A High-Field Polarized ^{3}He Target
for Jefferson Lab's CLAS12 Spectrometer

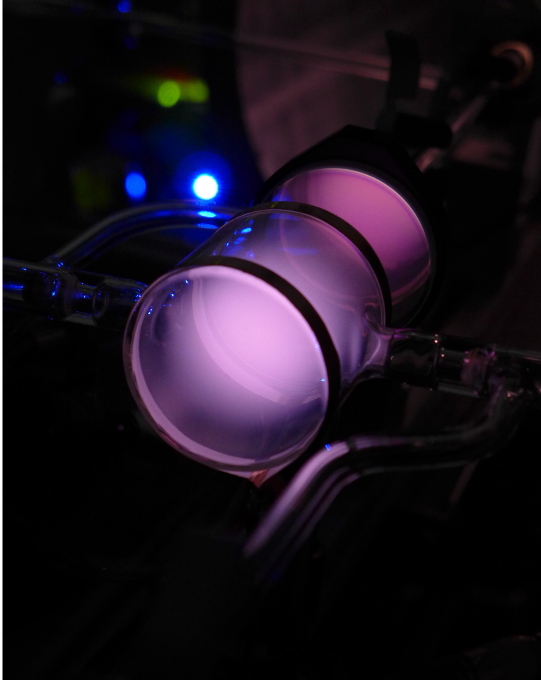
J. Maxwell

for CLAS12 Polarized 3He Collaboration

Jefferson Lab

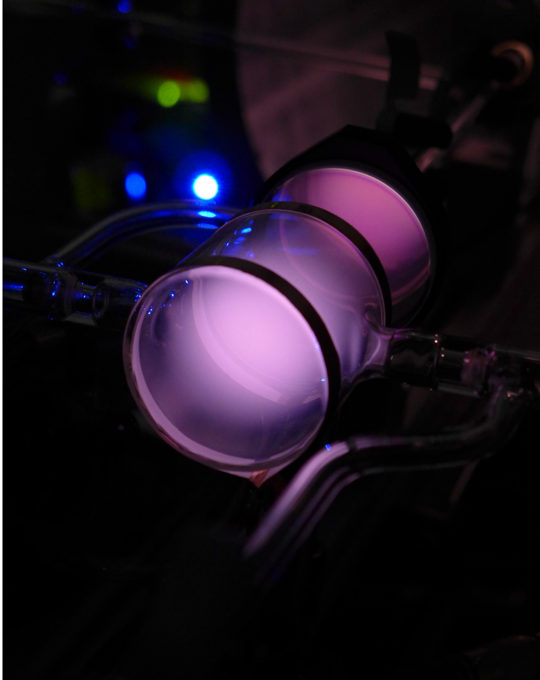
Massachusetts Institute of Technology

25th International Spin Symposium
September 26, 2023



Outline

1. Polarized ^{3}He for Nuclear Physics
   - Optical Pumping
   - Opportunity for a New Target
2. Proposed Target for CLAS12
   - Design
   - Development
3. Outlook
   - Path to In-Beam Tests
   - Transverse Polarization?



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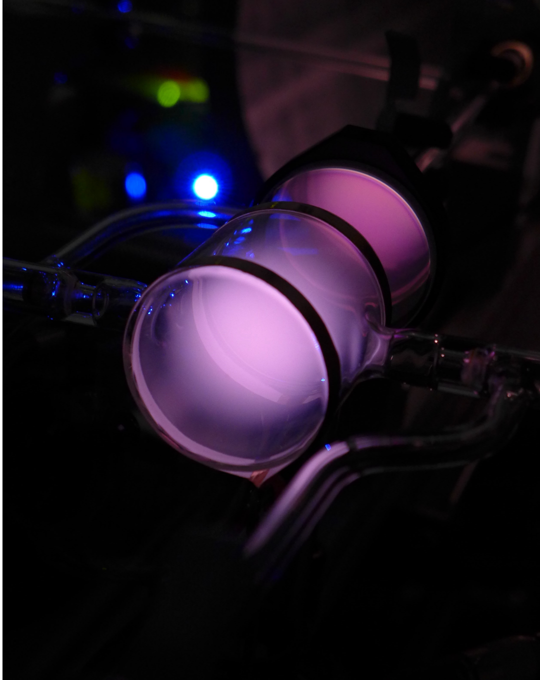
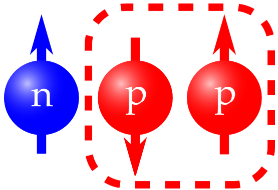


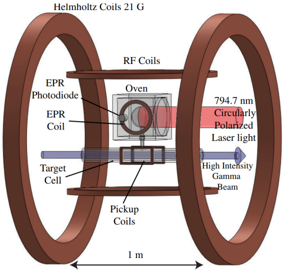
Why Polarized Helium 3?



- About 90% of the time, ^{3}He's 2 proton spins are anti-aligned in a spin singlet
- ^{3}He spin is primarily neutron spin
- By polarizing ^{3}He, we have a surrogate for polarized free neutrons

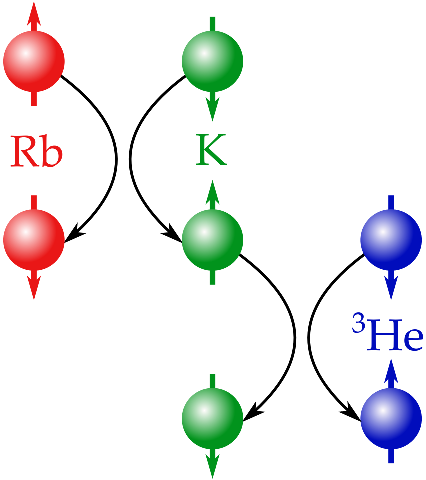
Polarized ^{3}He Targets at JLab

- 6 GeV era: 13 experiments in Hall A
- 12 GeV era: 7 experiments approved
- Spin Exchange Optical Pumping
- 60% in-beam polarization in 10 bar gas



Spin Exchange Optical Pumping

- Pump Rb in ~30 G holding field
  - 795 nm laser light: $5S_{1/2} \rightarrow 5P_{1/2}$
- Spin exchange polarizes K, then ^{3}He
- Pressures up to 13 atm
- Polarize in oven, transfer target cell
- $P_{Rb} \sim 95\%$, $P_{^3He} \sim 80\%$
  - In-beam reduced to $P_{^3He} \sim 60\%$
  - Longitudinal or **transverse**
- 13 exp. in Hall A 6 GeV, 7 approved 12 GeV
  - In 1991: 35% at 1 μA
  - Currently running in Hall A: 60% at 60 μA
- Never used in large acceptance Hall B



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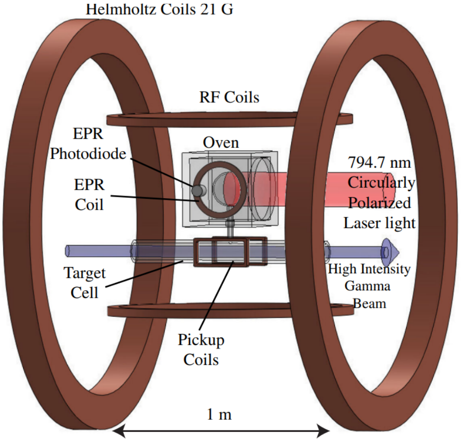

Gentile *et al.* RMP, 2017.

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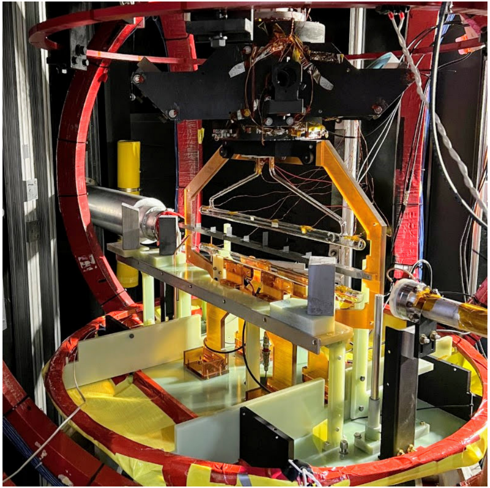
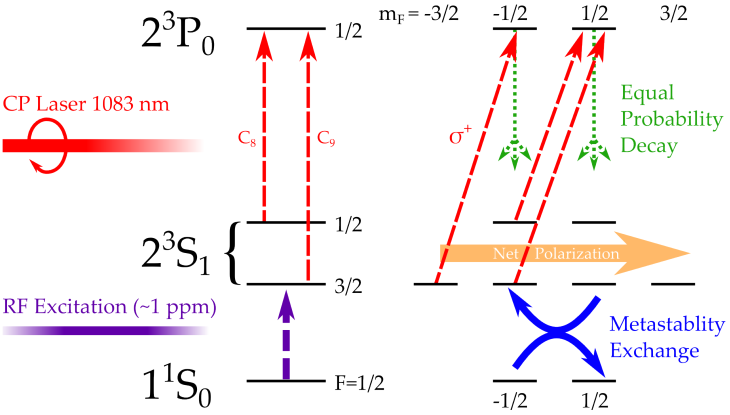


Metastability Exchange Optical Pumping

- 1963, Colgrove *et al* (TI)
- Pure ^{3}He, ∼30 G field
- Discharge promotes states to 2^3S_1
- Laser drives polarization
- Collisions between 2^3S_1 and ground state polarize nuclei
- Requires ∼2 mbar, >100 K
- 10^5 faster than SEOP
- 10^4 lower pressure has limited use for scattering experiments



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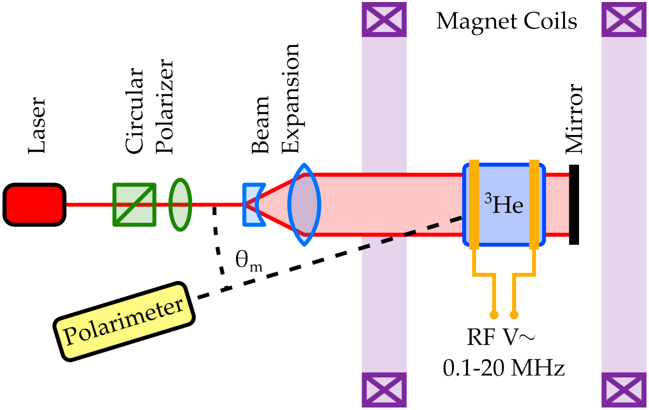


Metastability Exchange and Spin Exchange Optical Pumping

SEOP

- Pump: alkali metals in mixture
- Transfer: spin exchange
- Low pumping rate
- Walls carefully selected
- Needs oven (473 K)
- 100 W laser typical
- **Large pressure range (1 to 13 bar)**

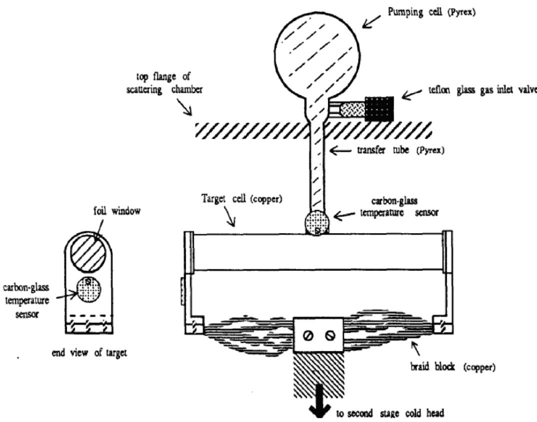
MEOP

- Pump: metastable population
- Transfer: metastability exchange
- High pumping rate
- Less sensitive to wall interactions
- Temperature above 100 K
- 4 W laser typical
- **Limited pressure ($\sim$1 mbar)**

- Pressure attainable has made SEOP the most attractive tool for JLab
- **Neither** have historically worked in high magnetic fields

MEOP Double-Cell Cryo Target: Bates 88-02

- Quasi-elastic asymmetries in 1988, 1993
- MEOP pumping cell at 2 mbar, 300 K, 30 G: 40% in-beam polarization
- Cu target cell at 2 mbar, 17 k
- Cu foil beam windows (4.6 μm)
- Cold surfaces coated with N_2 to reduce depolarization from wall interactions
- 7.2×10^{32} ^{3}He/cm^2/s Luminosity w/ 10μA
- P measurement performed in pumping cell
- P in target inferred from rate equations: P relaxation and diffusion



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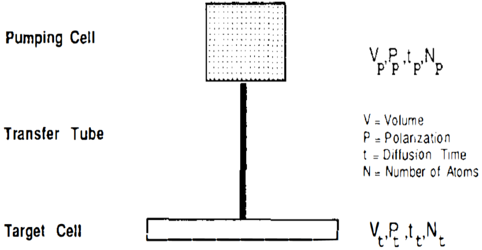
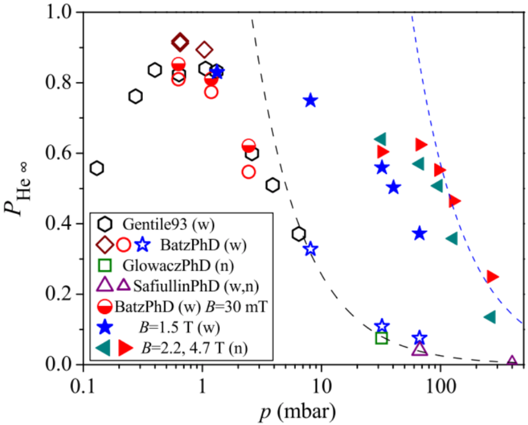


High Magnetic Field MEOP

- OP not historically done at high B
  - SEOP: Increasing wall relaxation
  - MEOP: Weak hyperfine coupling...?
- Kastler-Brossel Lab at ENS in Paris found by increasing B_0, MEOP effective at higher pressures

  (Nikiel-Osuchowska *et al*, Eur. Phys. J.D., 2013.)
- Near 60% at 100 mbar!
- Zeeman splitting separates states for laser pumping
  - Decouples relaxation paths
  - Creates probe peaks (Suchanek *et al.*, Euro Phys JST, 2007.)



Solid points above 1 T

From Gentile, Nacher, Saam, Walker (2017.)

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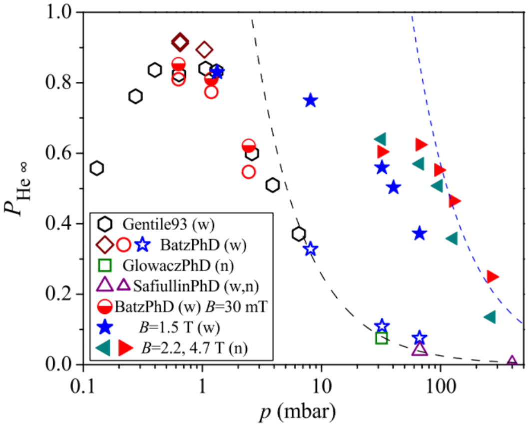

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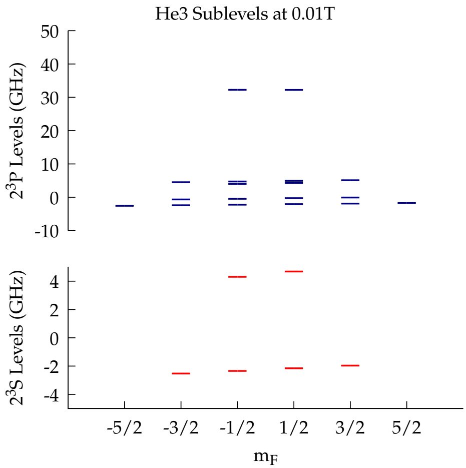

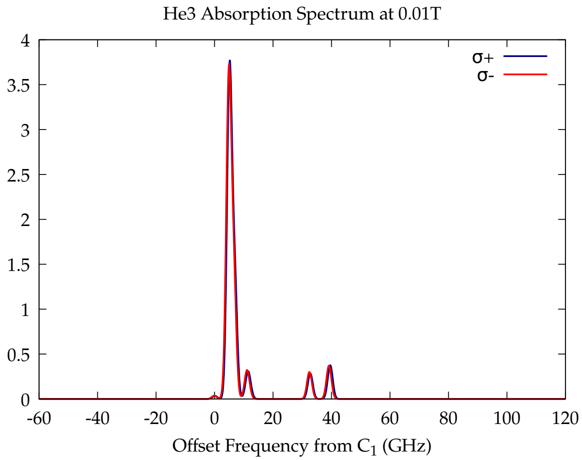

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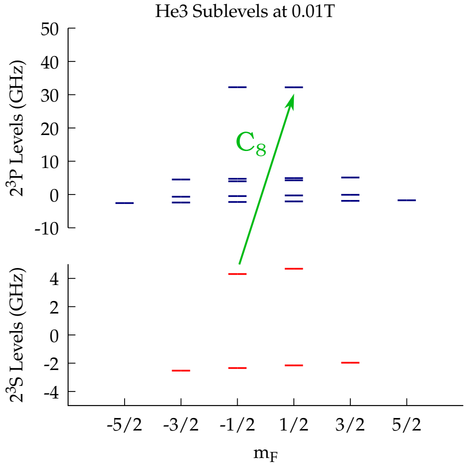

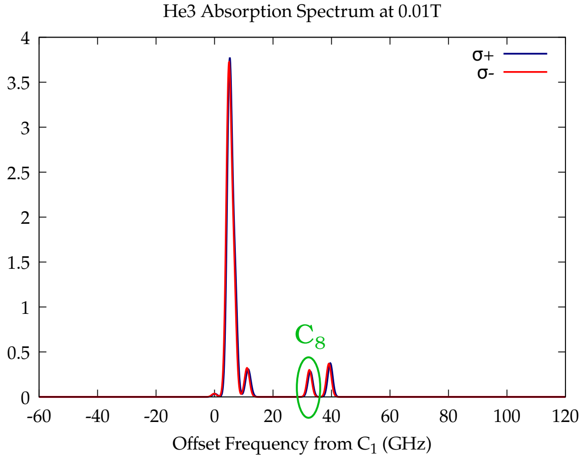

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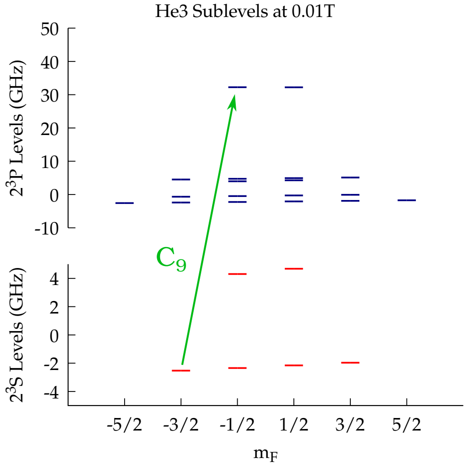

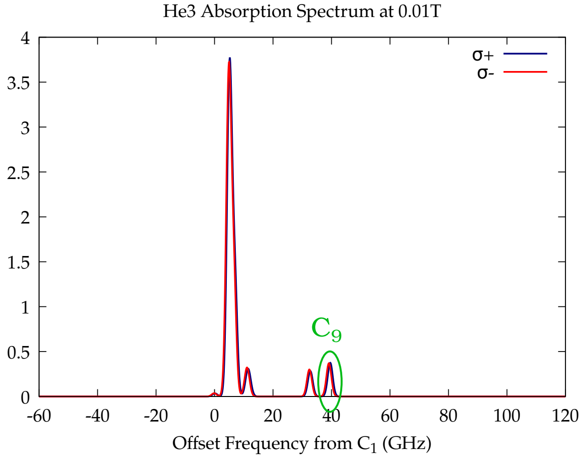

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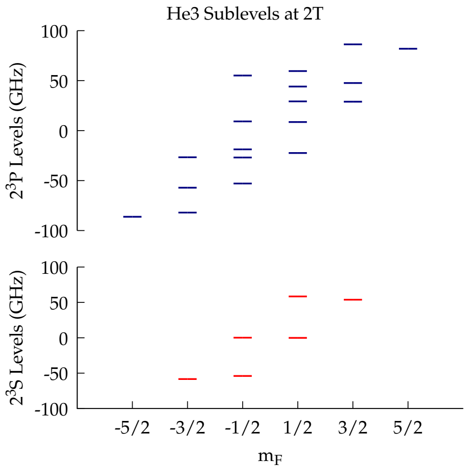

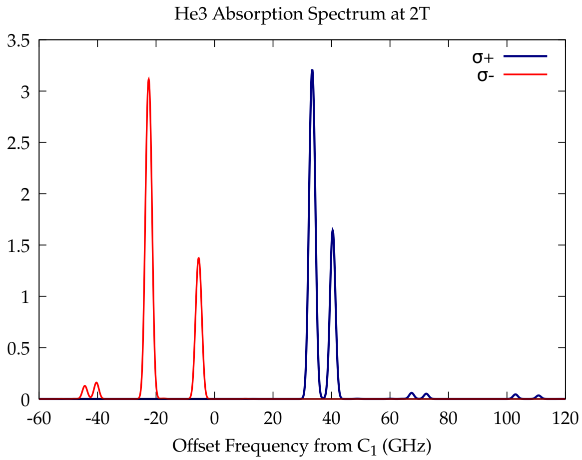

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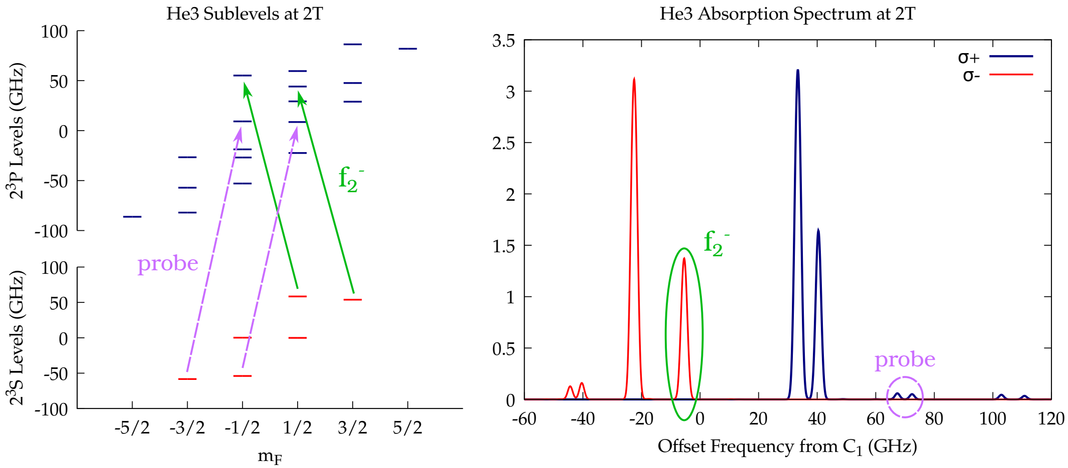

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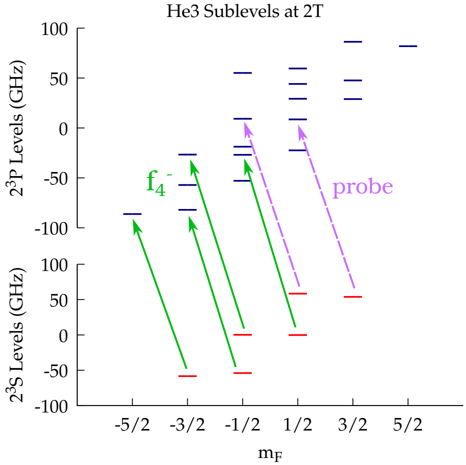

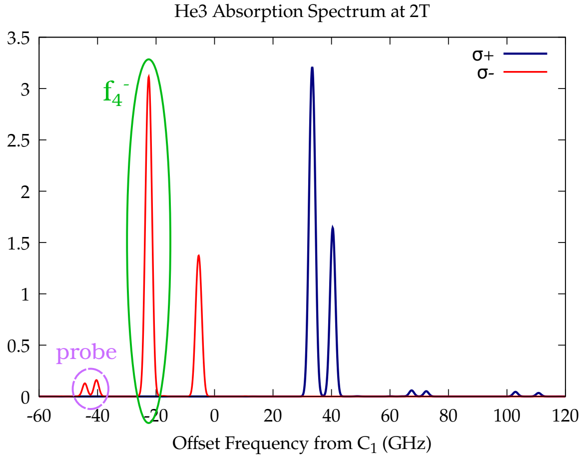

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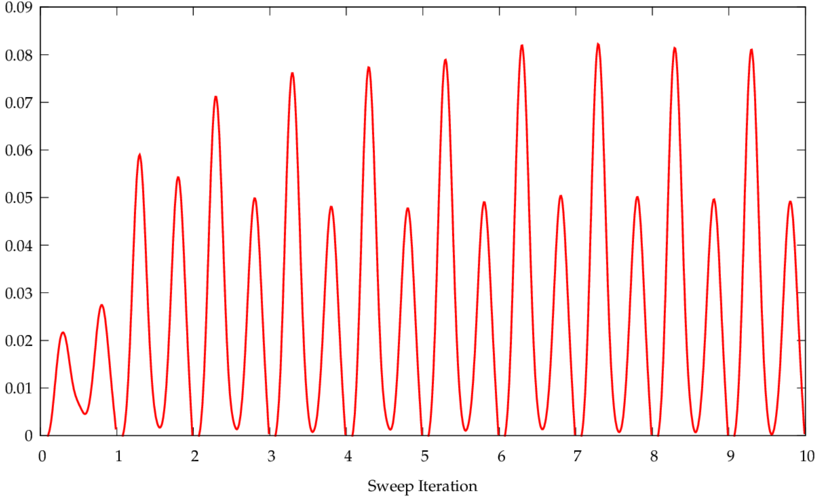
Measuring Optical Pumping via Probe Peaks



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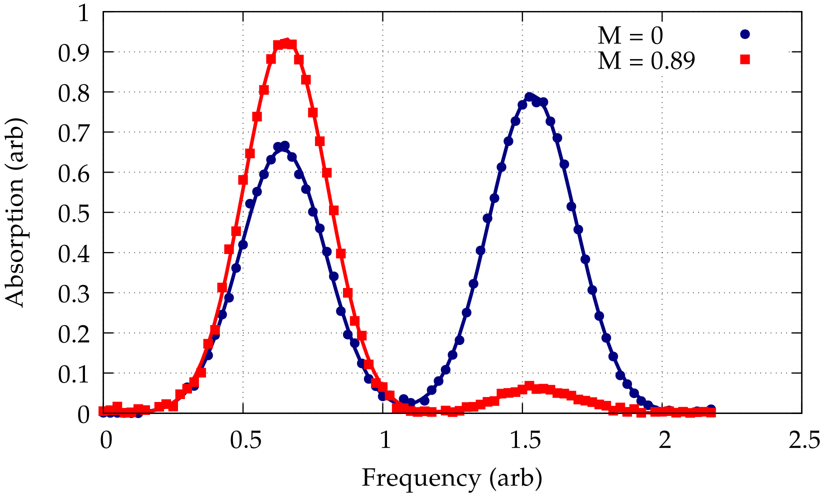
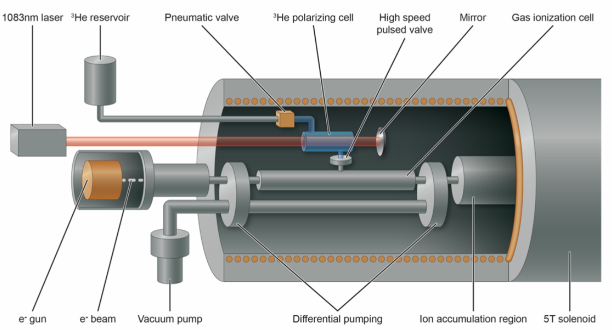


High Magnetic Field MEOP for EIC

- High field MEOP techniques already being applied for nuclear physics
- BNL-MIT: Polarized ^{3}He Ion Source for EIC (D. Raparia this morning)

- BNL's Electron Beam Ion Source operates at 5 T
- MEOP within 5 T field, transfer into EBIS for ionization and extraction
- Tests between 2 to 4 T gave nearly 90% at 1.3 mbar (Maxwell *et al.*, NIM A **959**, 2020)
- Installation in 2023



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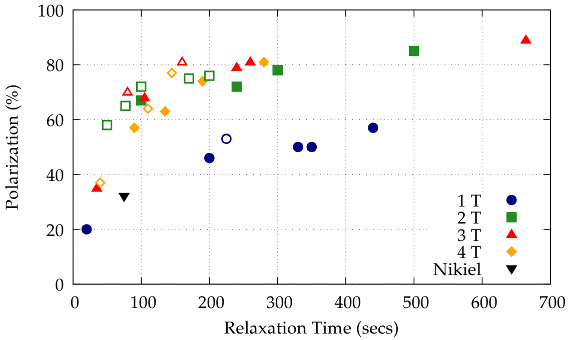
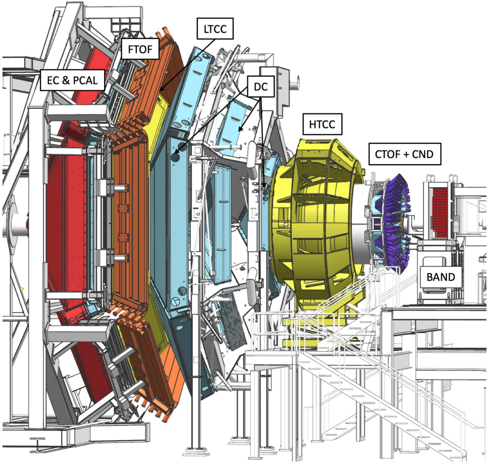


Results at 1.3 mbar

An Opportunity in Hall B's CLAS12

- CEBAF Large Acceptance Spectrometer for Jefferson Lab's 12 GeV upgrade
  - High luminosity electron scattering
  - Multi-particle final state response
  - 5 T solenoid in interaction region
- Proposal to PAC48: A program of spin-dependent electron scattering using a polarized ^{3}He target in CLAS12
  - P_T-dependence of n longitudinal spin structure
  - Nuclear corrections to SIDIS
  - Conditionally approved with A- rating
  - Spokespeople: Avakian, Maxwell, Milner, Nguyen
- Novel target needed for standard config



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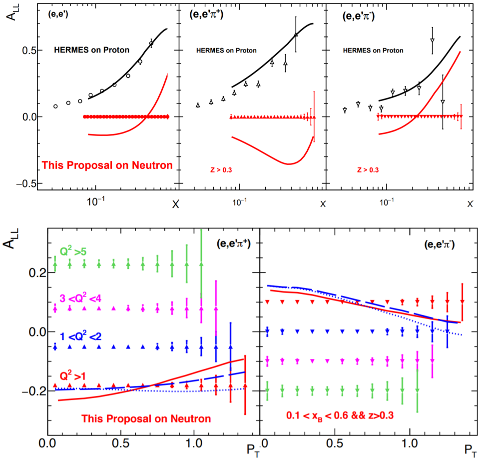

Creating a New Target for CLAS12

Double-Cell Cryo Target

- Polarize at 300 K
- Transfer to 5 K target cell
- Density increase 60×

+

High Field MEOP

- 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

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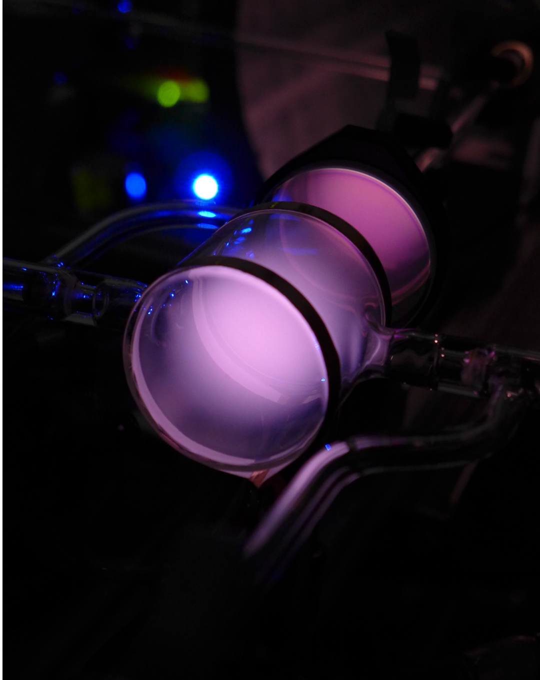

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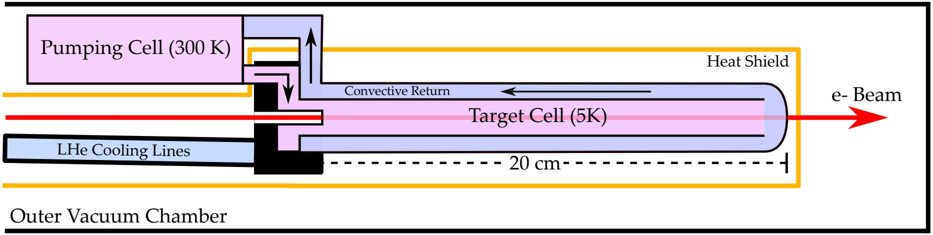

293 K Pumping Cell

- 200 cm^3 borosilicate glass
- MEOP to 60% polarization
- Annular cylindrical volume

5 K Target Cell

- 100 cm^3, 20 cm long aluminum cell
- Cooled by LHe heat exchanger
- Luminosity of 2.7×10^{34} nuc/cm^2/s at 0.5 μA

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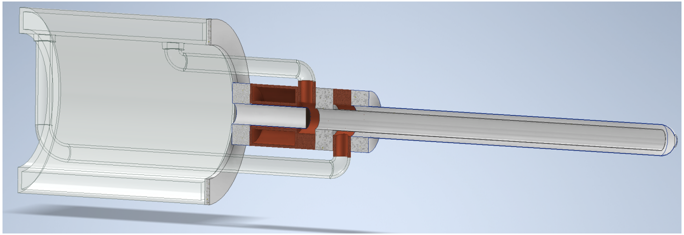

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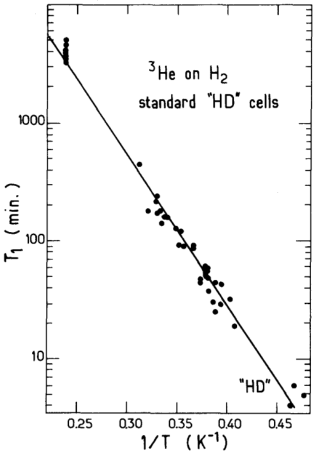
Depolarization Mechanisms

- Wall relaxation on Al: H_2 coatings yield days long relaxation at 4 K
  (Lefevre-Seguin, Low Temp. P. 1988.)
- Depolarization from transverse magnetic field gradients, dependent on pressure, temperature
  - In CLAS12 solenoid: minimal
- Beam produces $^3He_2^+$ ions: increase with density, but decrease with higher field.
  (Bonin, PRA, 1988)



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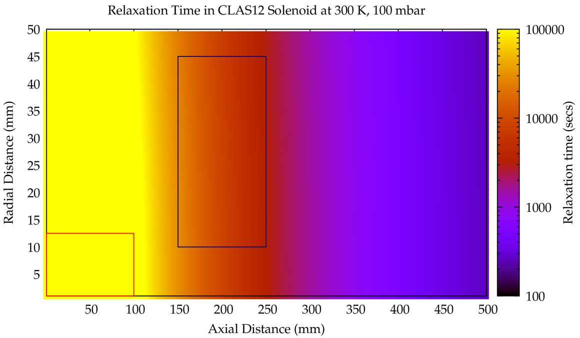

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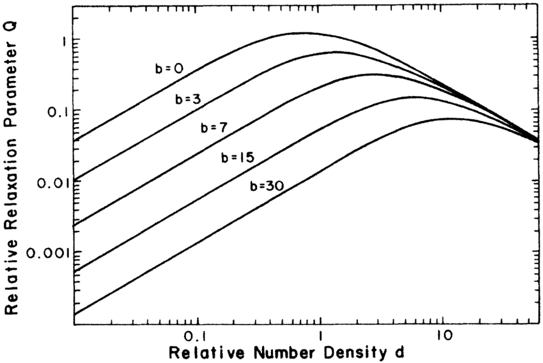
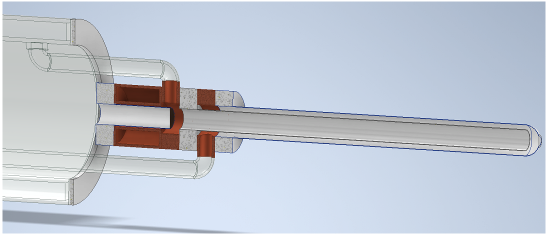


Cryogenics and Heat Load

- Heat loads on 5 K target cell:
  - Beam heating (<150 mW)
  - Pumping cell at 293 K, transfer through glass and gas (<500 mW)
  - Radiative heating minimized by heat shield (<20 mW)
- Pulse-tube cryocooler for 2.5 W at 4.2 K should be sufficient (Cryomech PT425)
- JLab's Hall D cryotarget provides liquid H_2 and He_2
  - Few modifications needed to design to support a MEOP double-cell cryotarget



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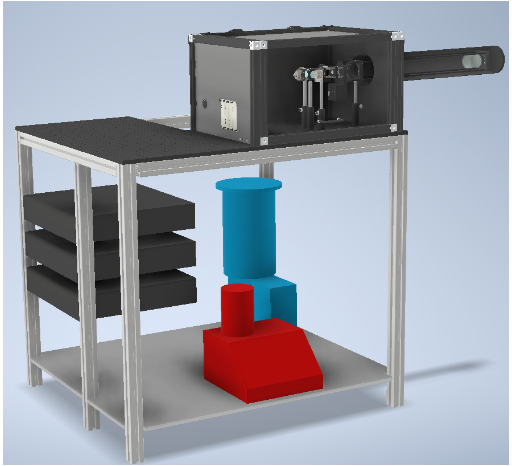
- High field MEOP test stand explore high field polarization vs. pressure and field, reproduce results of KBL
- Flow tests between cold and warm cells with Target Group's 4 K test stand
- Full, double-cell prototype to allow in-beam tests at injector test facility, perhaps in hall?



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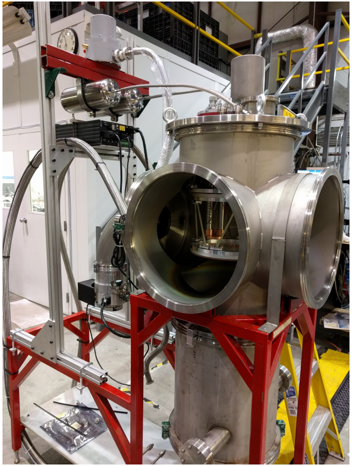

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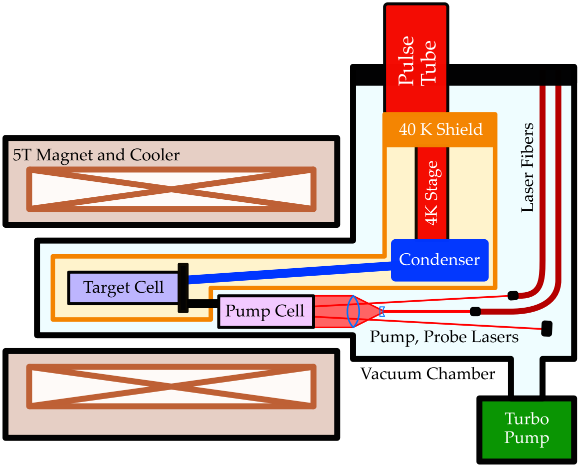
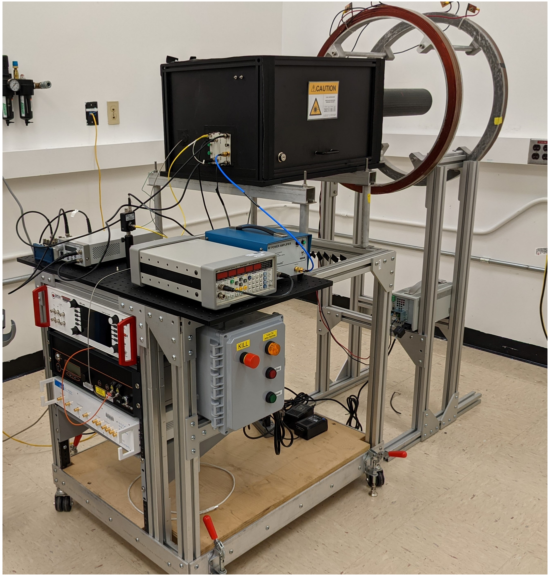


Beginning Polarization

- First MEOP pumping stand at JLab
  - Enclosed, interlocked system (class 1)
  - On wheels to allow transport to 5 T warm-bore solenoid
- Shakedown with low-field Helmholtz pair
  - Low-field, 668 nm liquid crystal polarimeter (Maxwell *et al.*, NIM A, 2014.)
  - Sealed ^{3}He cells at first
  - 60% nuclear polarization with 80 sec relaxation
- Unfortunately, pumping laser fiber sustained damage in preparation for high field tests, limiting power to 0.3 W



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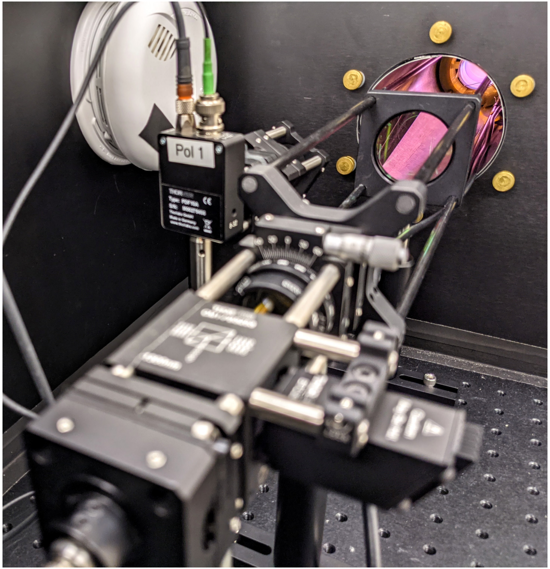
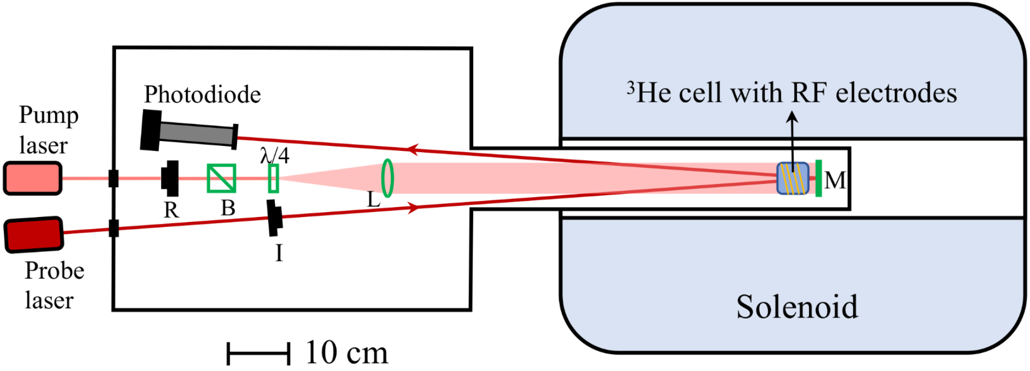


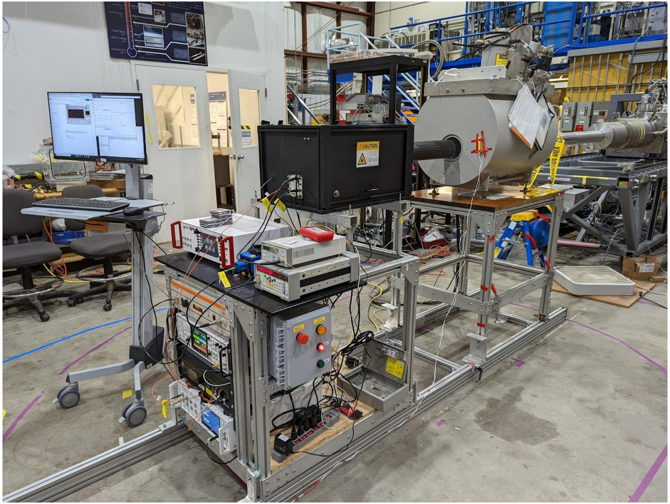
High Field Test Setup



(X. Li, 2023)

First High Field Tests

- High Field Polarization
  - Probe laser polarimetry with second, lower-power DFB laser (Suchanek *et al.*, Euro Phys JST, 2007.)
  - Wavelength meter
  - Python DAQ software
- Limited laser power, wavelength
  - Confirmed operation of probe polarimeter
  - Mapped pump and probe laser peaks at 2, 3, 4 T
- Once laser repaired, 77% achieved



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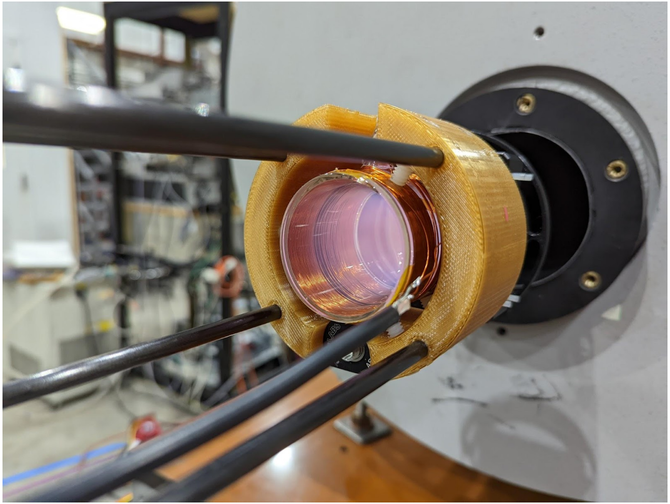

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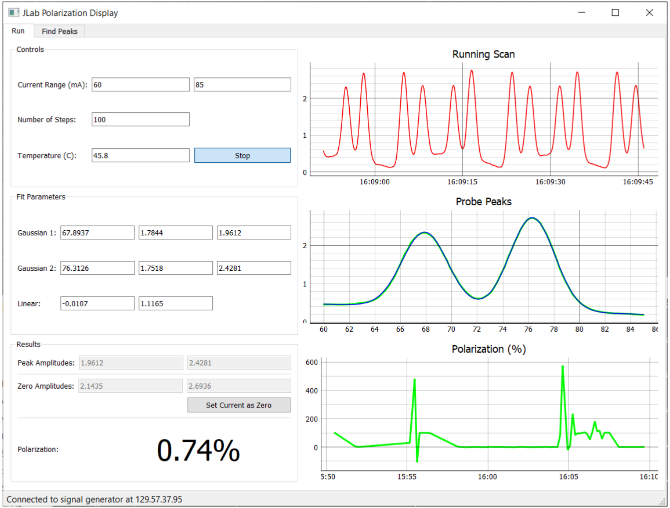

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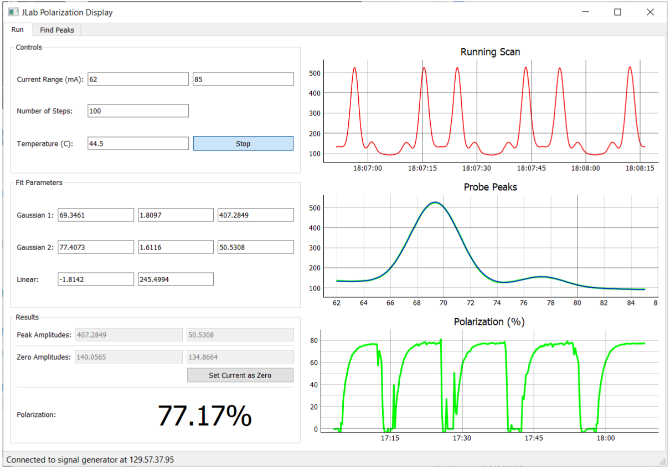

NIM A Paper Accepted (X. Li, *et al.*), Tests at 1.3 mbar

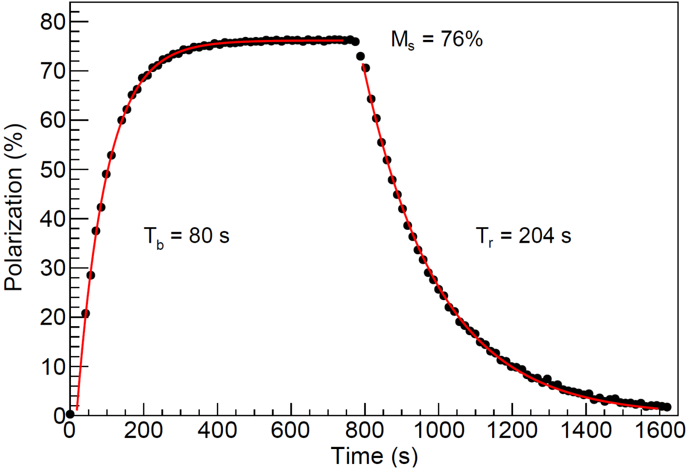

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Table 1: Steady-state nuclear polarization (M_s), build-up time (T_b) and discharge-on relaxation time (T_r) measured at 2, 3 and 4 T using the four optical pumping schemes and a pump laser output power of 3 W. The pumping rate (R) is calculated using Eq. 3.

B (T)	Transition scheme	M_s (%)	T_b (s)	R (atoms/s)	T_r (s)
2	f_2^+	49	113	1.4×10^{16}	278
	f_4^+	75	104	2.3×10^{16}	293
	f_2^-	50	129	1.3×10^{16}	297
	f_4^-	72	116	2.0×10^{16}	286
3	f_2^+	42	193	7.0×10^{15}	380
	f_4^+	70	194	1.2×10^{16}	369
	f_2^-	41	196	6.7×10^{15}	362
	f_4^-	70	193	1.2×10^{16}	374
4	f_2^+	38	226	5.4×10^{15}	388
	f_4^+	72	280	8.3×10^{15}	379
	f_2^-	38	280	4.4×10^{15}	375
	f_4^-	69	224	1.0×10^{16}	404

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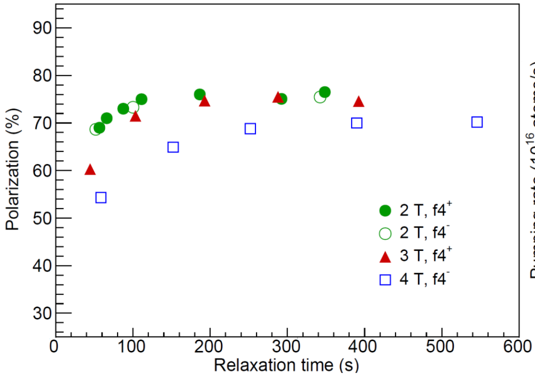

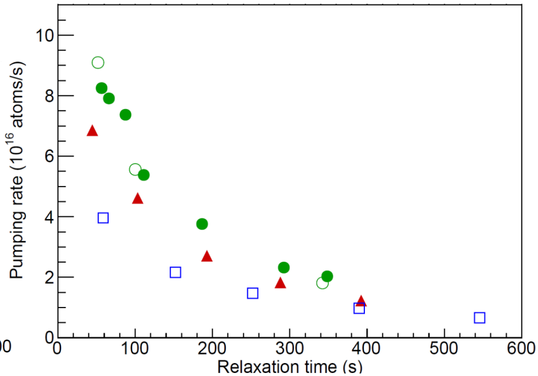

Taken using same cell from BNL tests (Maxwell, 2020). Slightly less polarization.

Preparations for Varied Pressure

- New, valved pumping cell
  - Turbopump, getter, RGA on hand
  - Gas panel in preparation
  - Significant baking, pumping needed to reach clean gas
- Recondenser installed
  - LHe for magnet is costly, inconvenient
  - Operate for months with this setup
- Laser upgrades
  - Old laser fiber repaired
  - New laser with wider 300 GHz tuning band arrived, allows 5 T. Faulty.
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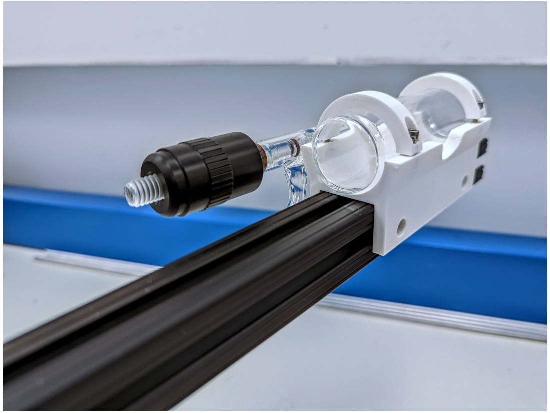

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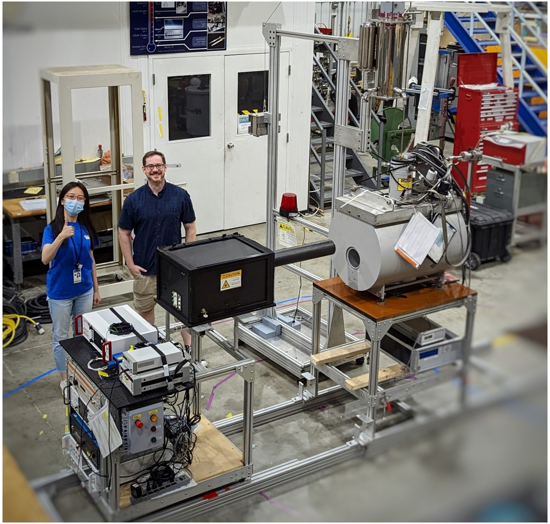
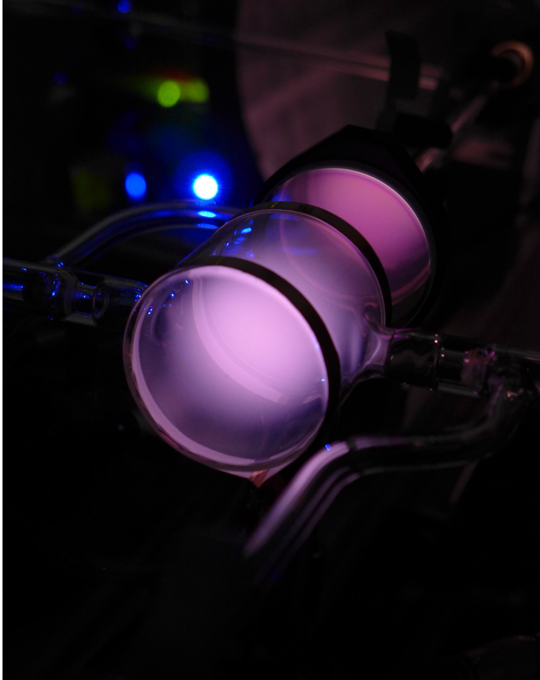


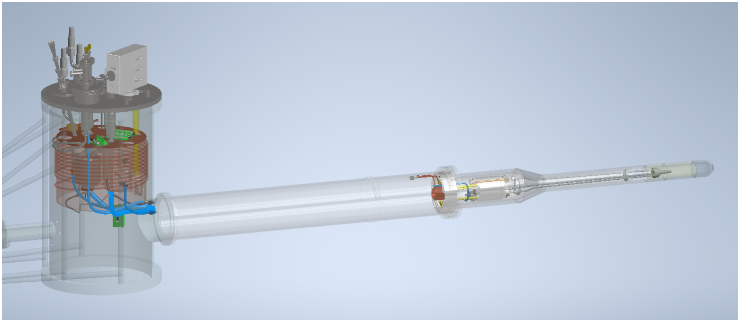
Outline

1. Polarized ^{3}He for Nuclear Physics
   - Optical Pumping
   - Opportunity for a New Target
2. Proposed Target for CLAS12
   - Design
   - Development
3. Outlook
   - Path to In-Beam Tests
   - Transverse Polarization?



New Hall B Cryotarget: Liquid Hydrogen, Helium Targets

- Modular evaporator to allow the mounting of our MEOP cells
- Will provide beam-ready physical, cryogenic infrastructure: get in hall sooner



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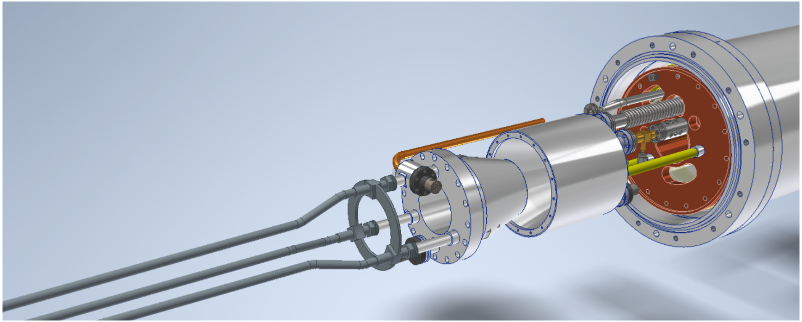

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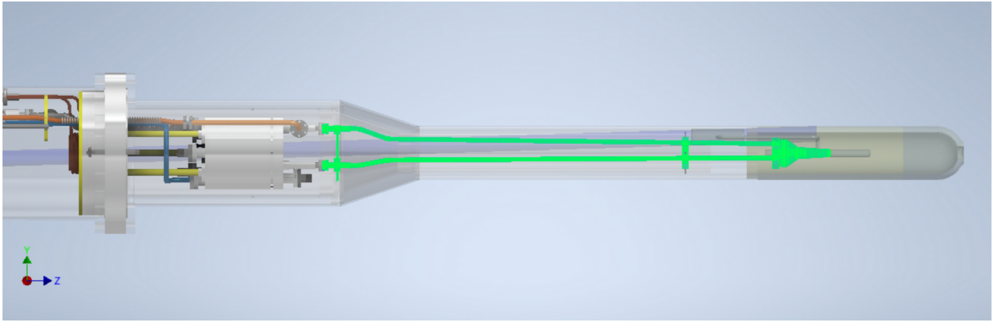

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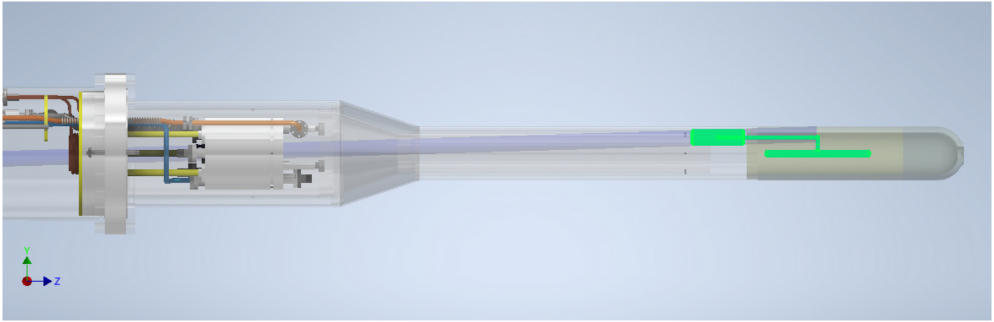

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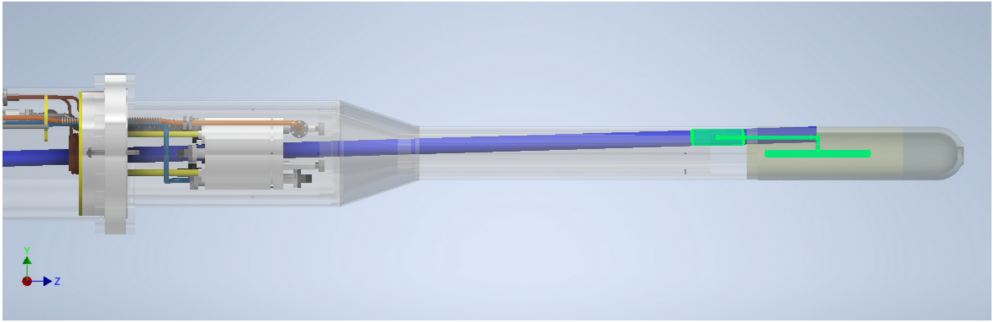

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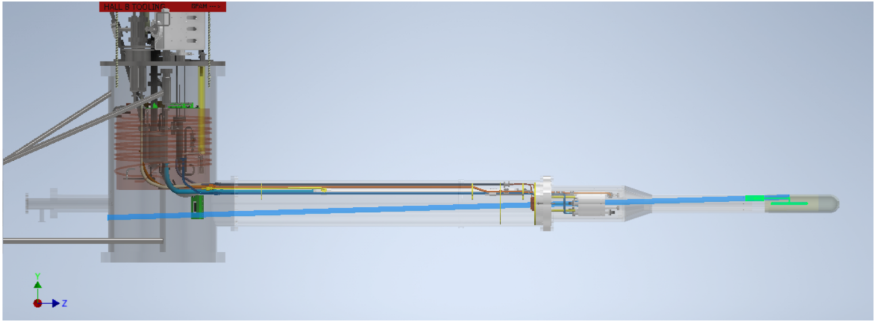

Key Development Questions

- Can we reproduce, improve the polarization performance of the KBL group?
- How much polarization relaxation is expected at 100 mbar and 5 K in 0.5 μA beam while inside a 5 T magnetic field?

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- During the accelerator down before a scheduled cryotarget run, we can install and polarize our MEOP cells
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Projected Schedule

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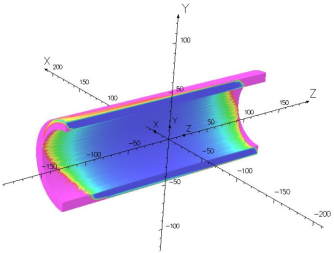
Transverse Polarized ^{3}He in CLAS12?

- Three high-impact Hall B experiments hoped to use transversely polarized HD-Ice Target
- Transverse with CLAS12: bulk superconductor
  - Cancel 2 T ∥ CLAS12 field
  - Create a 1.5 T ⊥ holding field
- For ^{3}He: same but holding field ∼50 G
- Pumping cell in longitudinal field
- Rotate spin adiabatically in transit to target cell



MgB2 cylinder:
86 mm Ø
250 mm long
7 mm wall

1.25 T transverse magnetization
2.0 T axial shield
5x10-3 uniformity (Y_{20}/Y_{00})
over 20 mm radius sphere

M. Lowry

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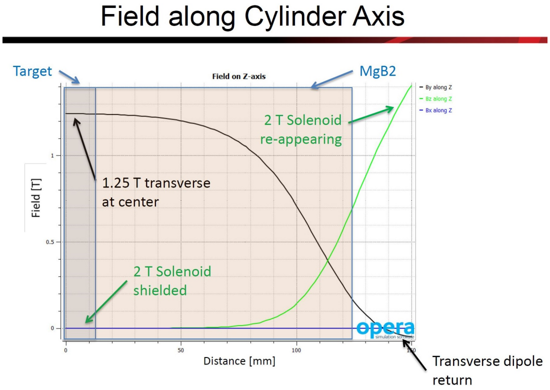

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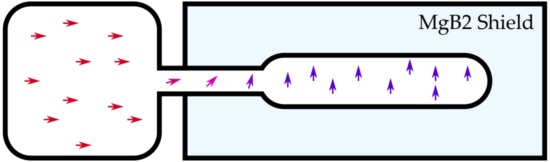


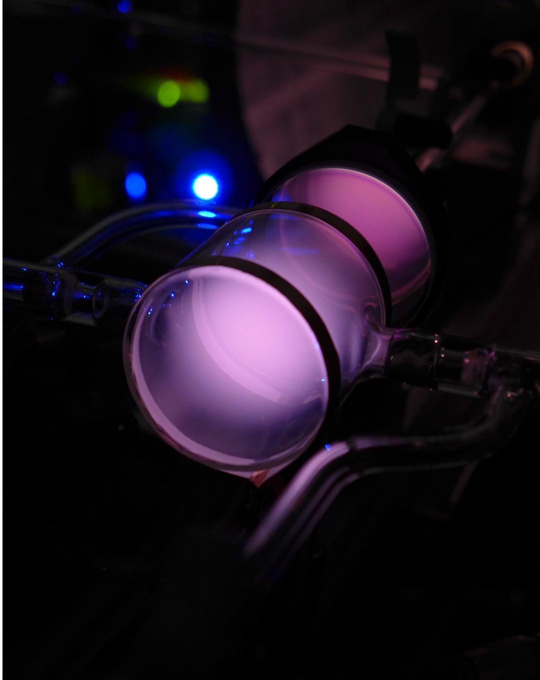
Summary

- A polarized ^{3}He target in CLAS12 would offer a wide new class of observables of quark and gluonic structure in the neutron.
- We are developing a novel target system to operate within CLAS12 without significant modification to the spectrometer.
- Combines the successful design of the Bates 88-02 double-cell cryotarget with new developments in high magnetic field MEOP.
- Polarization tests have begun at Jefferson Lab, with an aggressive development schedule aiming to provide a target to Hall B within the next few years.

CLAS12 Polarized 3He collaboration:

- **MIT**: R. Milner, X. Li
- **JLab**: H. Avakian, J. Brock, C. Keith, J. Maxwell, D. Meekins, D. Nguyen

Thank you for your attention!



Parameter	Bates 88-02 Target Achieved	CLAS12 Target Proposed
Pumping cell pressure (mbar)	2.6	100
Pumping cell volume (cm^3)	200	120
Target cell volume (cm^3)	79	100
Target cell length (cm)	16	20
Number of atoms in pumping cell	1.2×10^{19}	3×10^{20}
Number of atoms in target cell	6×10^{19}	1.5×10^{22}
Holding field (T)	0.003	5
Polarization	40%	60%
Incident electron beam energy (GeV)	0.574	10
Cell temperature (K)	17	5
Target thickness (^{3}He/cm^2)	1.2×10^{19}	3×10^{21}
Beam current (μA)	10	2.5
Luminosity (^{3}He/cm^2/s)	7.2×10^{32}	4.5×10^{34}

Spin-Dependent Scattering from Polarized ^{3}He in CLAS12

- Proposal to JLab PAC 48 for 30 days
  - P_T-dependence of the neutron longitudunal spin structure
  - Nuclear corrections to SIDIS
- Complement to studies on dueteron
- Synergistic with efforts such as SoLID
- Luminosity 2.7×10^{34} nucleons/cm^3/s with 0.5 μA beam current
- Approved with A- rating, conditional on target development