Polarized ^{3}He in High Magnetic Fields

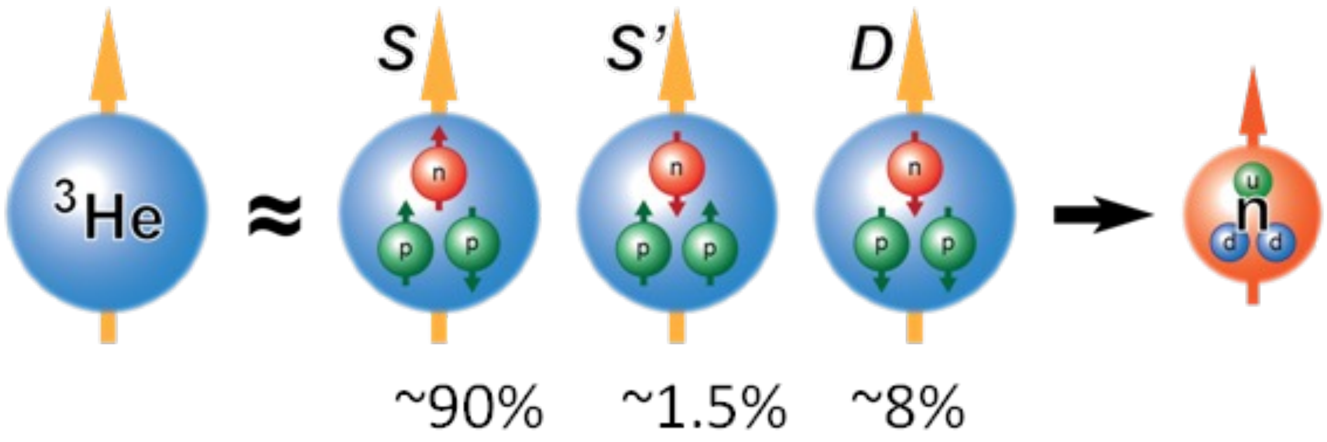
Xiaqing Li (李夏卿)
Shandong University

2nd Workshop on Polarized Beams and Targets
Huizhou, April 2, 2026

Polarized ^{3}He: Effective Polarized Neutron

^{3}He nucleus:

- *S* state ~90%
- Proton spins canceled out
- Neutron carries nuclear spin



Polarized ^{3}He: Effective Polarized Neutron

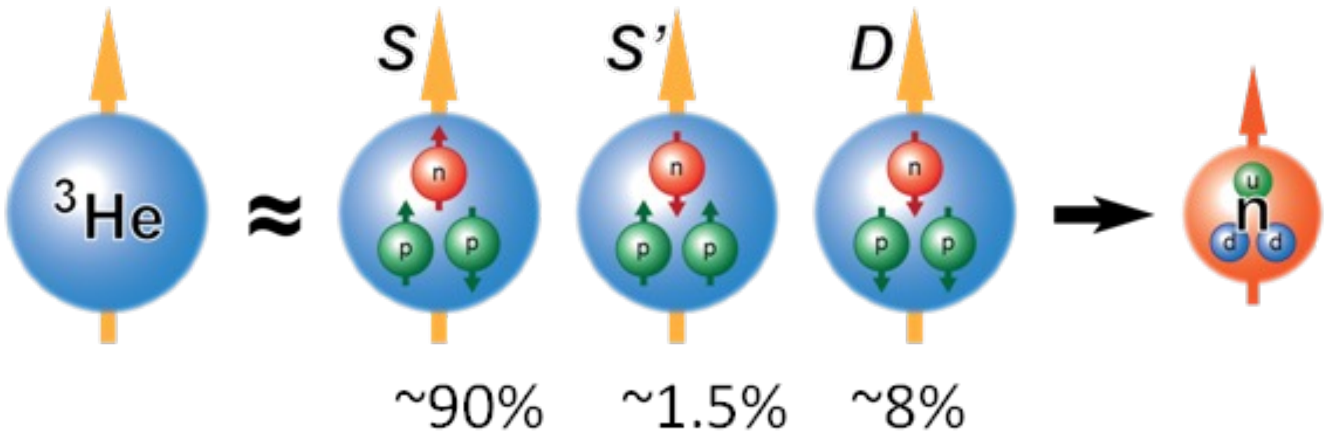
^{3}He nucleus:

- *S* state ~90%
- Proton spins canceled out
- Neutron carries nuclear spin

How to polarize ^{3}He nucleus:

💡 **Optical pumping** techniques

- **Spin-exchange (SEOP)**
- **Metastability-exchange (MEOP)**

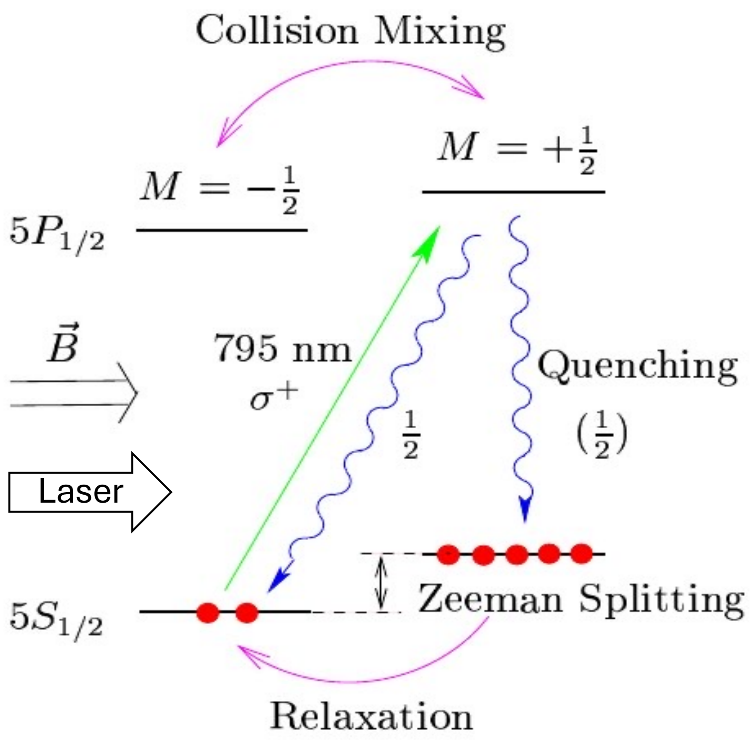


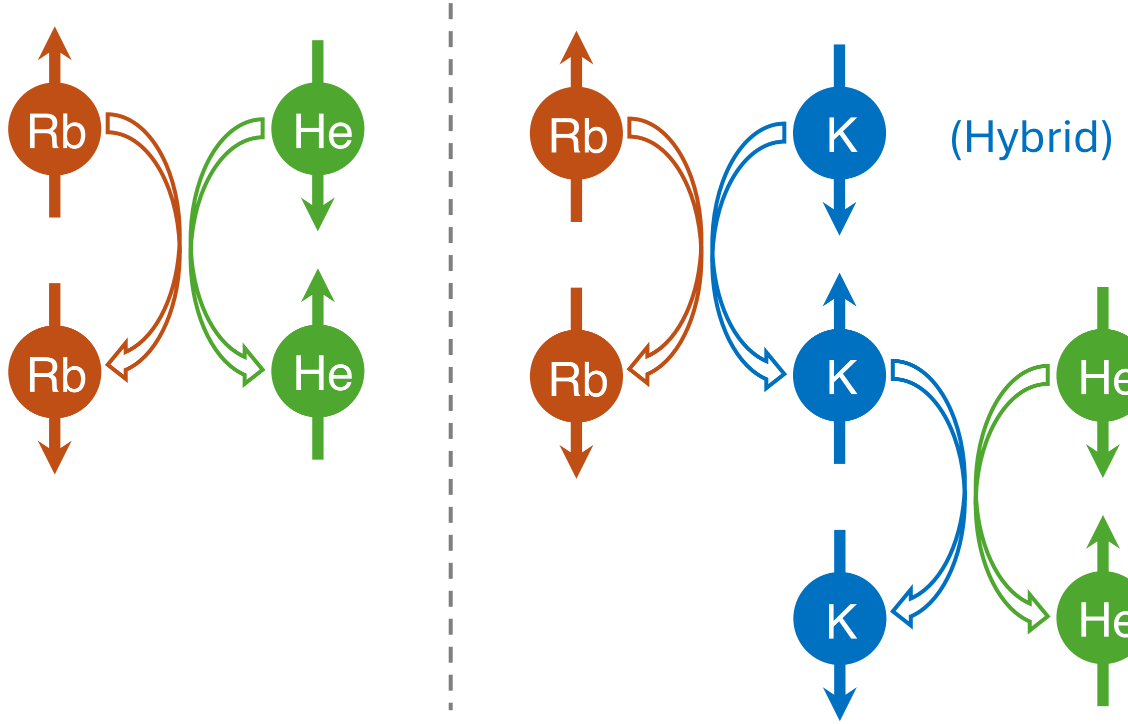
Spin-Exchange Optical Pumping (SEOP)

I. Optically pump alkali-metal atoms in ^{3}He gas mixture

II. Spin exchange between alkali electrons and ^{3}He nuclei

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

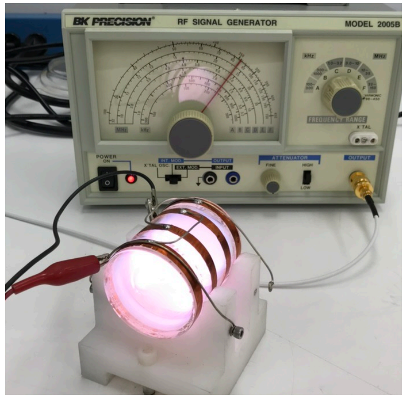




Spin-exchange collisions

Metastability-Exchange Optical Pumping (MEOP)

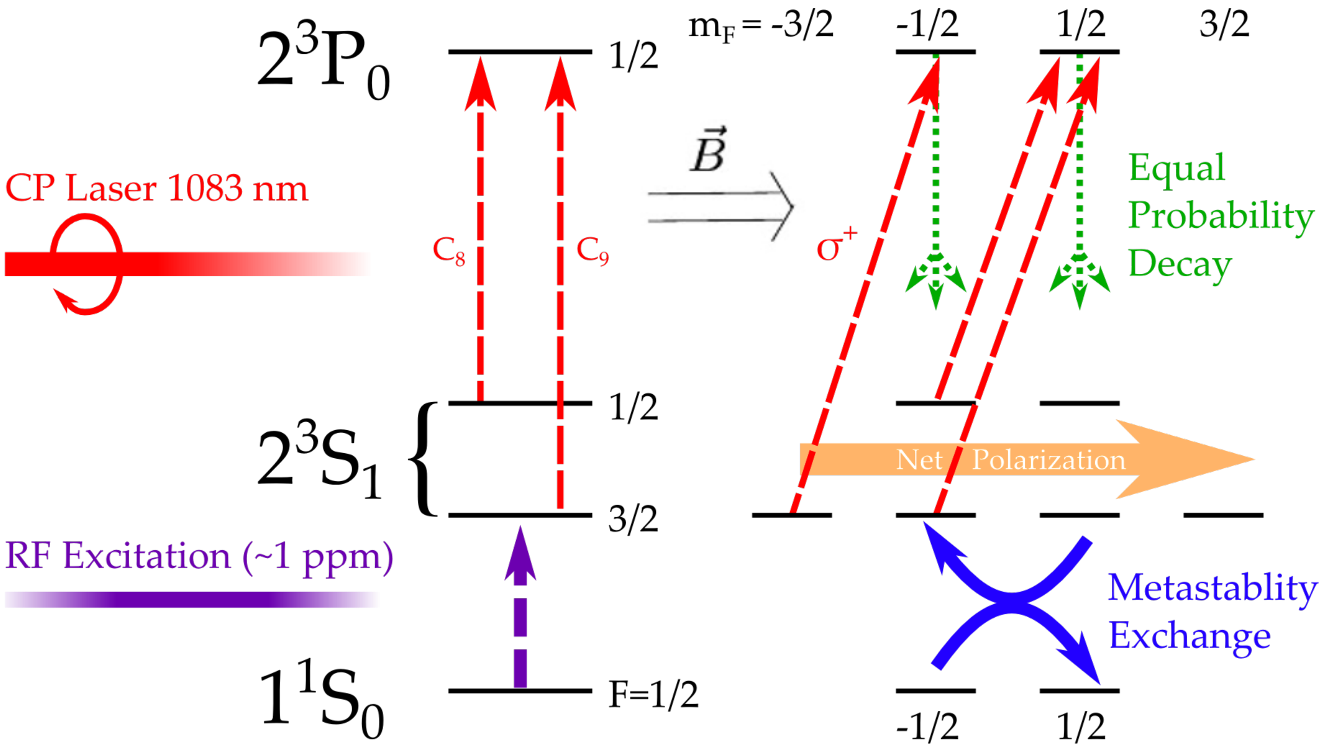
I. RF excitation: promote a small portion of ^{3}He atoms to metastable state 2^3S_1



II. Optical pumping: laser driven polarization of 2^3S_1 atoms

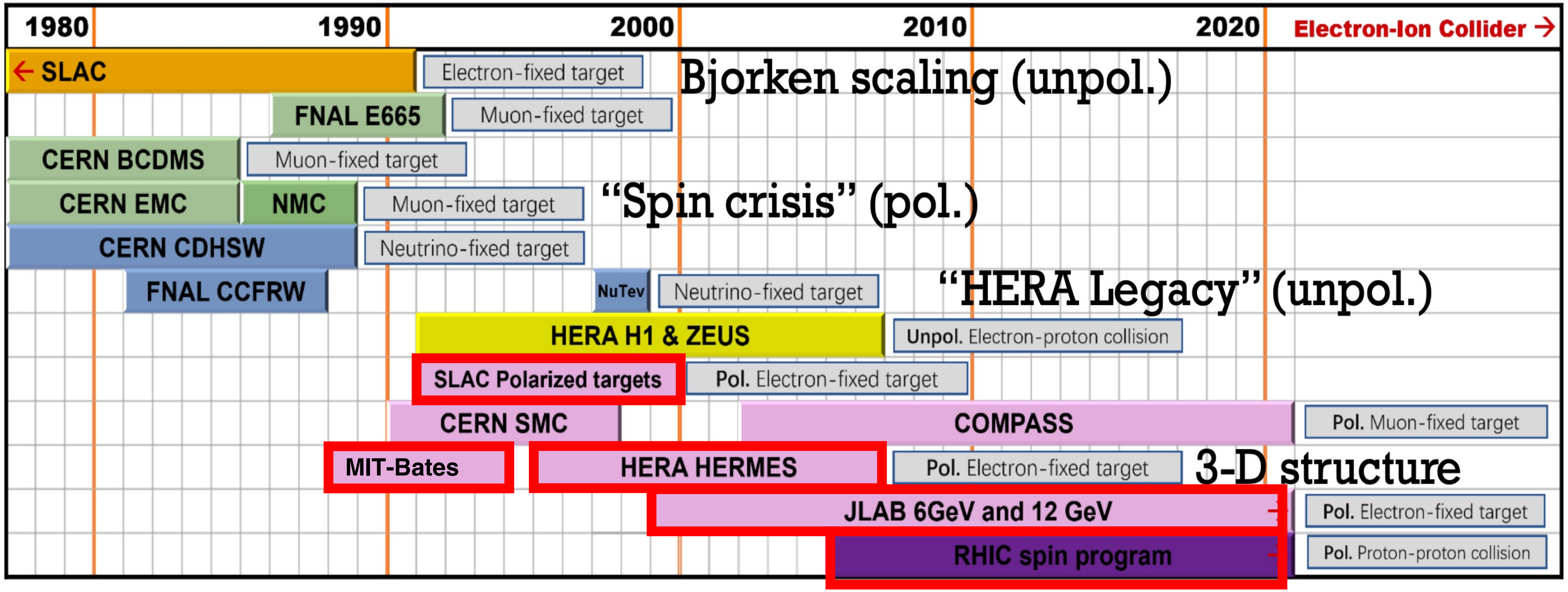
III. Metastability exchange collisions between 2^3S_1 and ground state polarize ^{3}He nuclei

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



Polarized ^{3}He Targets in History

- Widely used in lepton scattering experiments

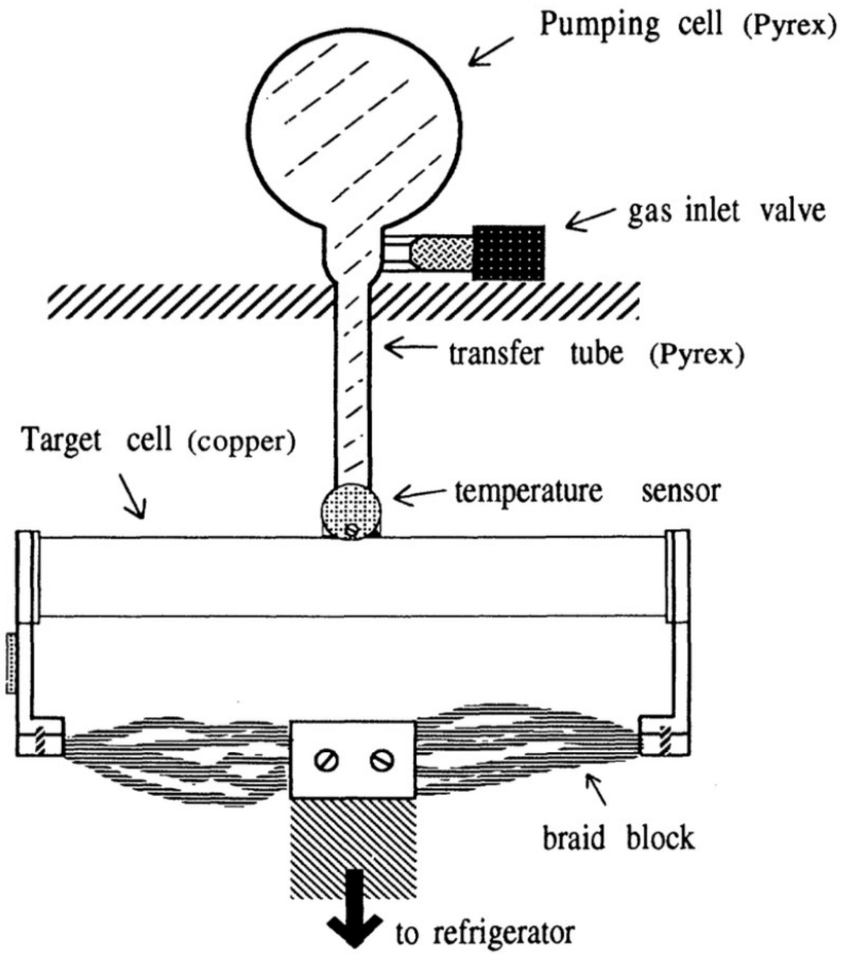


- Study spin structure of the nucleon

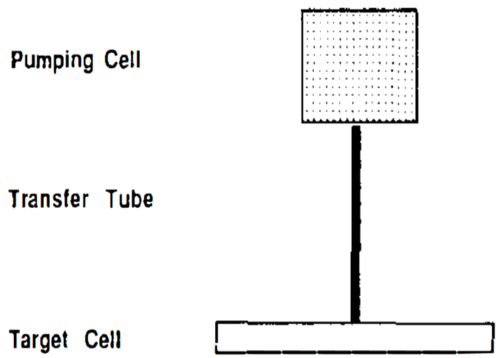
SEOP approach
- MIT-Bates
- SLAC
- JLab
- TUNL

MEOP approach
- MIT-Bates
- HERMES
- MAMI
- (JLab)
- (RHIC)

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



- First laser-driven MEOP polarized ^{3}He target
- Double-cell design
  - Pumping cell: room temperature, 2 mbar
  - Target cell: 17 K, 2 mbar
  - Polarization measured from pumping cell and well inferred for target cell
  - ~40% in-beam polarization achieved



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

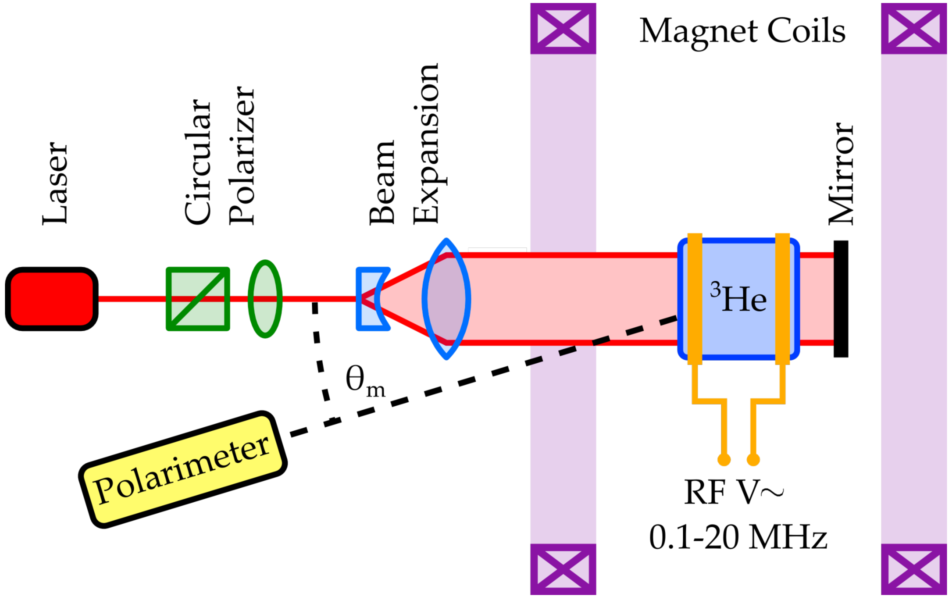
$$\frac{dP_t(t)}{dt} = -\frac{P_t(t)}{\tau_t} + \frac{P_p(t) - P_t(t)}{t_t}$$

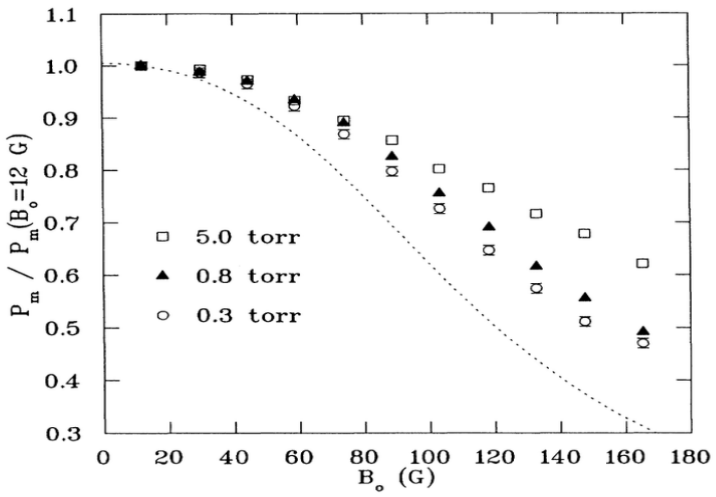
$$P_p(t) = a_s e^{-t/\tau_s} + a_l e^{-t/\tau_l}$$

C.E. Jones et al., PRC 47, 110 (1993); PRL 65, 698 (1990)

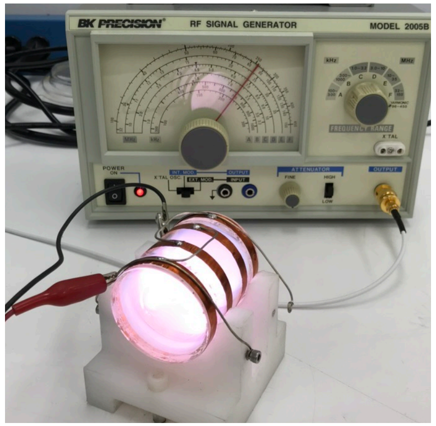
Polarimetry for MEOP (Low Field)

- Measure the degree of circular polarization of the 668 nm flourescence light emitted by the metastable ^{3}He
- Directly obtain the electron polarization
- Infer nuclear polarization by NMR calibration
- Only work in low magnetic fields



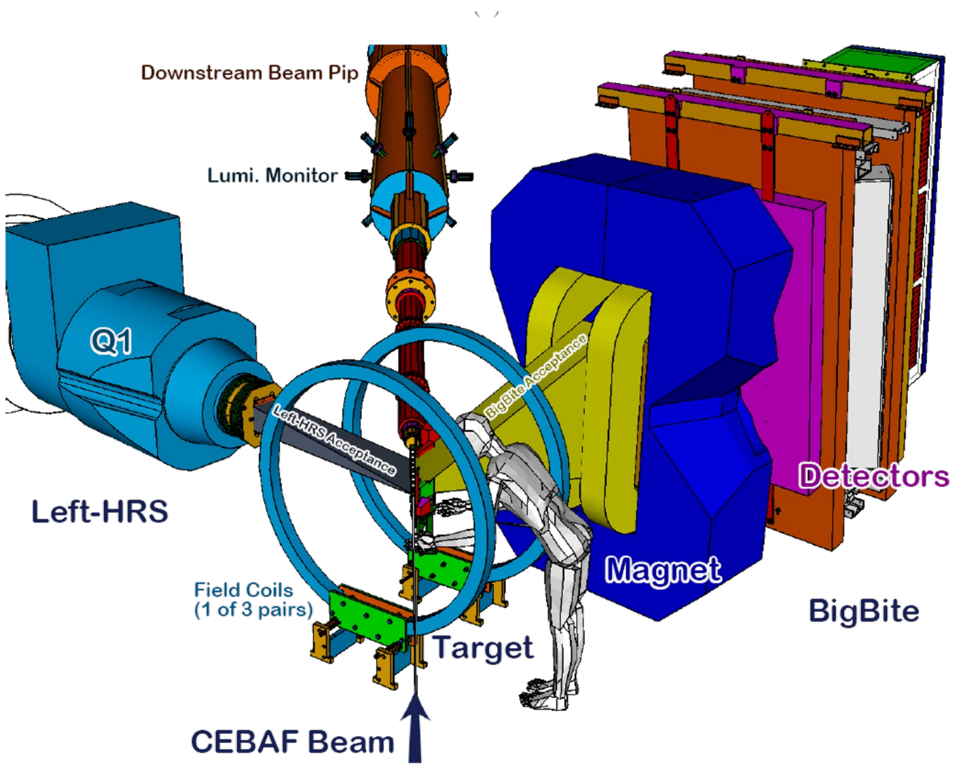


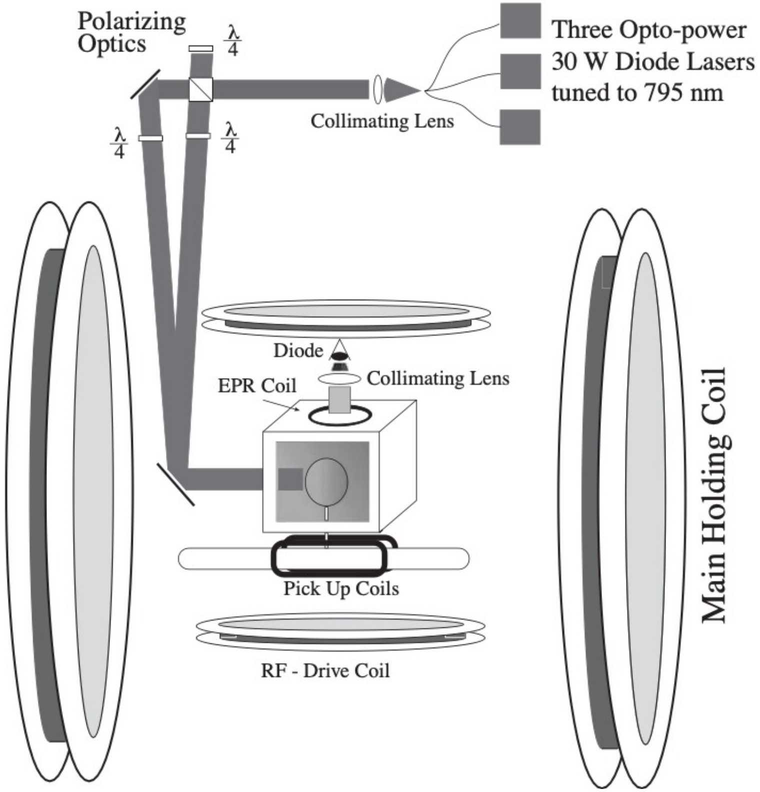
J.D. Maxwell et al., Nucl. Instr. and Meth. A 764, 215 (2014)

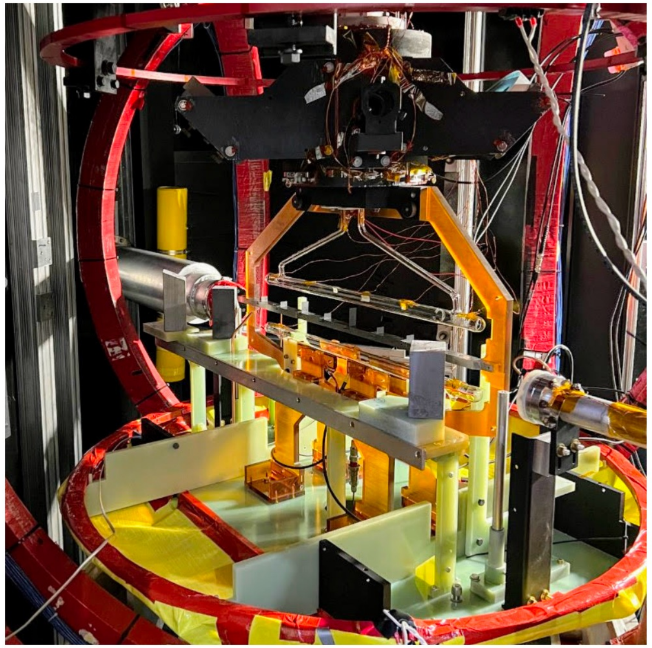


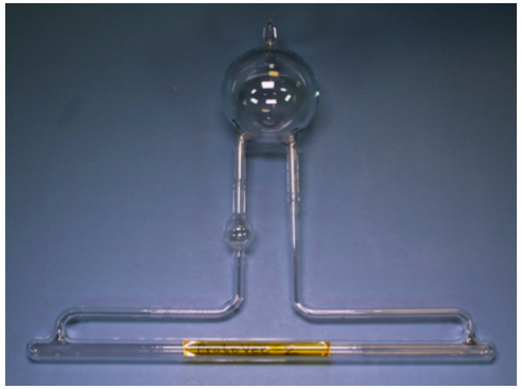
W. Lorenzon et al., Phys. Rev. A 47, 468 (1993)

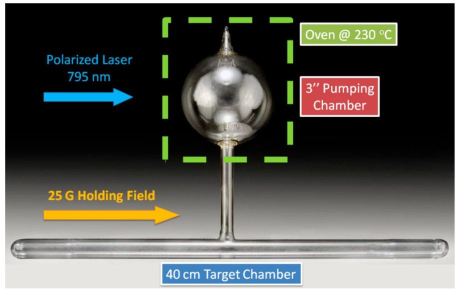
Polarized ^{3}He Targets at Jefferson Lab Hall A











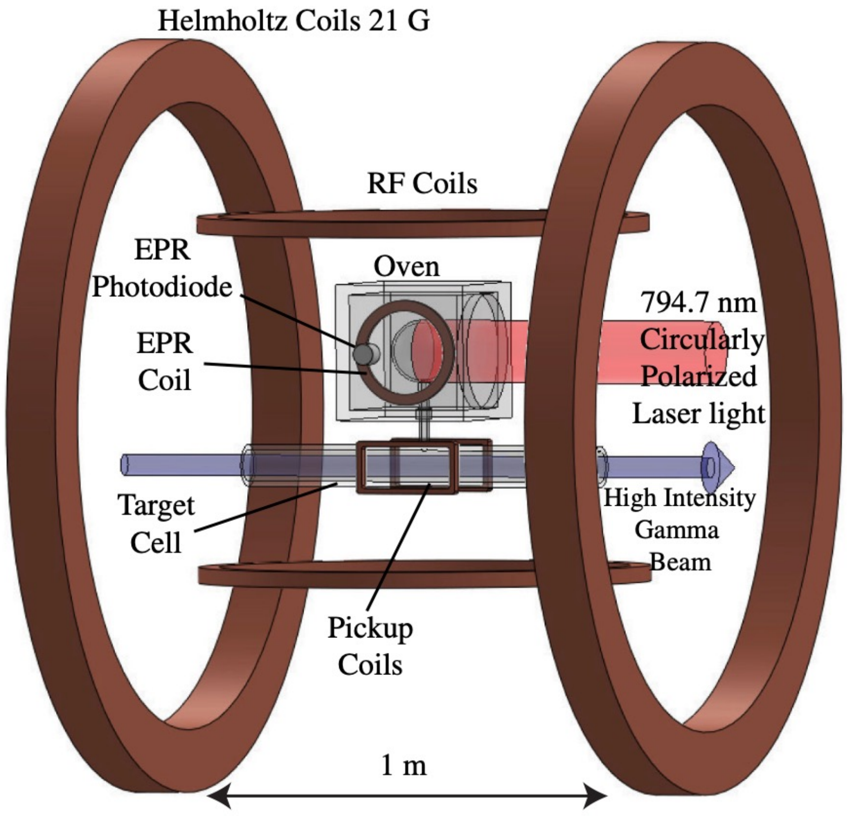
^{3}He nuclear polarization: 30-55%

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

Polarimetry for SEOP

➢ Nuclear Magnetic Resonance (NMR)
- 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 (EPR)



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

Polarized ^{3}He in High Magnetic Fields

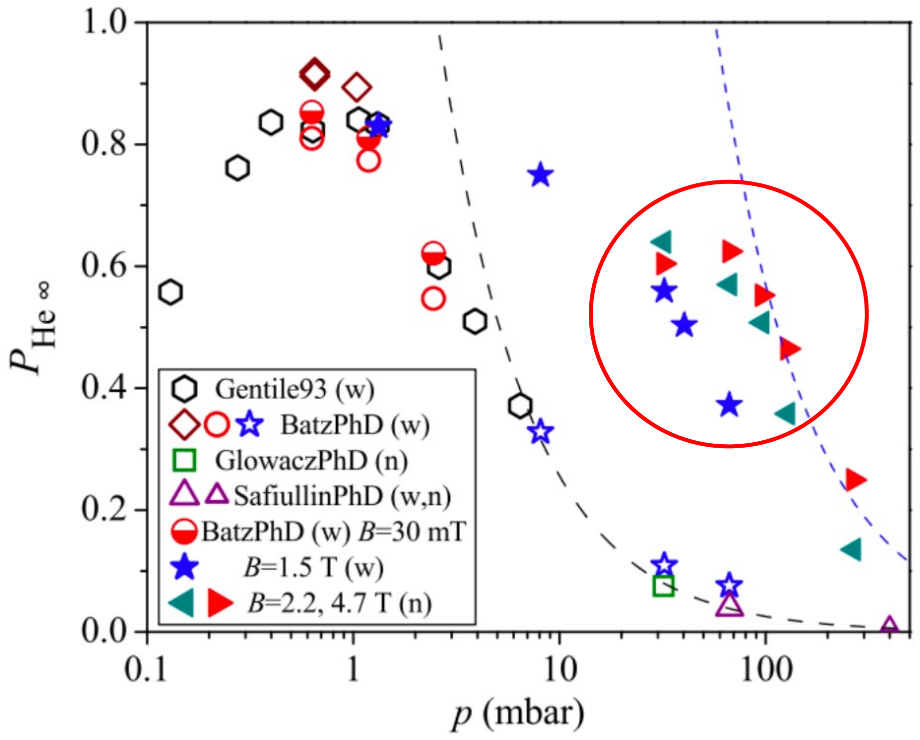
- Historically impossible
  - For SEOP due to increasing wall relaxation
  - For MEOP due to hyperfine decoupling

- High-field MEOP breakthrough in 2010's
  - Research at Laboratoire Kastler Brossel, ENS, Paris motivated by MRI demands
  - MEOP efficient at higher pressures and high fields

    Courtade *et al.*, Hyperfine Interactions 127, 451 (2000)

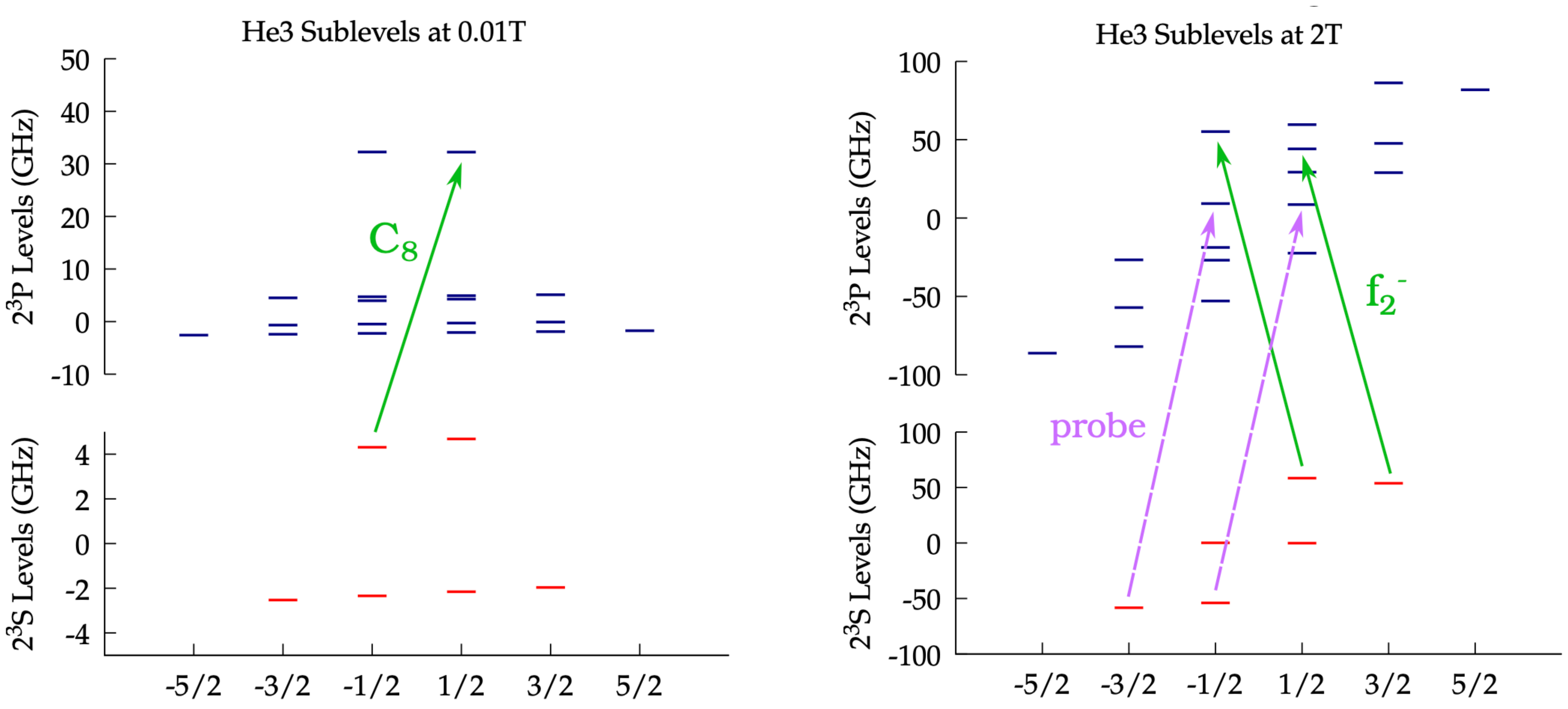
  - Successfully produced nearly 60% polarization at 100 mbar and 4.7 T

    Nikiel-Osuchowska *et al.*, Eur. Phys. J. D 67, 200 (2013)



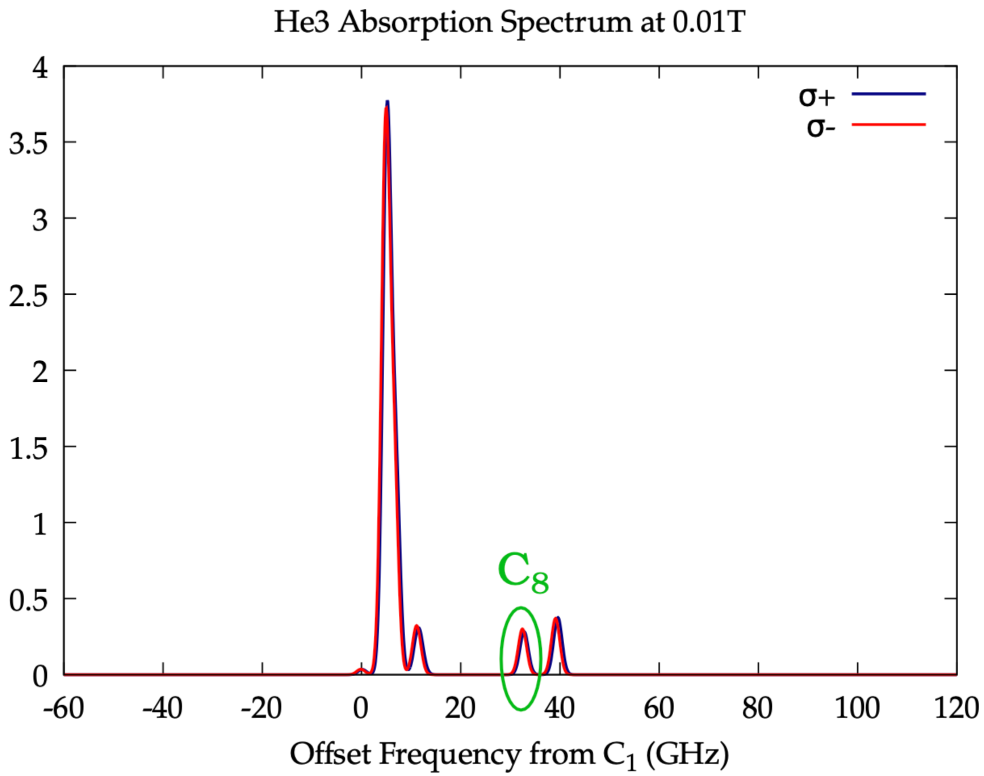
T.R. Gentile et al., Rev. Modern Phys. 89, 045004 (2017)

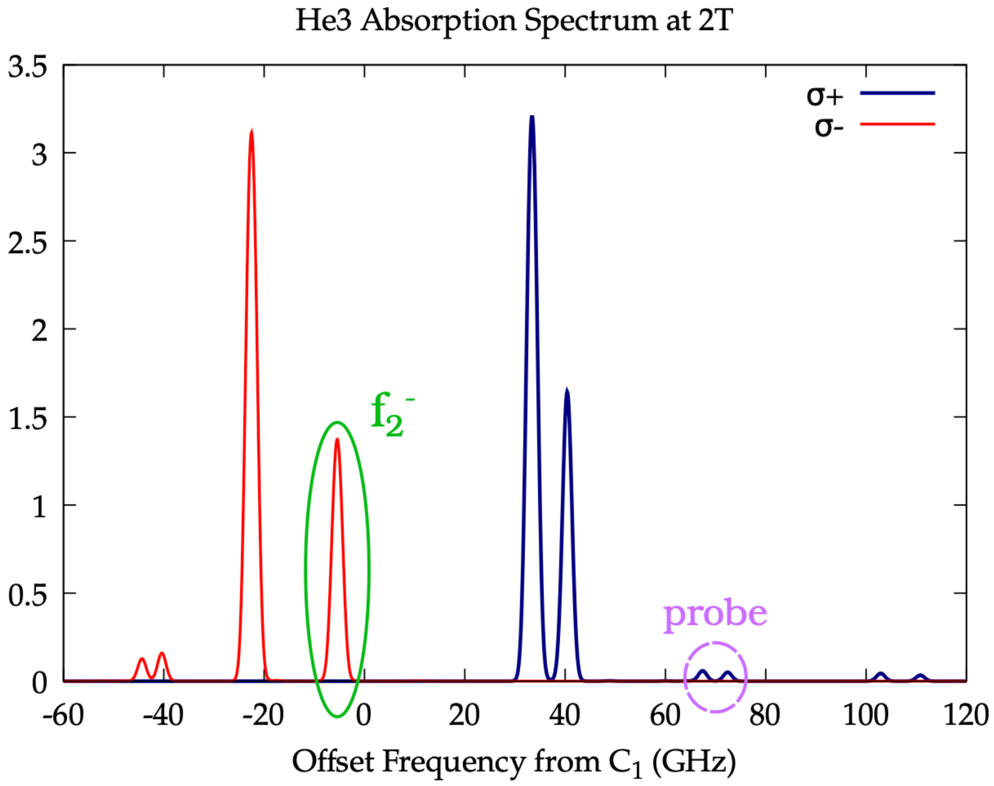
Zeeman Sublevels Significantly Modified in High Magnetic Fields



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

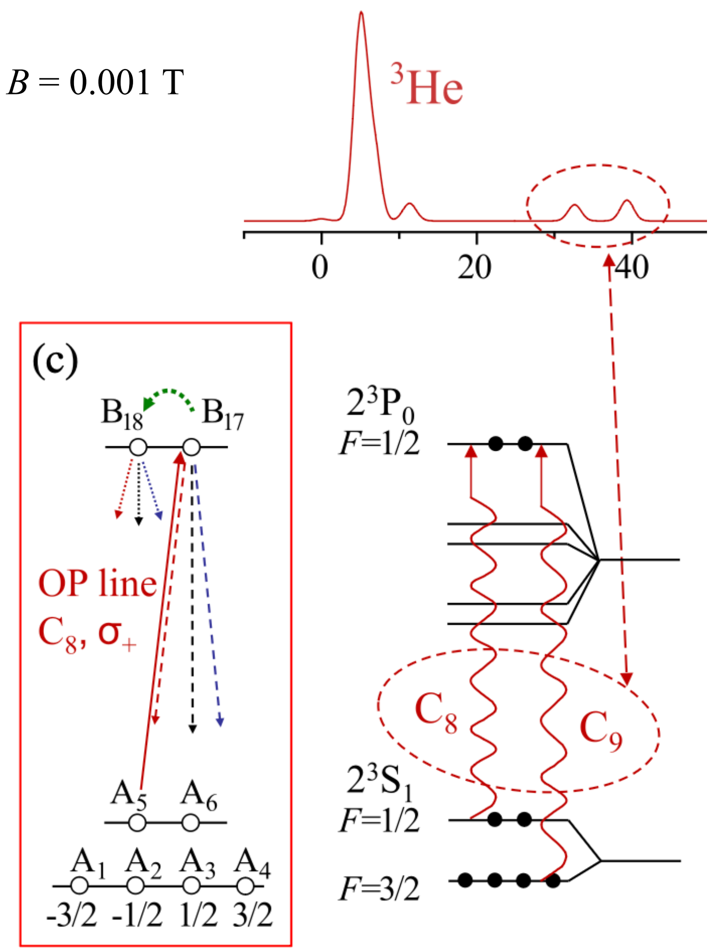
Zeeman Sublevels Significantly Modified in High Magnetic Fields

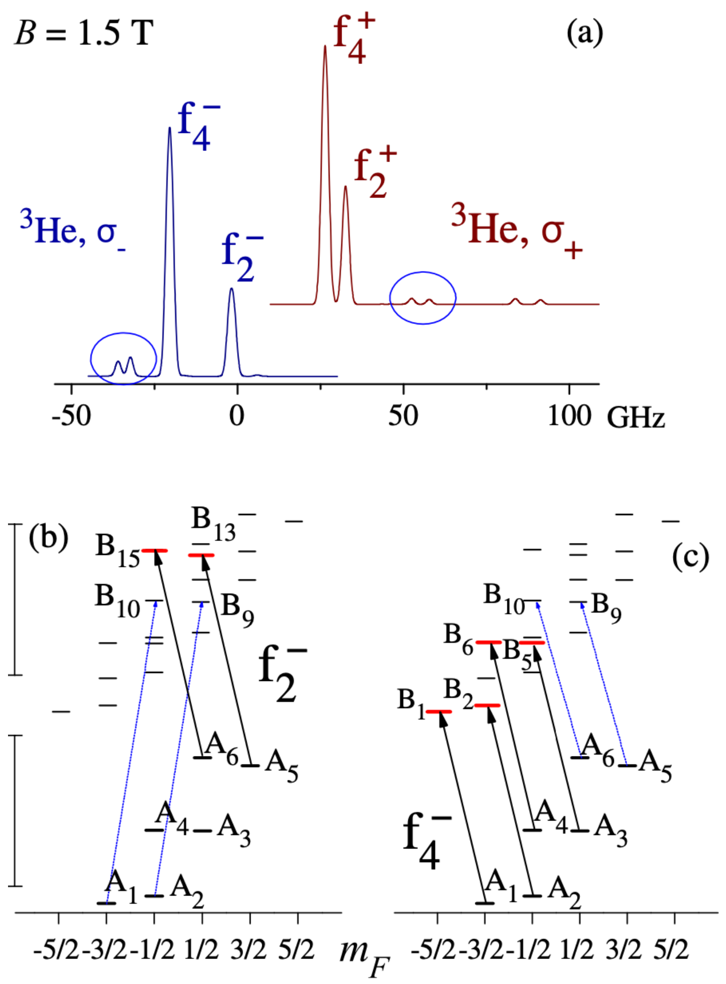




Figures based on Courtade (2002), Nikiel (2013), from calculation by Nacher.

Low Field vs. High Field MEOP

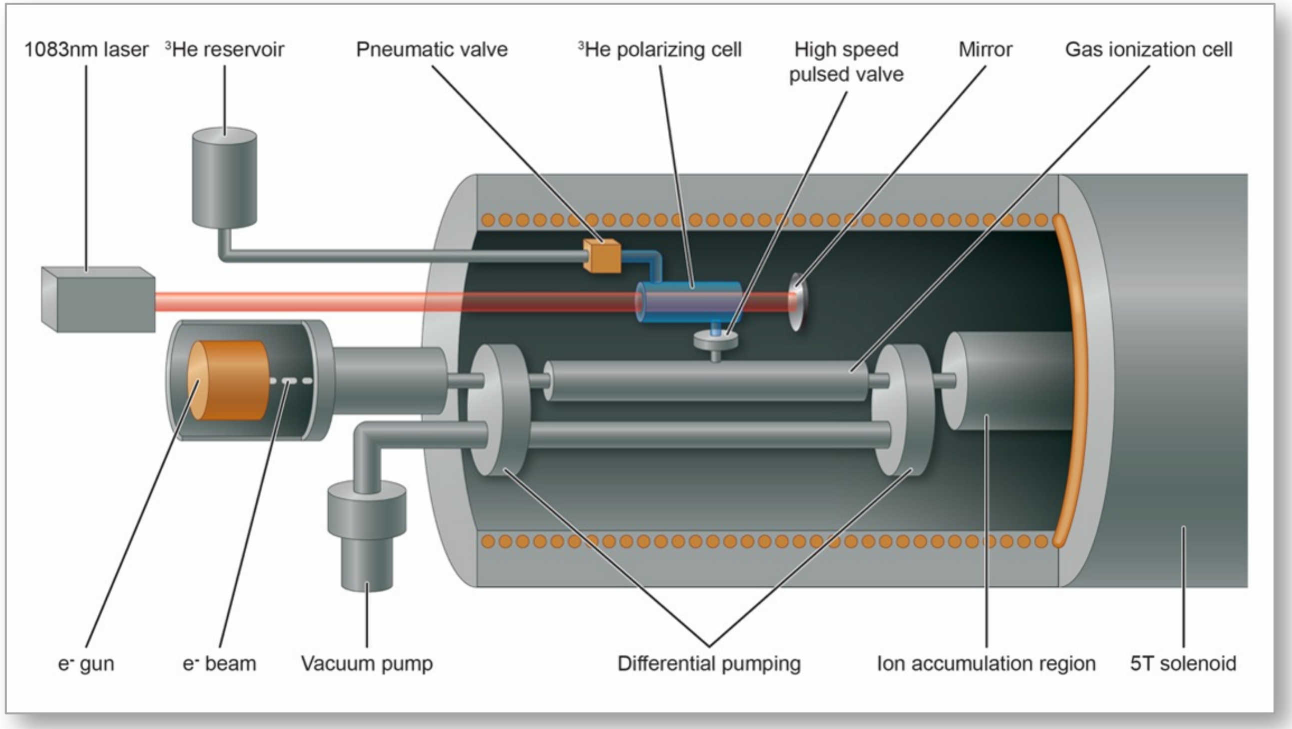


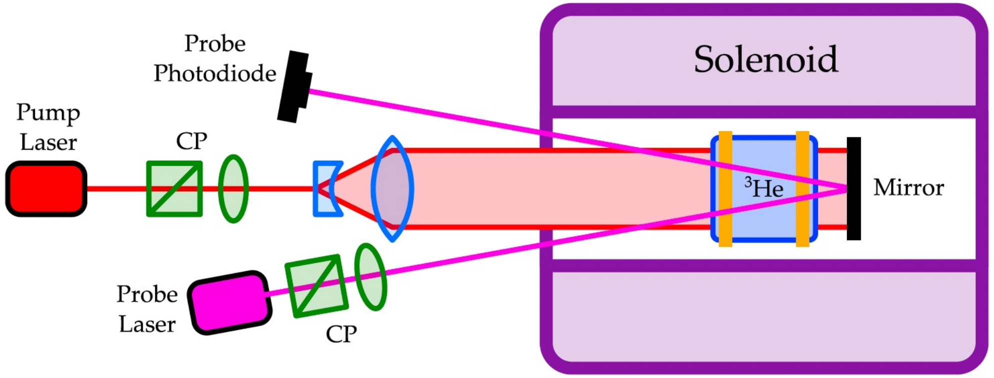


T.R. Gentile et al., Rev. Modern Phys. 89, 045004 (2017)

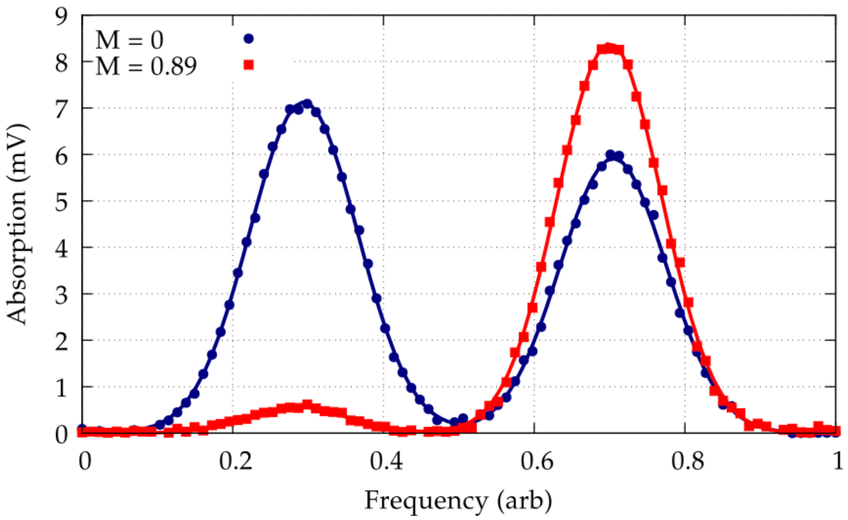
Polarized $^3He^{++}$ Source for the Future EIC

- Polarizing within 5 T field using MEOP, then transfer into EBIS for ionization and extraction
- High-field polarimetry method for MEOP





Nuclear Inst. and Methods in Physics Research, A 959 (2020) 161892



Polarized $^3He^{++}$ Source for the Future EIC

- First high-field MEOP application in high energy nuclear physics
- On-going effort by BNL-MIT collaboration

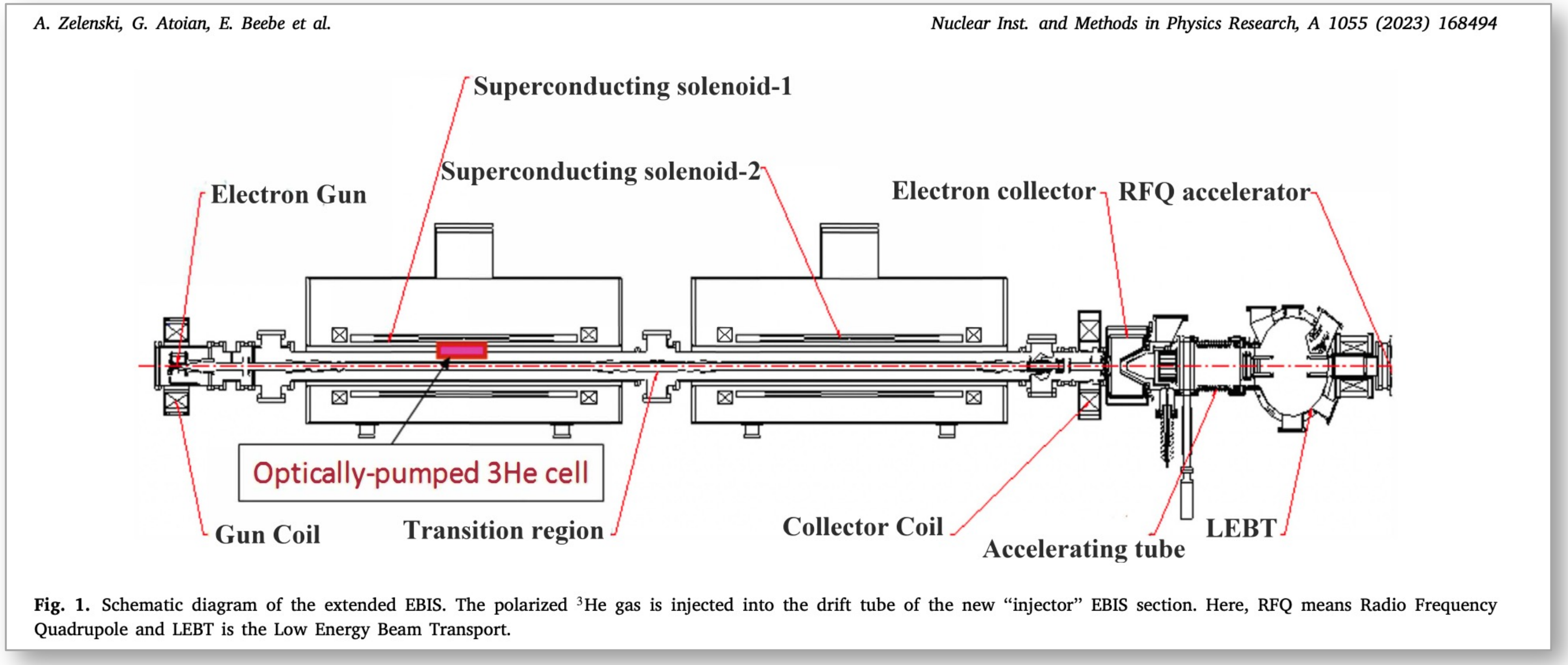
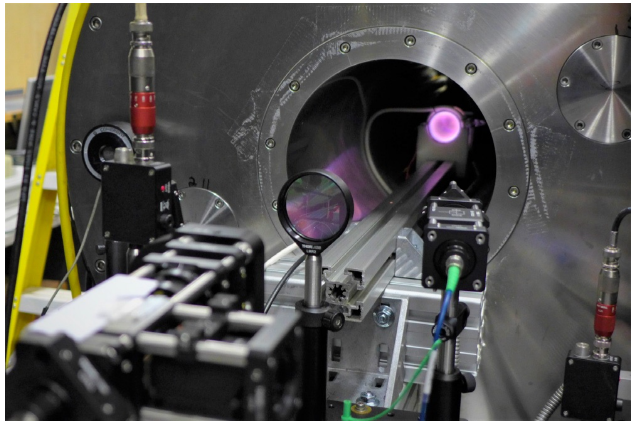
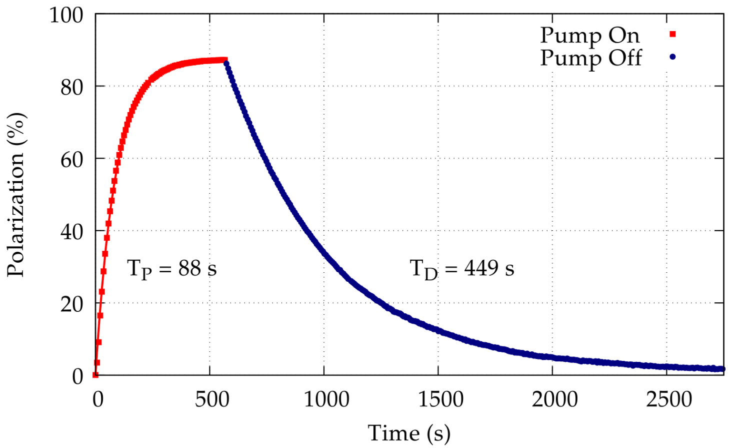


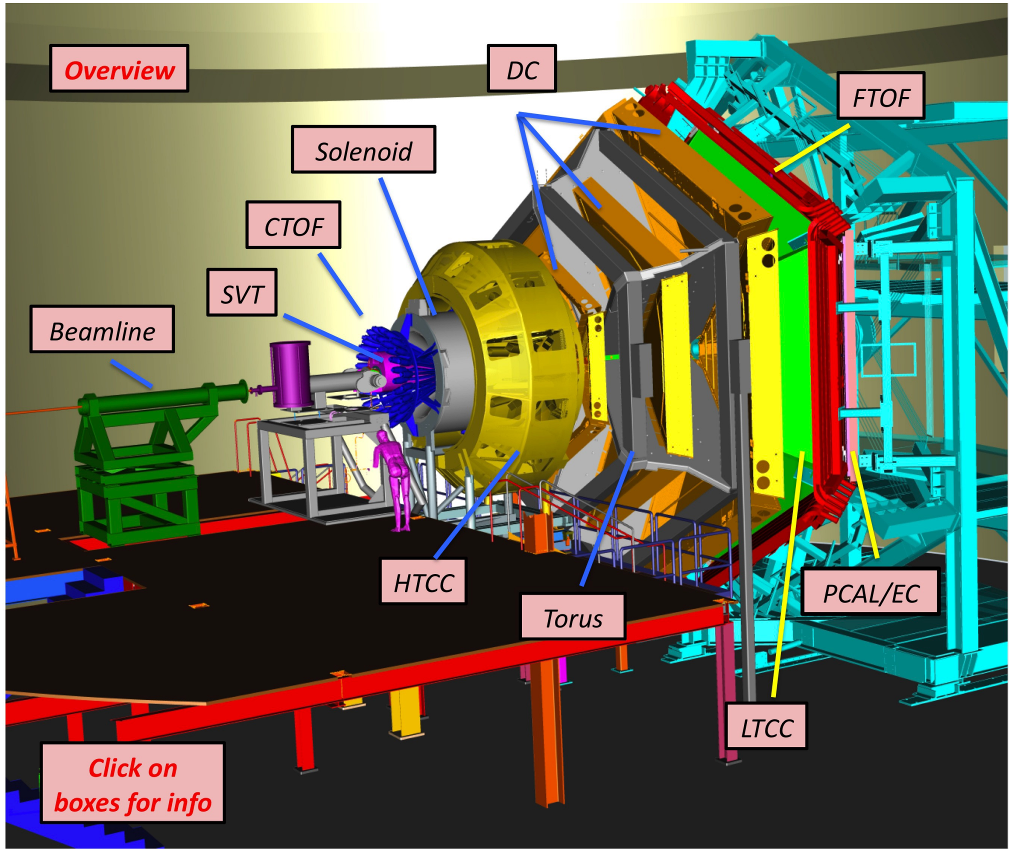
Fig. 1. Schematic diagram of the extended EBIS. The polarized ^{3}He gas is injected into the drift tube of the new "injector" EBIS section. Here, RFQ means Radio Frequency Quadrupole and LEBT is the Low Energy Beam Transport.



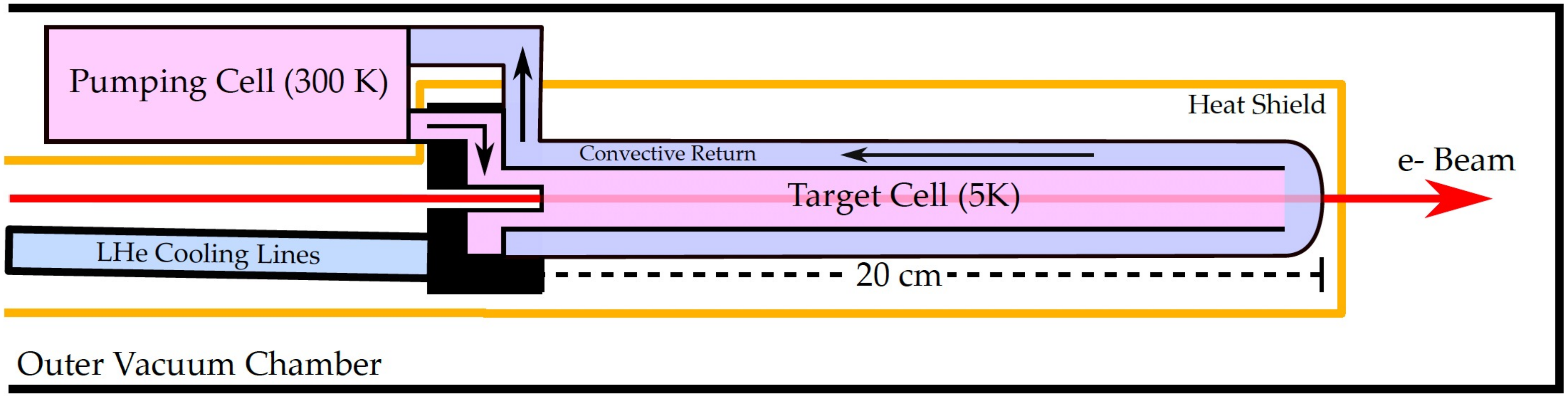


Novel Polarized ^{3}He Target at JLab

- First high-field polarized ^{3}He target used for scattering experiments
- Designed for spin-dependent electron scattering using a polarized ^{3}He target
  - ➢ **SIDIS and nucleon spin structure**
  - ➢ Tagged DIS (deuteron tagging)
  - ➢ Quasi-elastic scattering
  - ➢ Nuclear corrections to SIDIS
  - ➢ Deeply virtual exclusive processes
- Approved for 30 days of running at 10.6 GeV electron energy upon target construction
- Ongoing target R&D by JLab-MIT-UTK-SDU



Novel 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

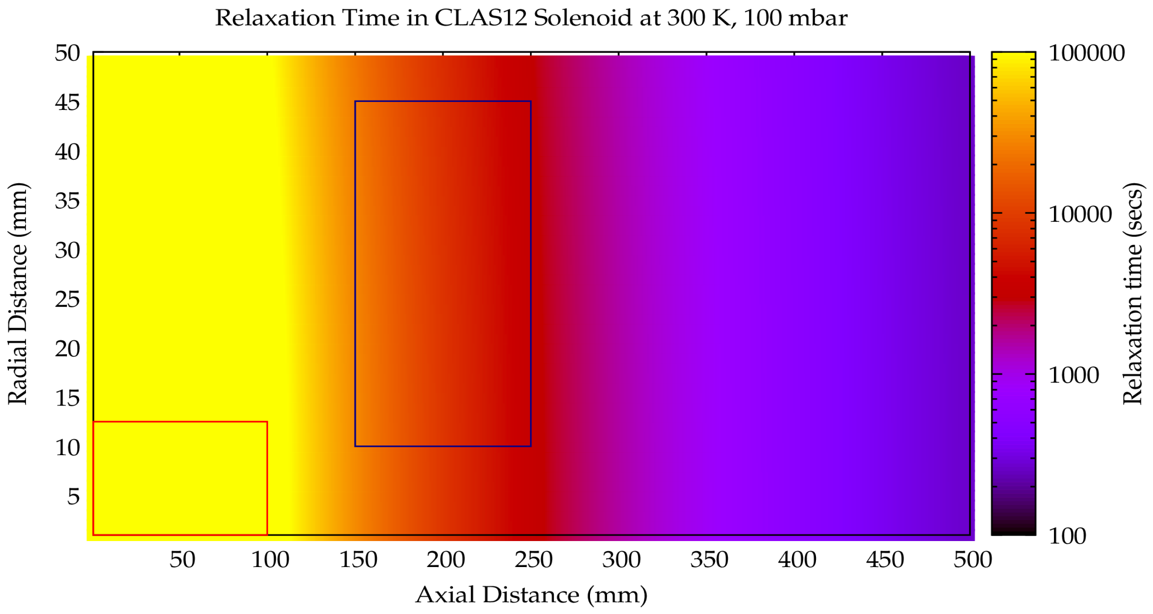
Target cell (5 K)

- 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

^{3}He 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)

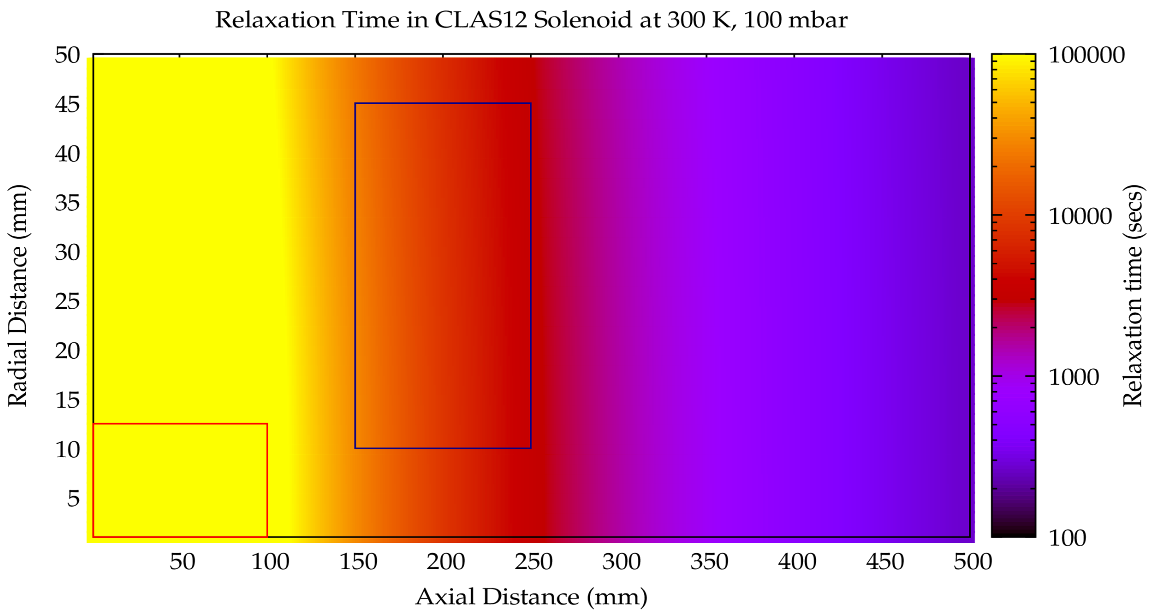


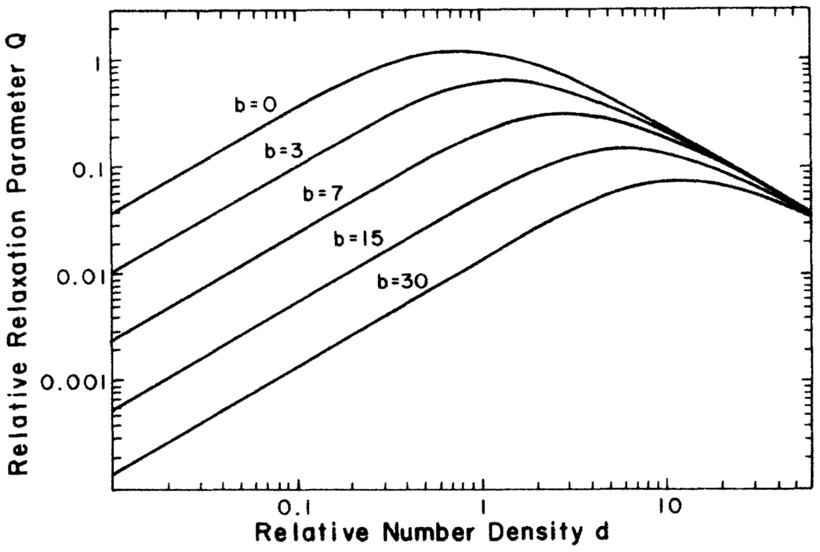
^{3}He Depolarization Mechanisms

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

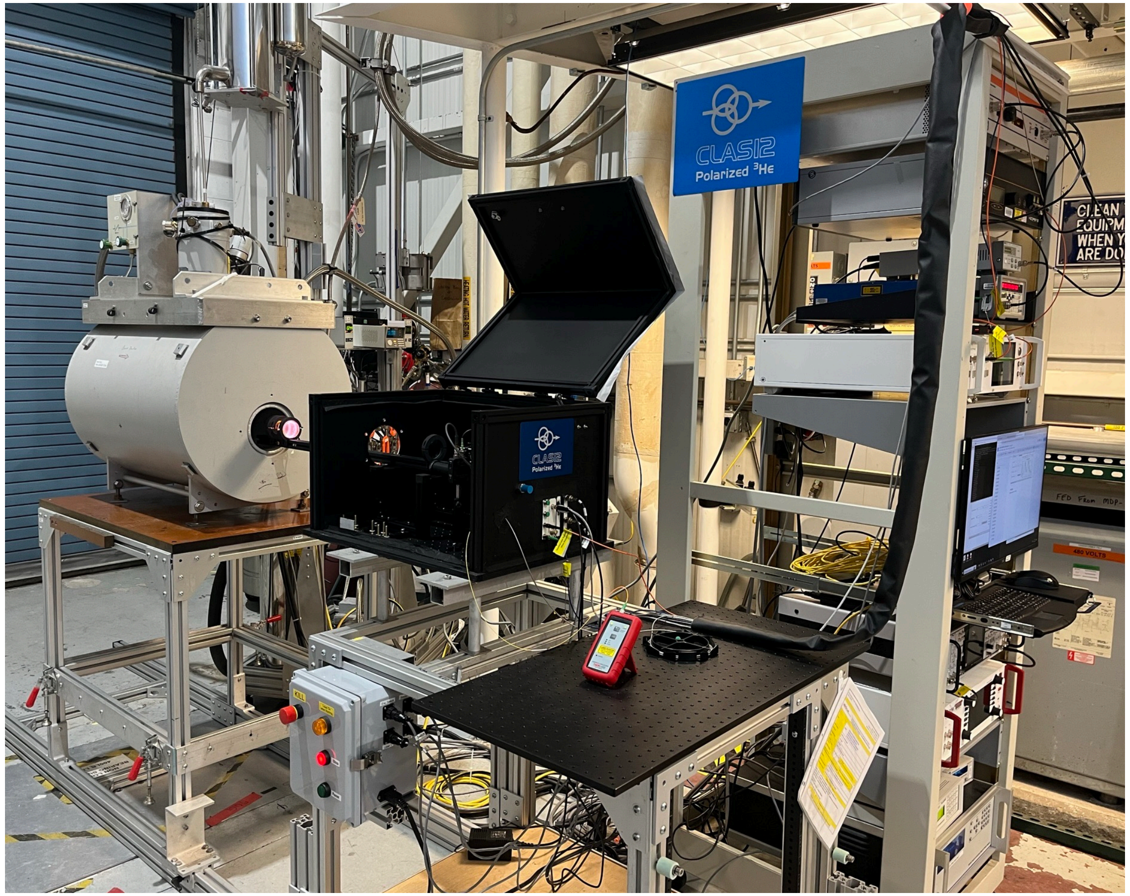
    J.D. Maxwell and R.G. Milner, Nucl. Instr. and Meth. A **1012,** 165590 (2021)
- Ionizing radiation
  - $^3He_2^+$ ions from the beam
  - suppressed in higher fields

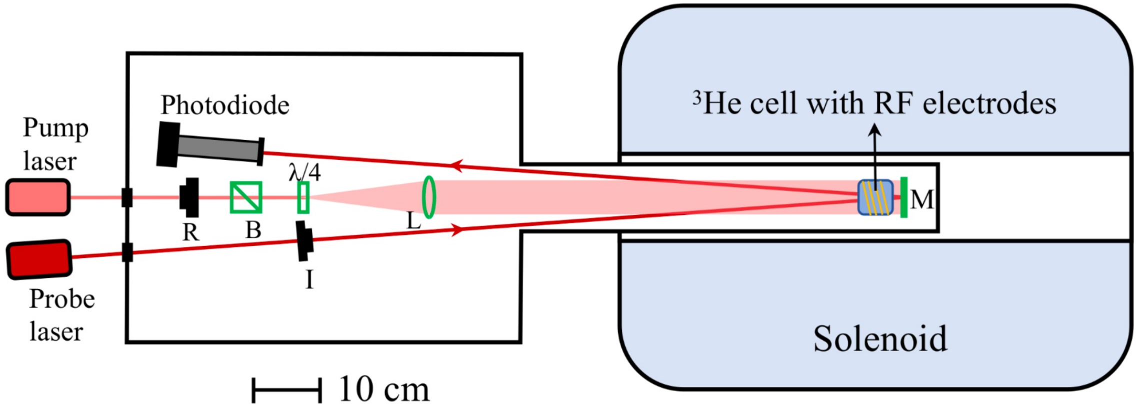
    K. Bonin *et al.*, Phys. Rev. A **37**, 3270 (1988)
  - to be validated by in beam tests

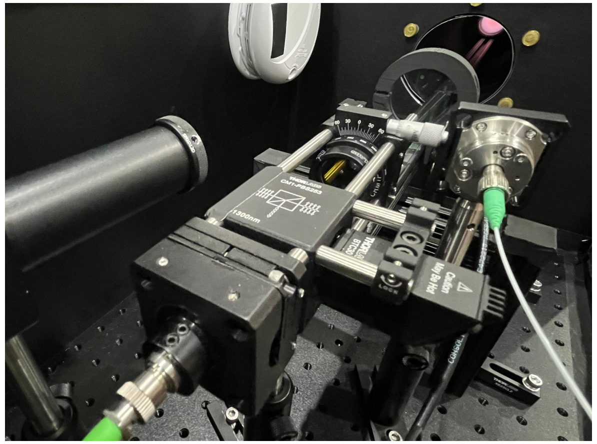




Systematic Studies for High Field MEOP





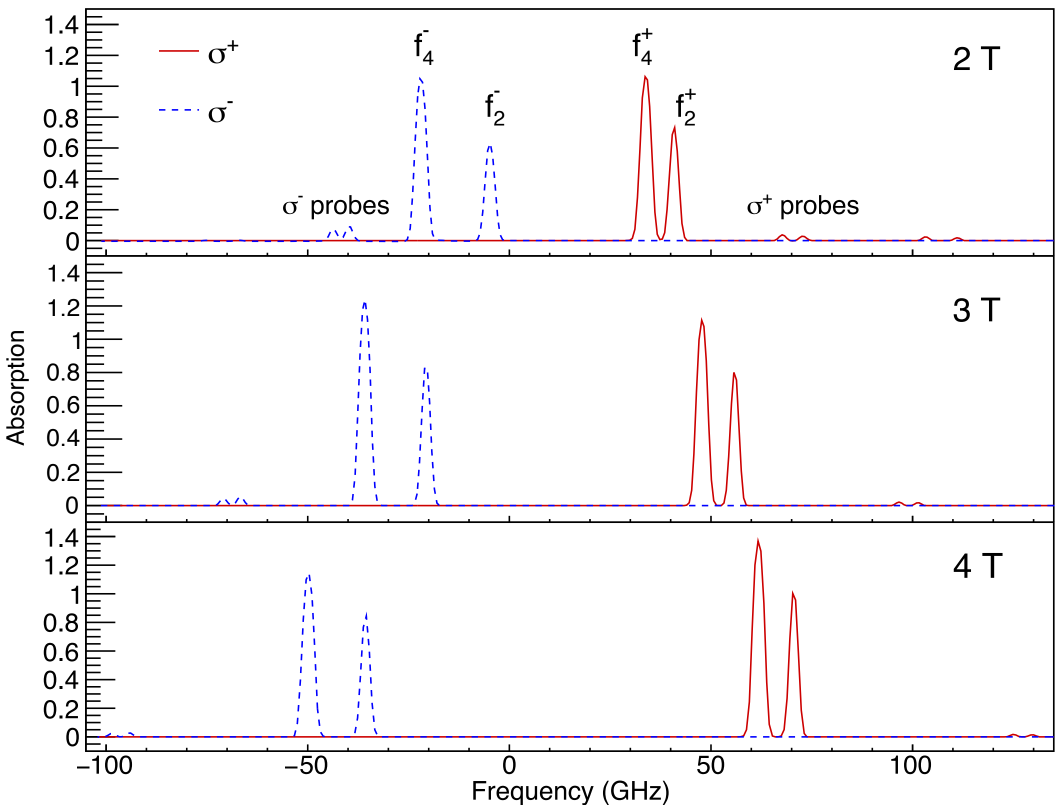


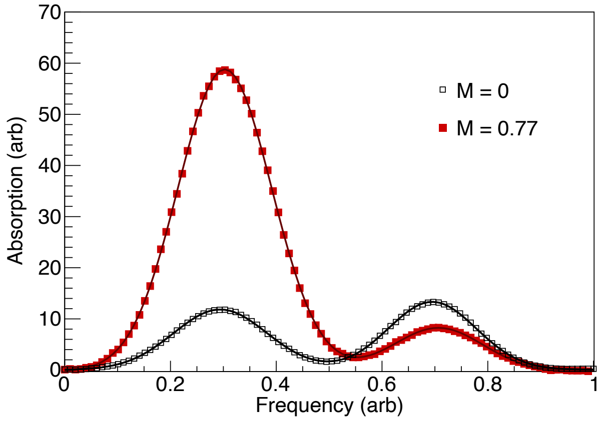
B = 0

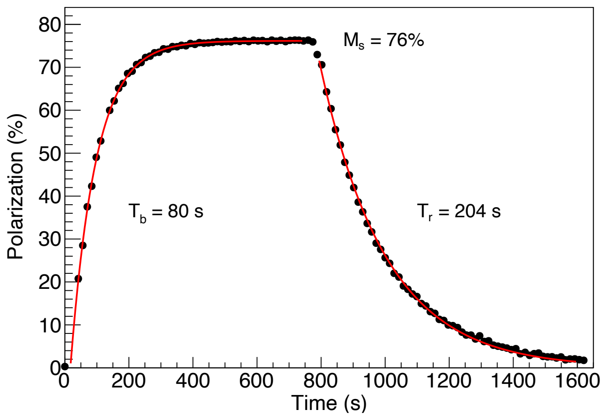
B = 2 T

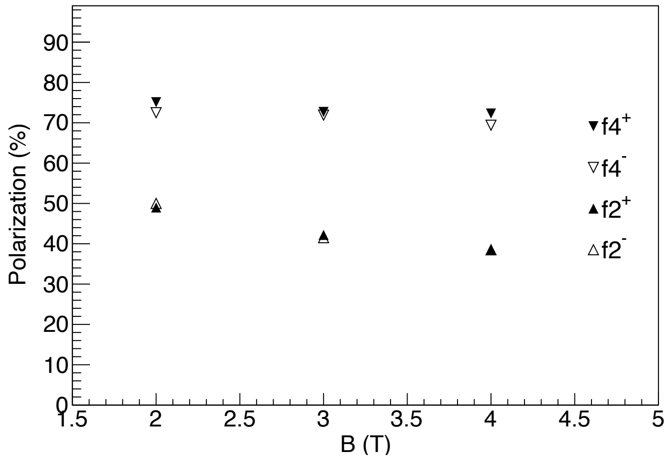
X. Li et al., Nucl. Instr. and Meth. A 168, 792 (2023)

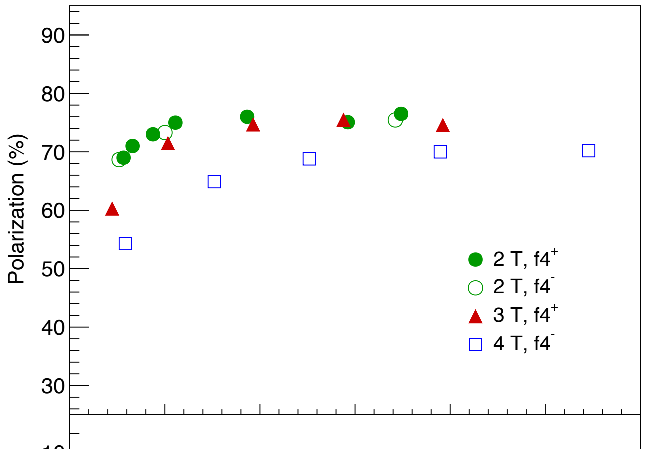
Systematic Studies for High Field MEOP





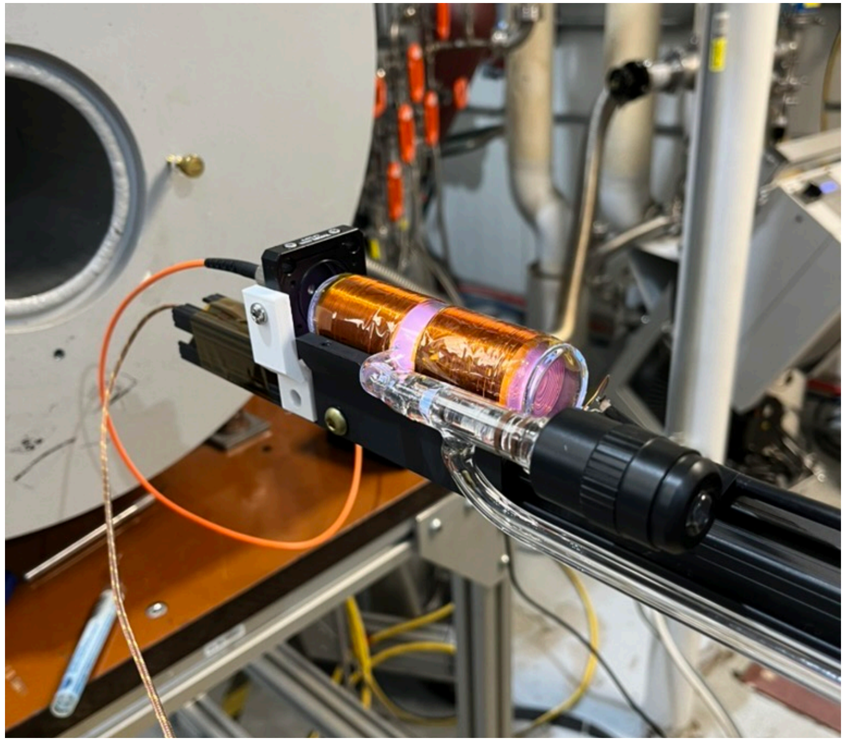




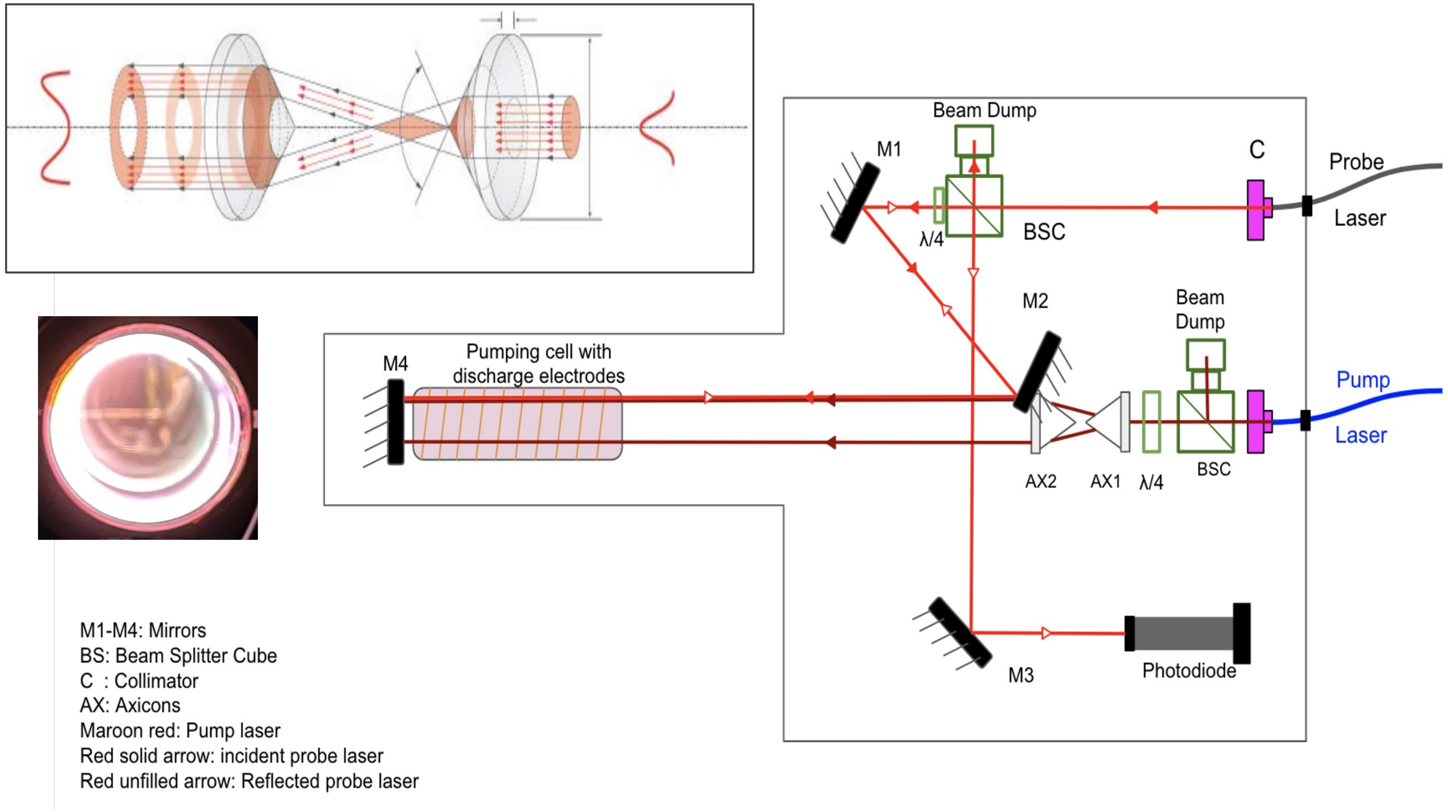


X. Li et al., Nucl. Instr. and Meth. A 1057, 168792 (2023)

Further Exploration for High Field Tests



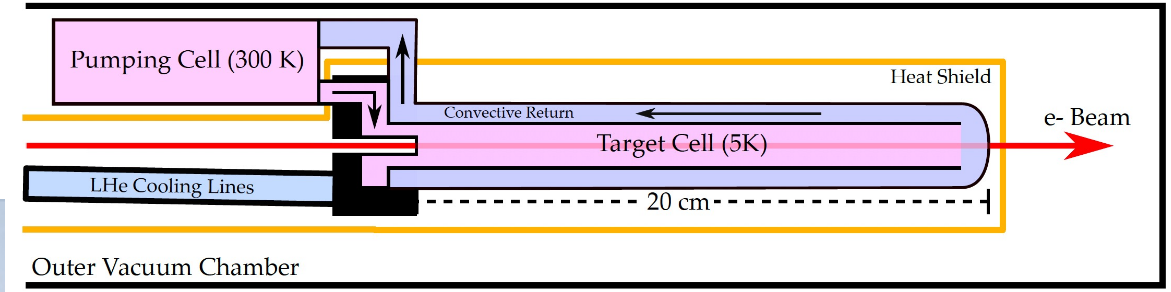
Fillable cell for varied pressure tests

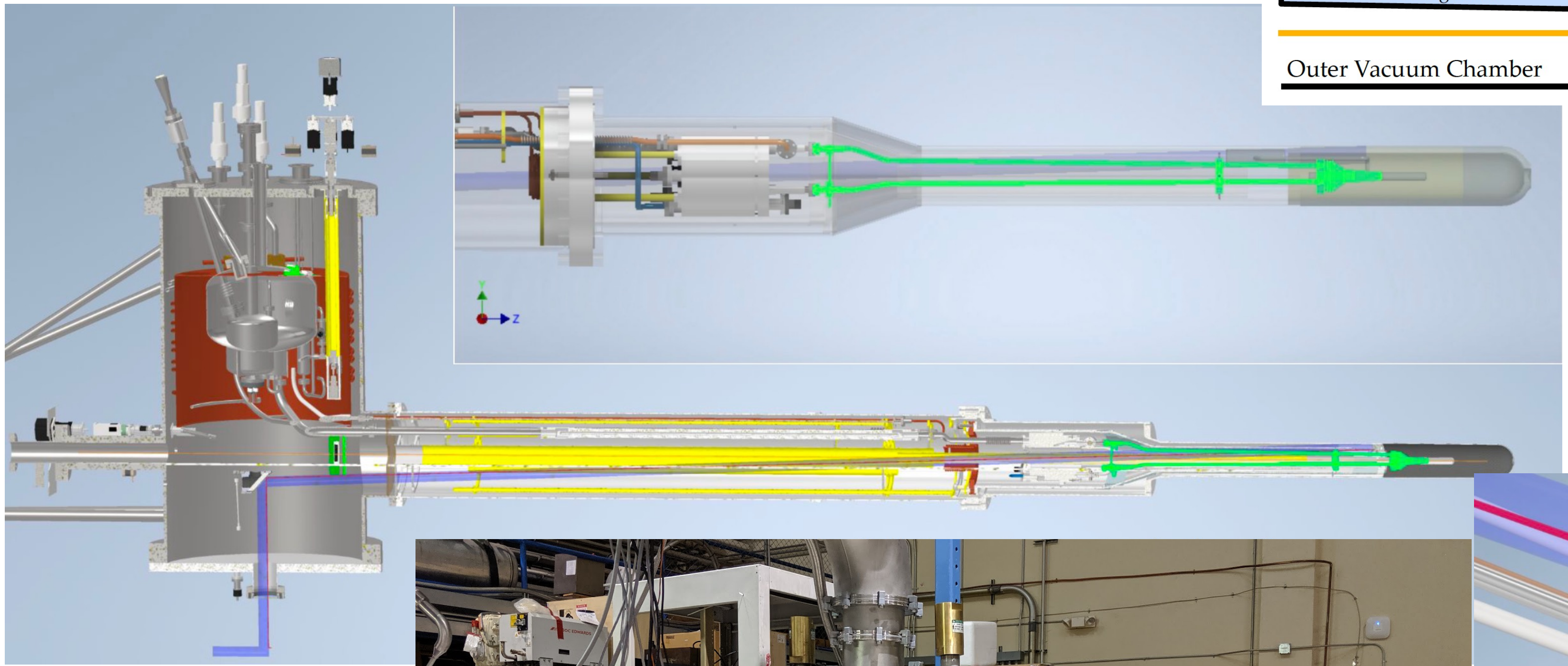


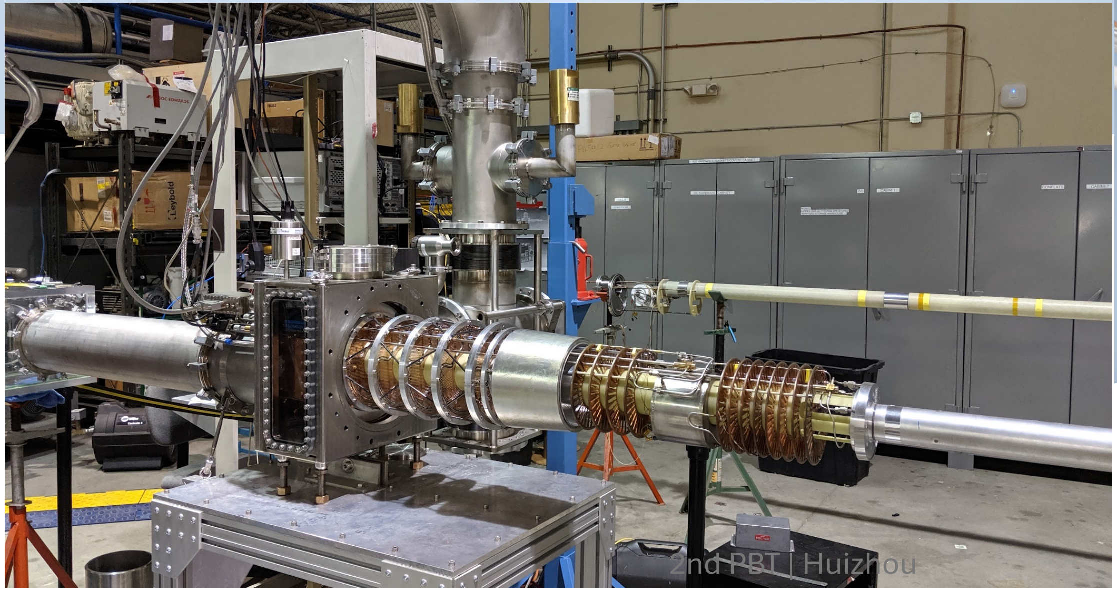
Improved optics layout to better capture the discharge

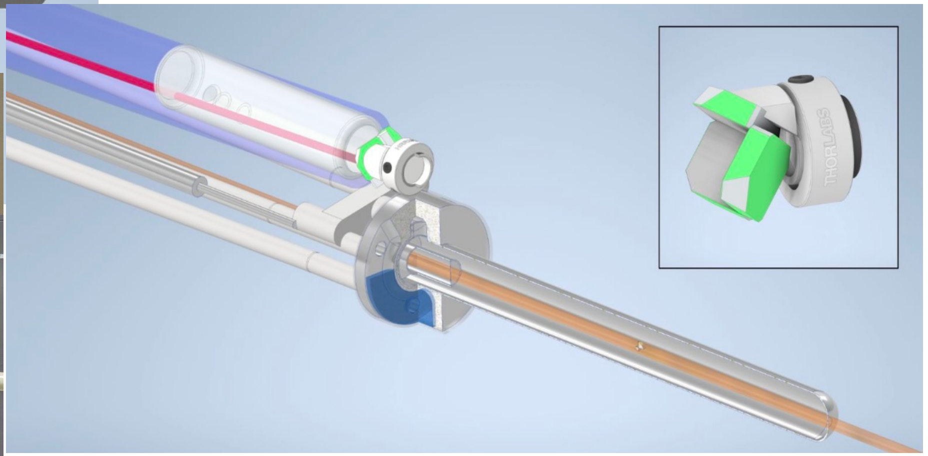
P. Pandey et al., Nucl. Instr. and Meth. A 1081, 170870 (2026)

Double Cell Designing





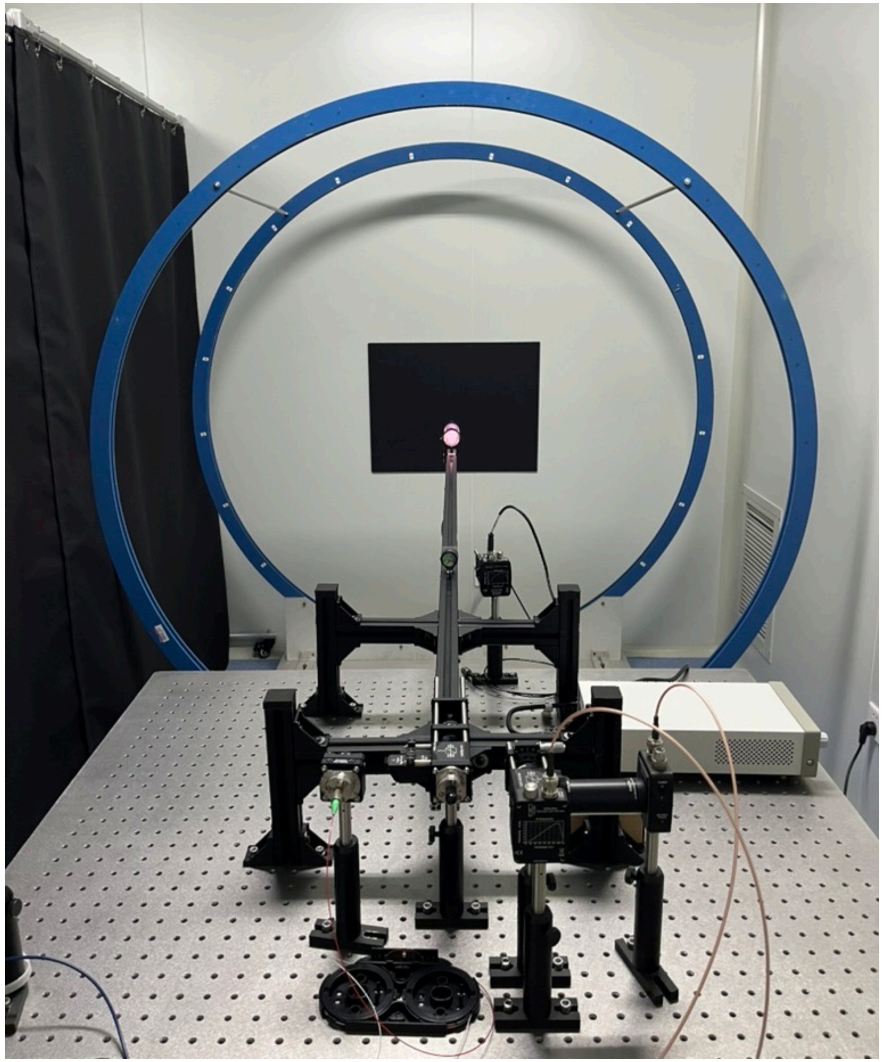


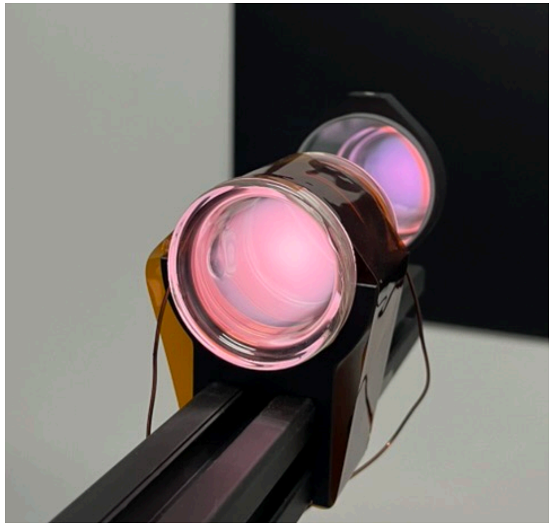


- ➢ Double cell will be coupled to existing pulse tube cryocooler

CAD by J. Brock

New Polarized ^{3}He Lab at Shandong University



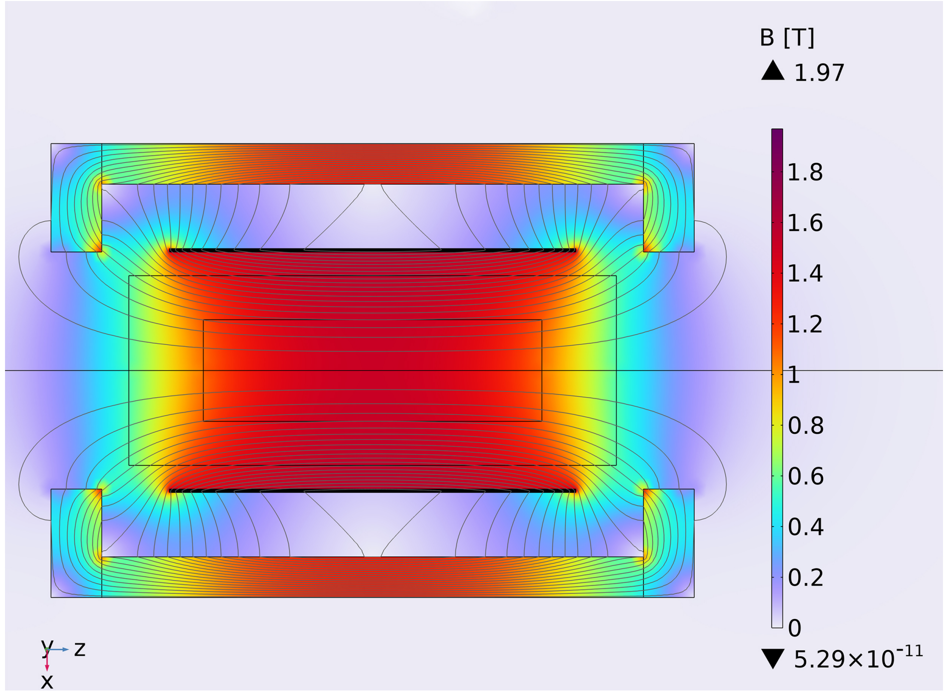


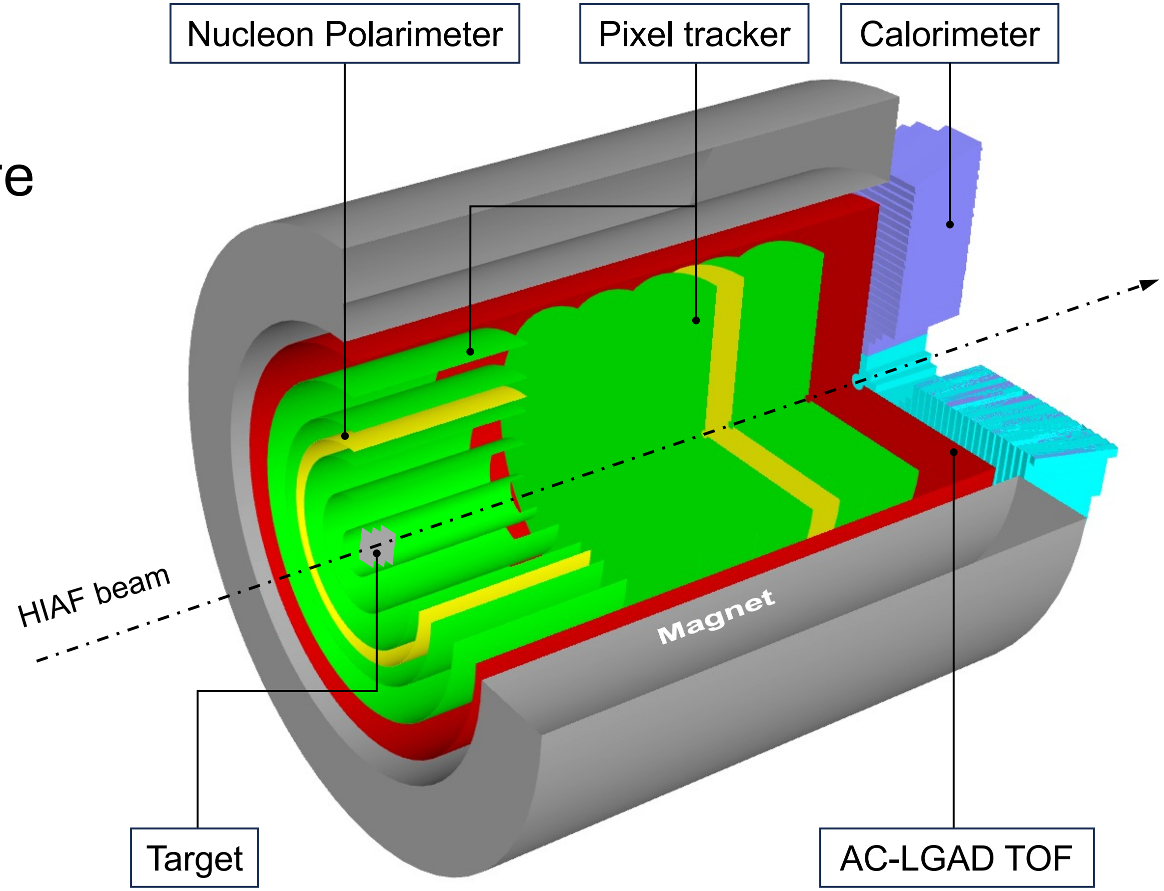
1 Torr ^{3}He gas cell supported by CSNS

- Low field MEOP system established
- To be upgraded to high field MEOP tests

Develop a High Field $\overrightarrow{^{3}\mathrm{He}}$ Target at H-NS

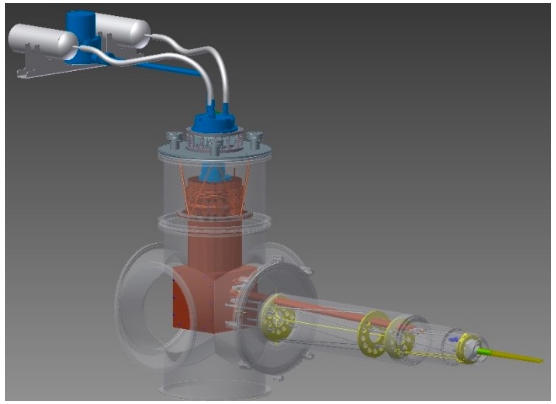
- Opimized target location
  - ➢B-field map within the solenoid bore

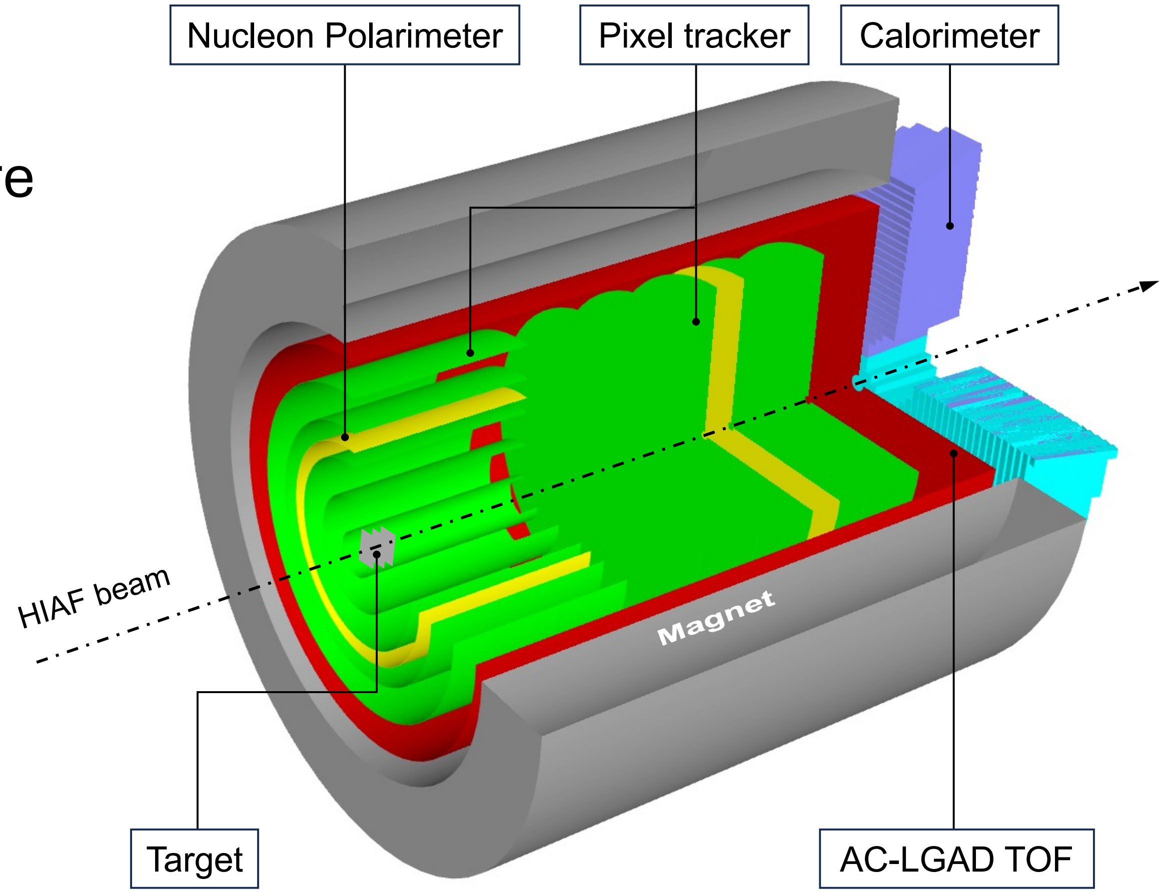




Develop a High Field $^3\overrightarrow{\mathrm{He}}$ Target at H-NS

- Opimized target location
  - ➢B-field map within the solenoid bore
- Target thickness request
  - ➢Beam current available
- Pulse tube cooling techniques
  - ➢Need cryogenic expertise





Summary

- Polarized ^{3}He is a powerful effective polarized neuteron target
- Nuclear polarization achieved using optical pumping (OP) techniques
- Traditional OP operates in low magnetic fields ~0.001 T
- Novel OP techniques enable ^{3}He nuclear polarization at 1-5 T
- New MEOP polarize ^{3}He lab established on SDU Qingdao campus
- Aim to develop a new high-field polarize ^{3}He target for H-NS

Thanks for your attention!