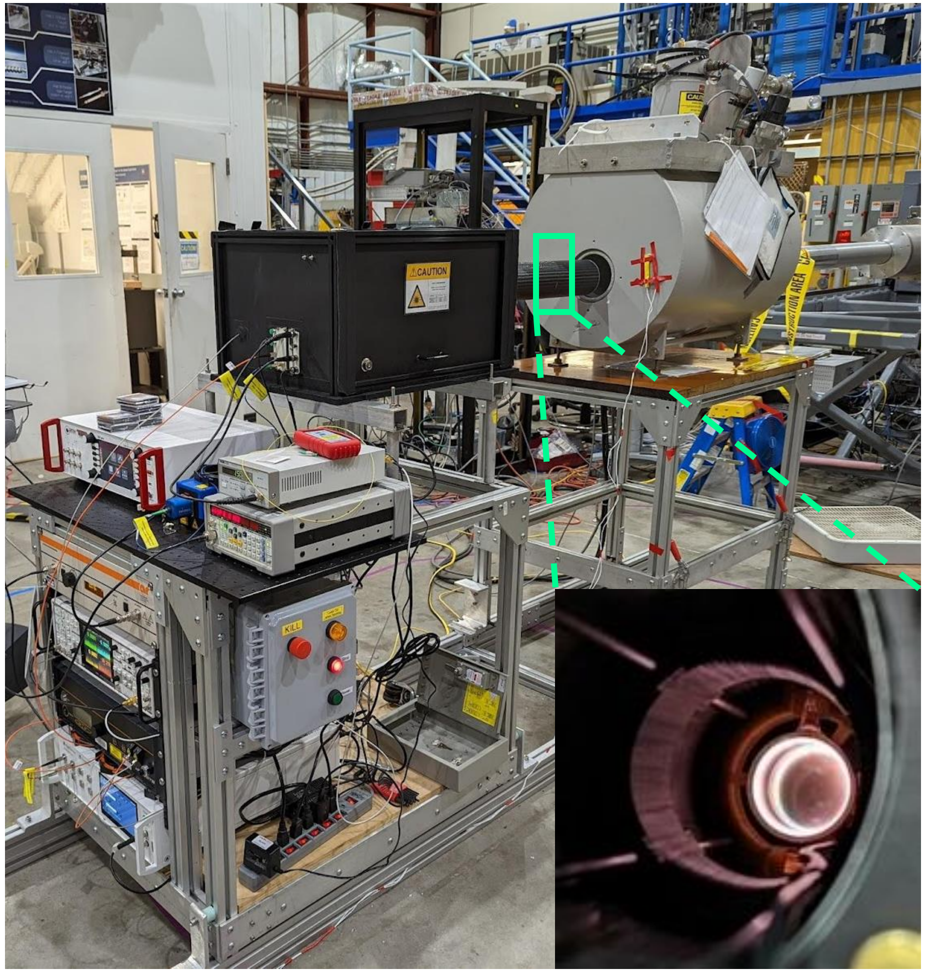
Target Development: Step 2 - High Field Test

- 5-T warm-bore solenoid (tests up to 4 T)
- 1-mbar sealed ^{3}He cell
- 1083-nm probe laser
- 45% polarization with limited laser power
- ~100 seconds relaxation with discharge on

First ^{3}He polarization in high field (2 T) at JLab

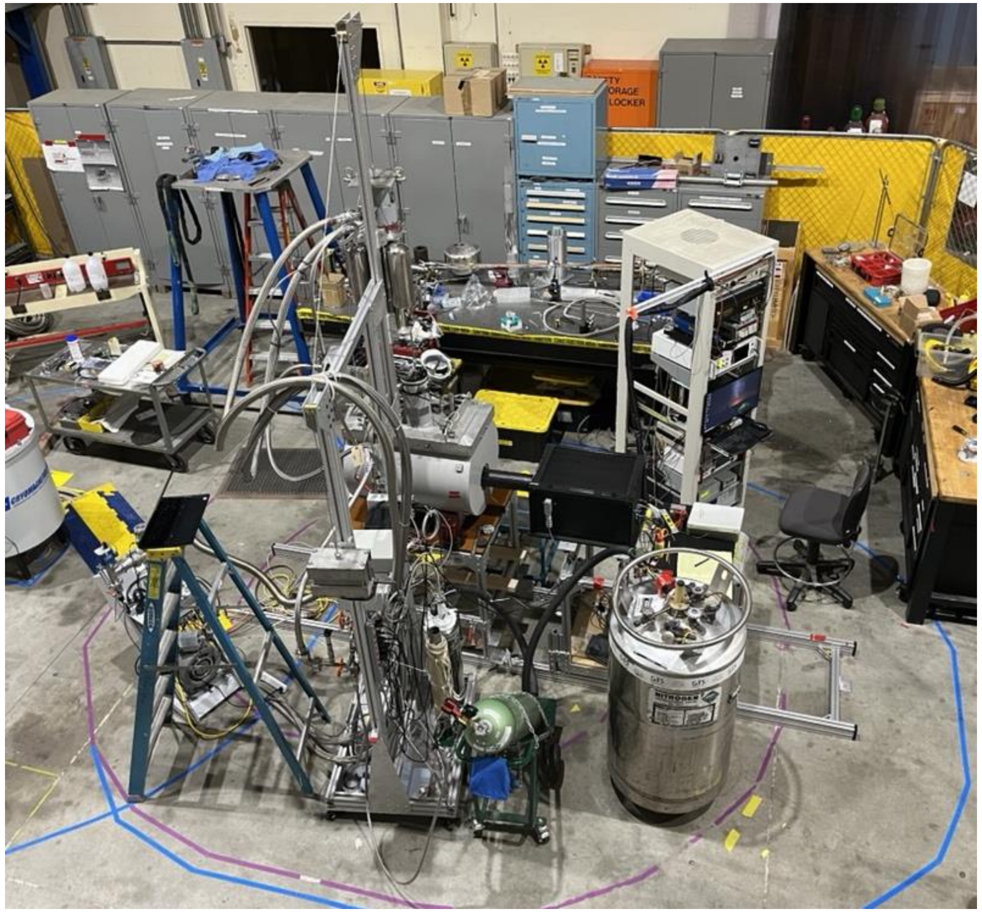


Polarized ^{3}He test system in 2022

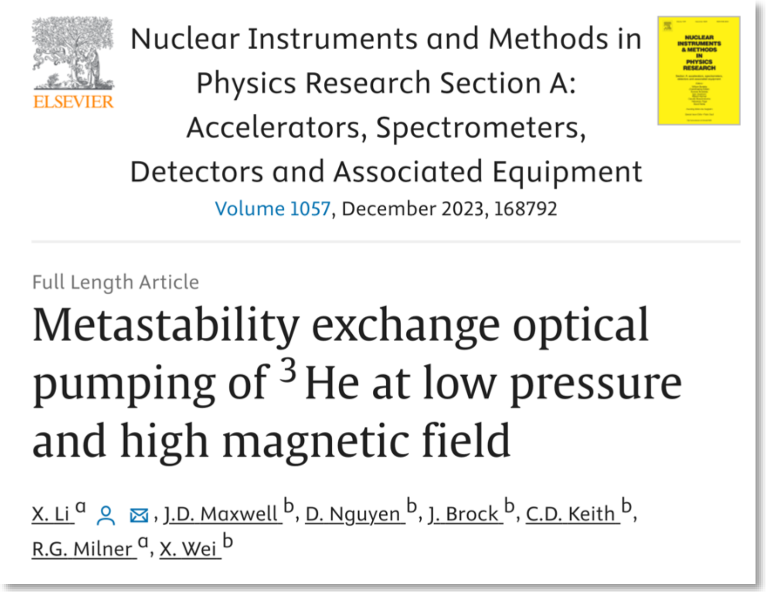


Target Development: Step 3 - High Field Systematic Studies

JLab MEOP polarized ^{3}He test system in 2023



High Field MEOP Systematic Studies



ELSEVIER

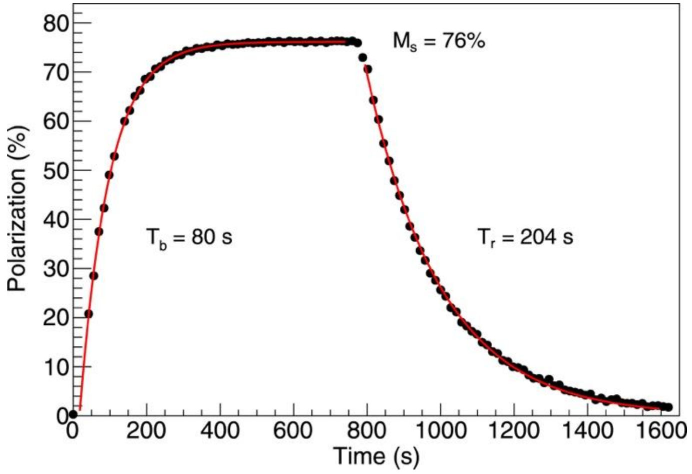
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

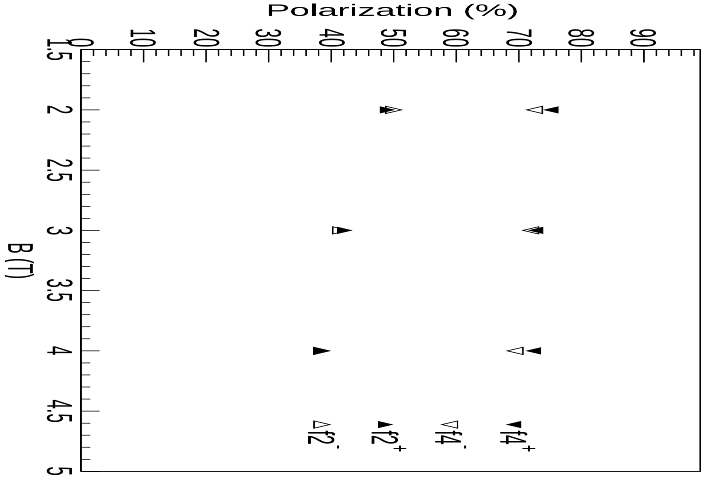
Volume 1057, December 2023, 168792

Full Length Article

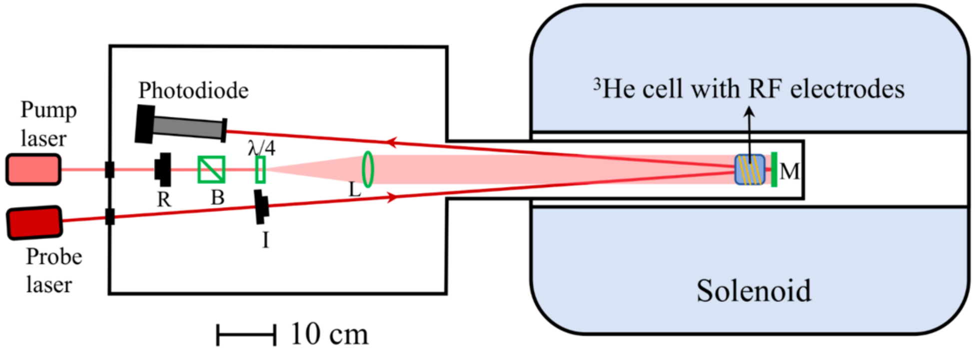
Metastability exchange optical pumping of ^{3}He at low pressure and high magnetic field

X. Li [a], J.D. Maxwell [b], D. Nguyen [b], J. Brock [b], C.D. Keith [b], R.G. Milner [a], X. Wei [b]



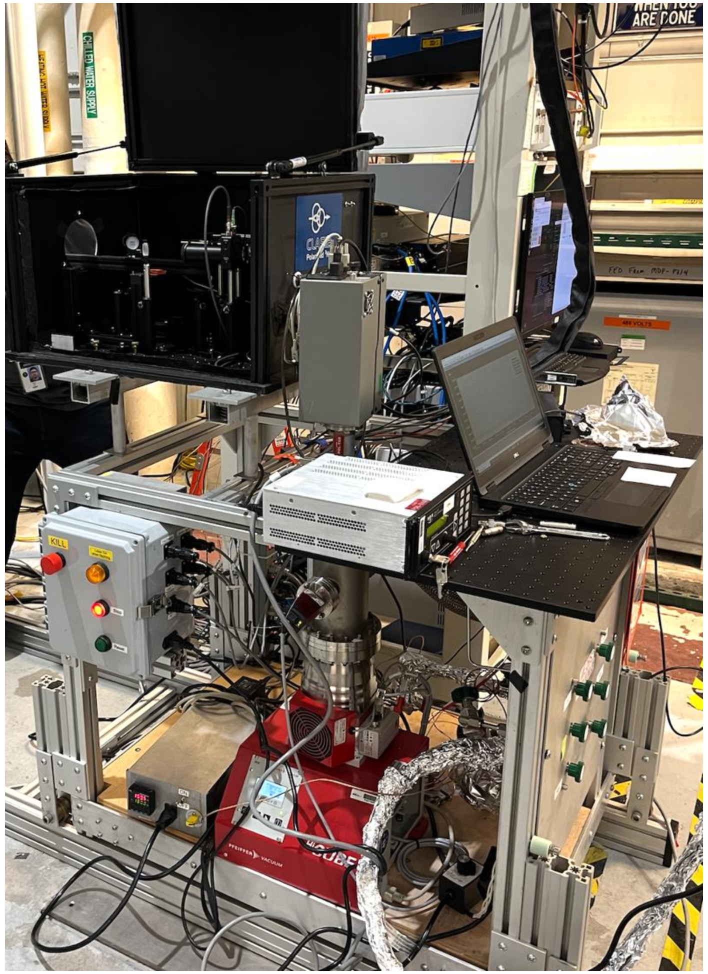


Effects of different transitions, laser power, discharge and B field on pumping rate and max polarization

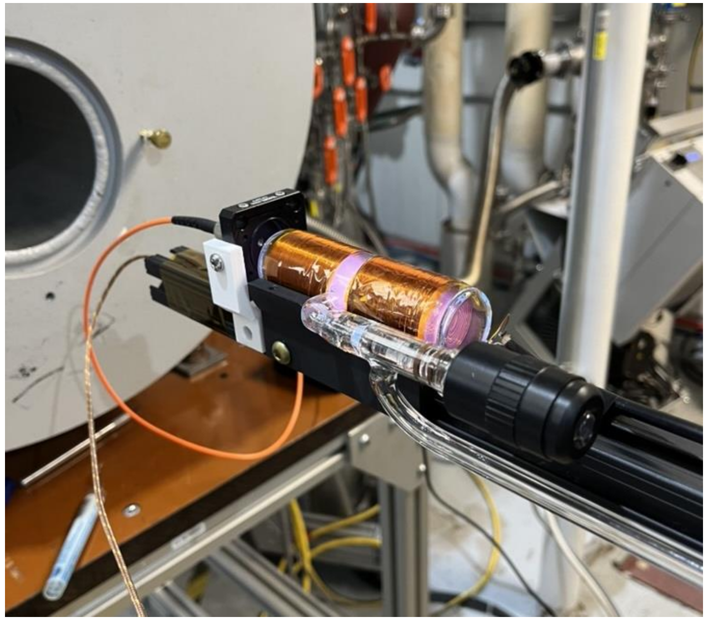


Target development step 4. variable pressure (ongoing)

JLab MEOP polarized ^{3}He test system in 2024



- New valved cell allows for varied gas pressure



- New 1083-nm laser accommodated to 5-T field
- Fillable gas system

Summary

- Nucleons are building blocks of the visible universe, knowledge of the spin structure of the nucleon is still incomplete
- Spin polarized ^{3}He is a powerful effective polarized neutron target
- New techniques for polarized ^{3}He in high magnetic fields will provide new opportunities for spin studies at the state-of-the-art QCD facilities
- Development on novel polarized ^{3}He target and ion source using high-field MEOP is underway and expected to provide unprecedented improvement in understanding nucleon spin structures

Thanks for your attention!