SHANDONG UNIVERSITY

Polarized ^{3}He Using Optical Pumping

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Shandong University

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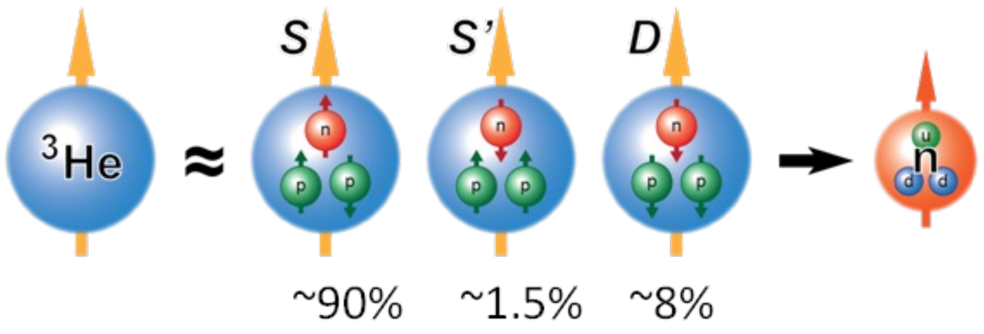
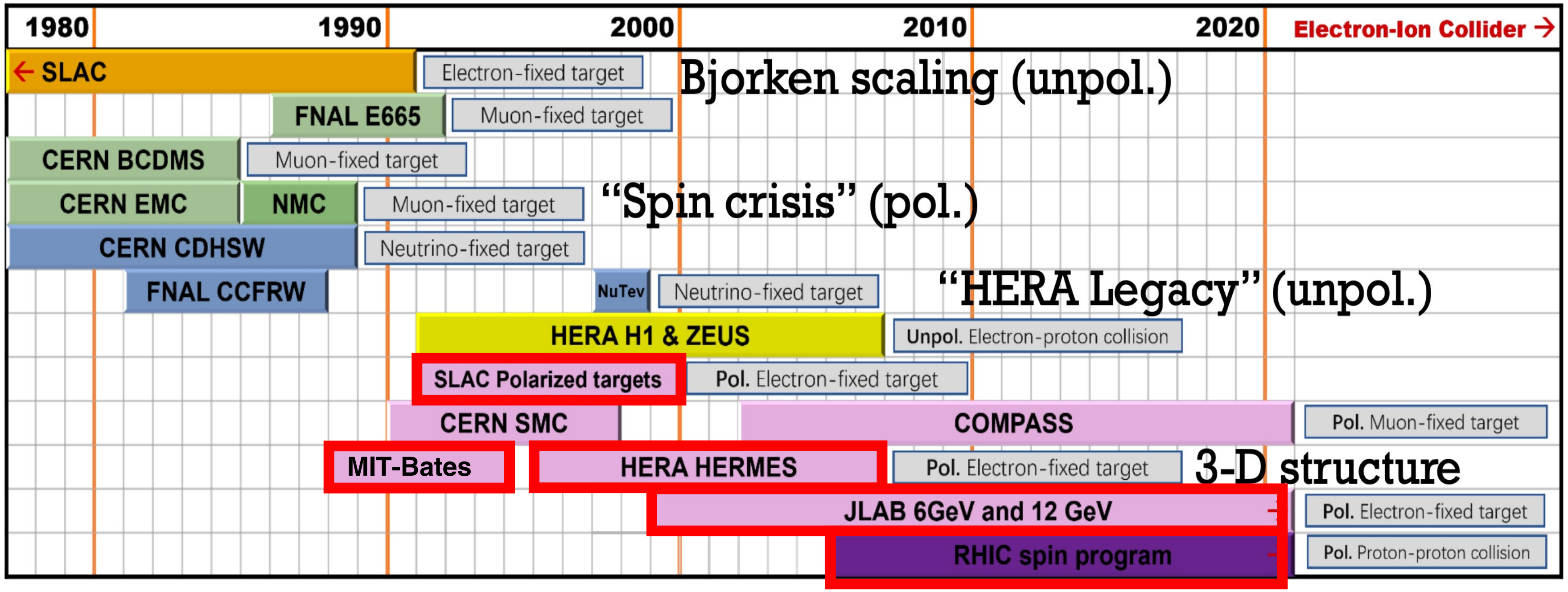
Polarized ^{3}He: Effective Polarized Neutron

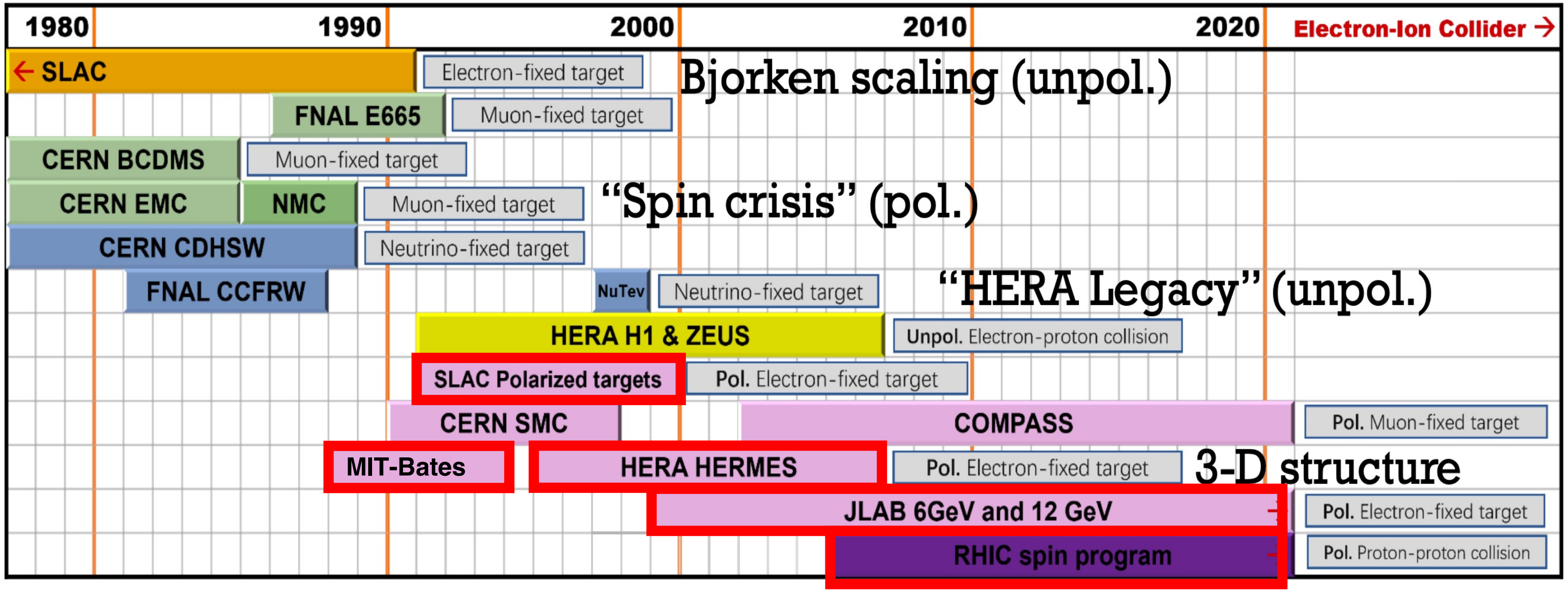
- ^{3}He nucleus: *S* state ~90%
  - 2 proton spins anti-parallel
  - Neutron carries most of the nuclear spin
- Widely used in lepton scattering experiments to study neutron electromagnetic and spin structure





How to Polarize ^{3}He Nucleus

💡 **Optical pumping** techniques
- **Spin-exchange** optical pumping (**SEOP**)
- **Metastability-exchange** optical pumping (**MEOP**)



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

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

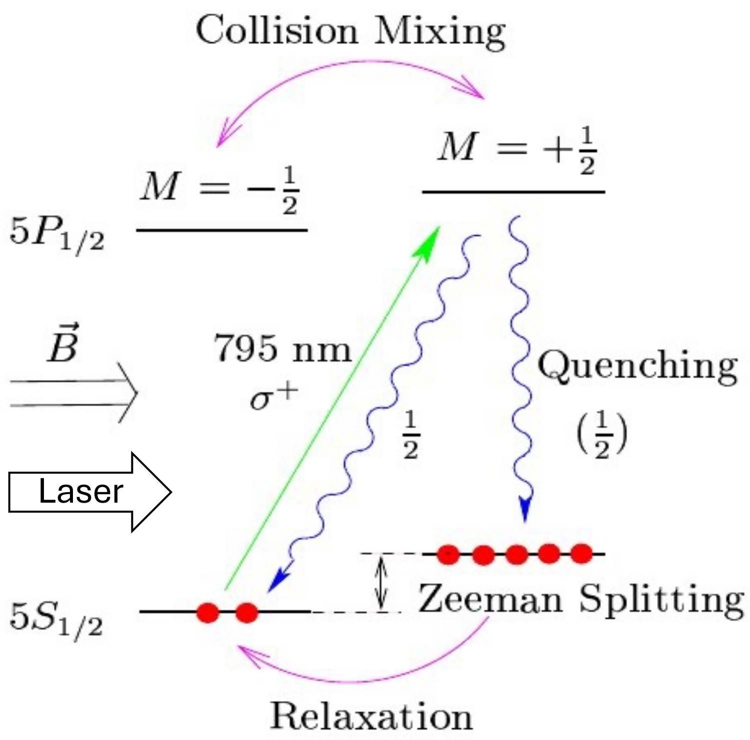
❖ May also use Atomic Beam Source (ABS) method to polarize ^{3}He nucleus

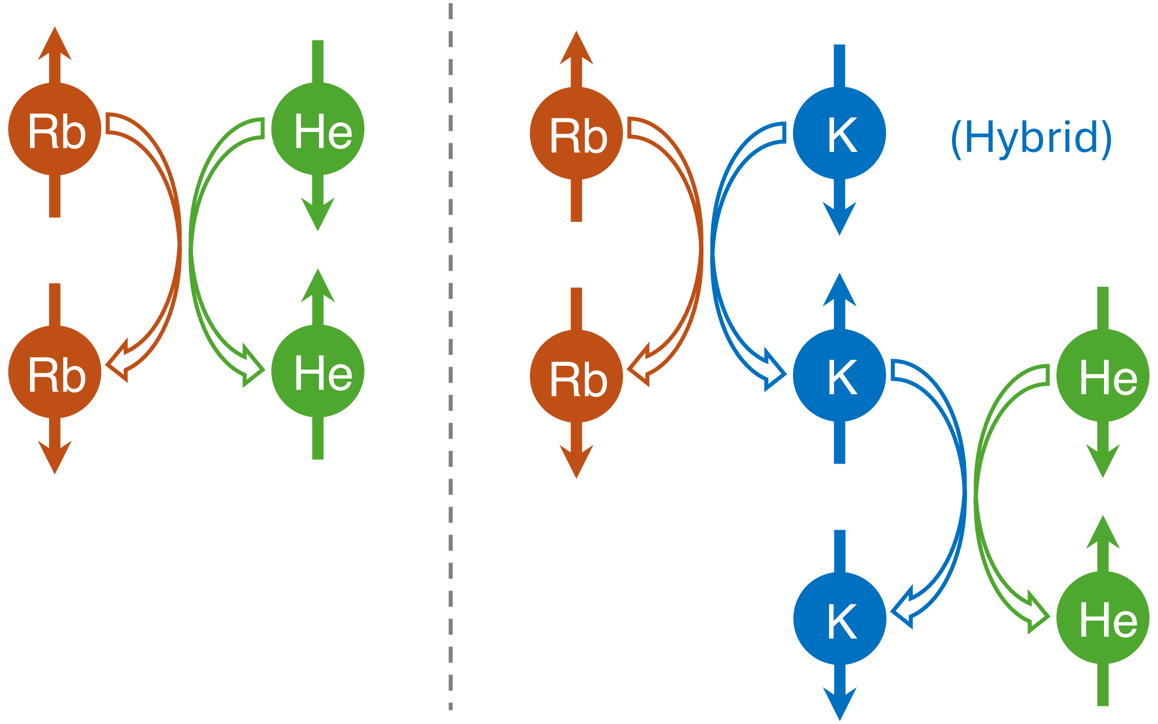
Spin-Exchange Optical Pumping (SEOP)

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)

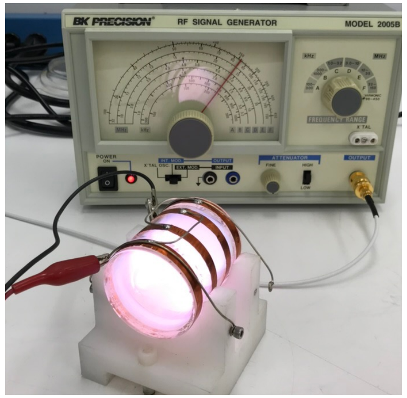




Spin-exchange collisions

Metastability-Exchange Optical Pumping (MEOP)

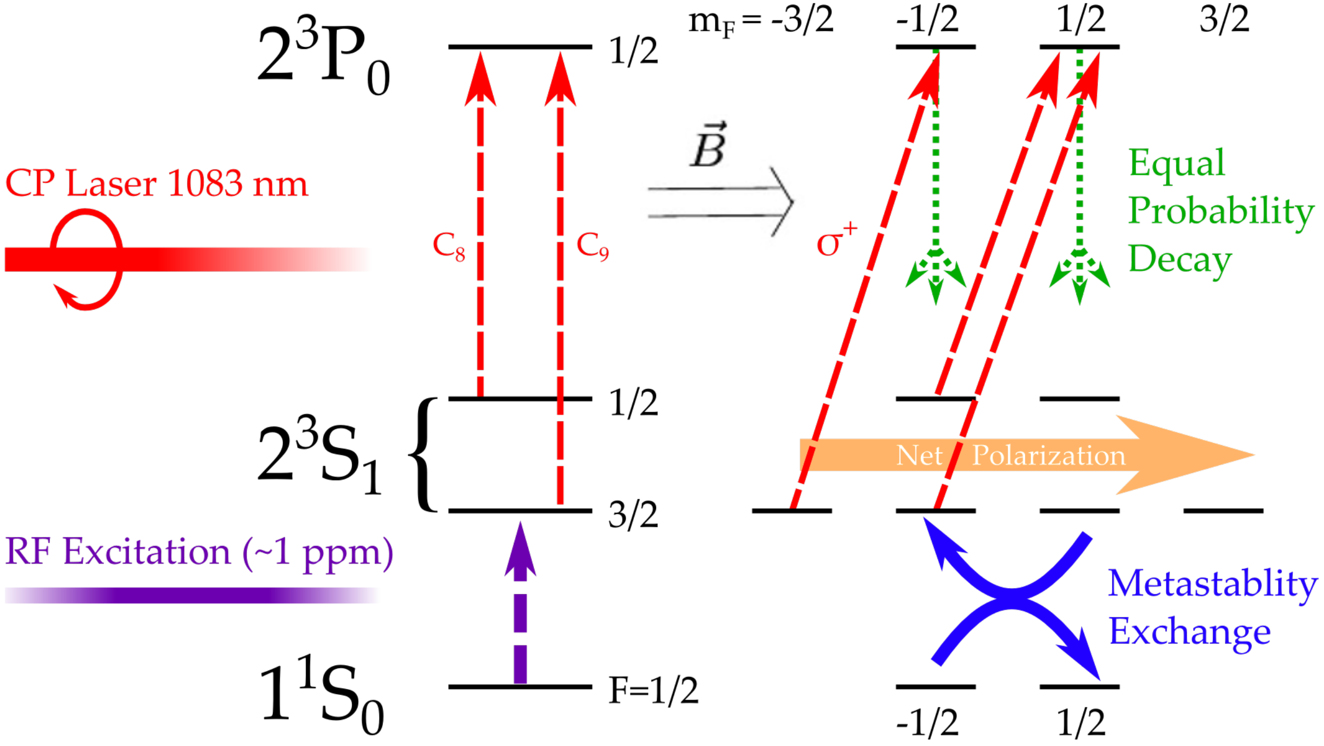
I. RF excitation: promote a small portion of ^{3}He atoms to metastable state 2^3S_1



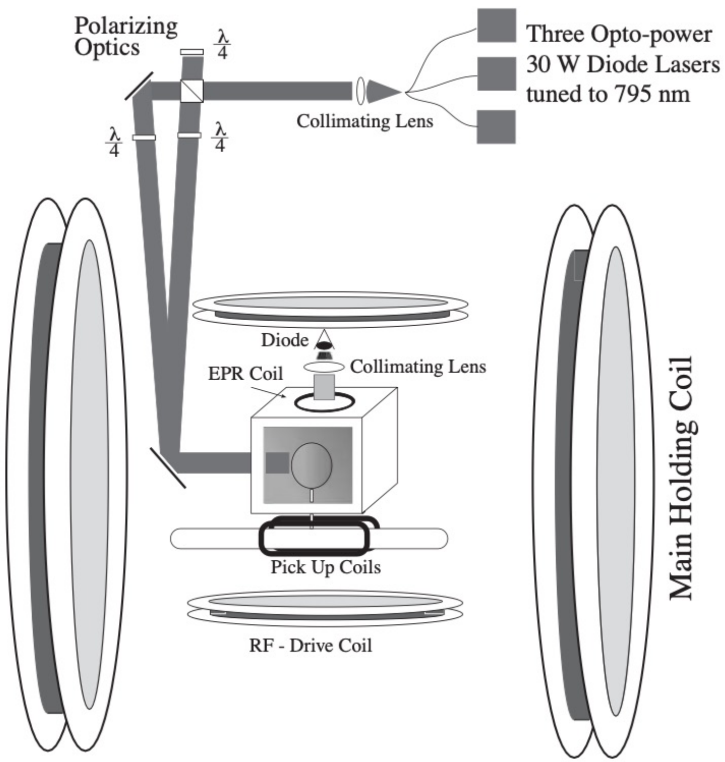
II. Optical pumping: laser driven polarization of 2^3S_1 atoms

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

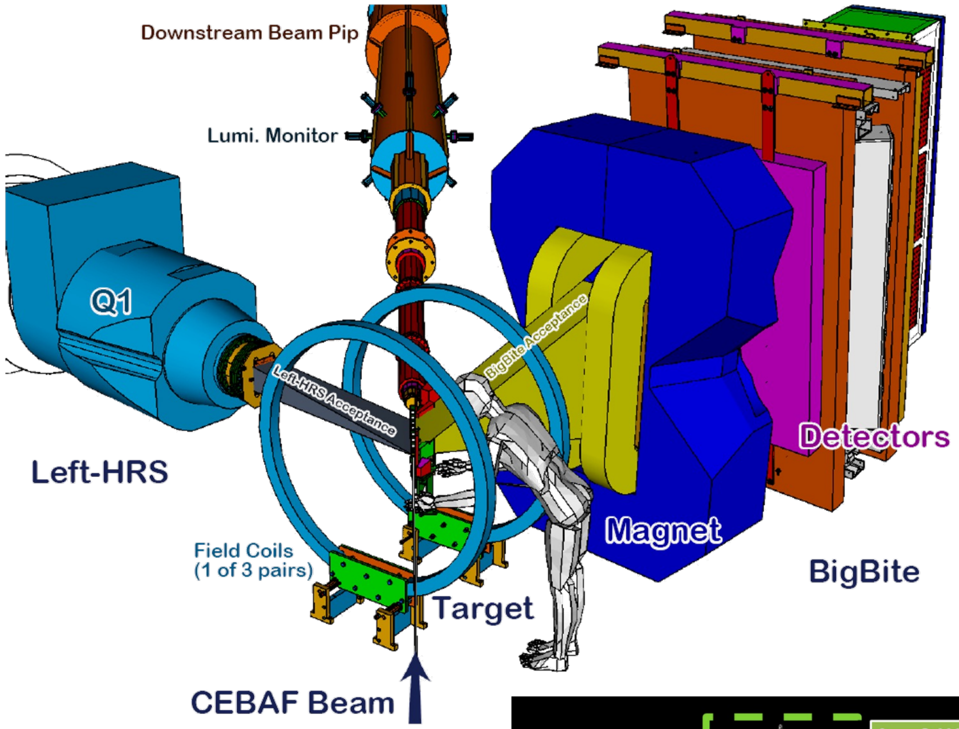
Colegrove, Schearer, Walters, PRL 132, 2561 (1963)

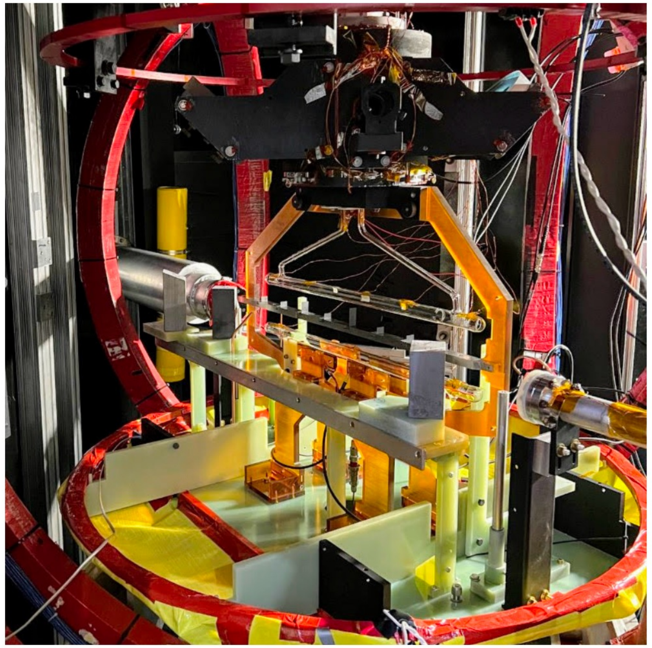


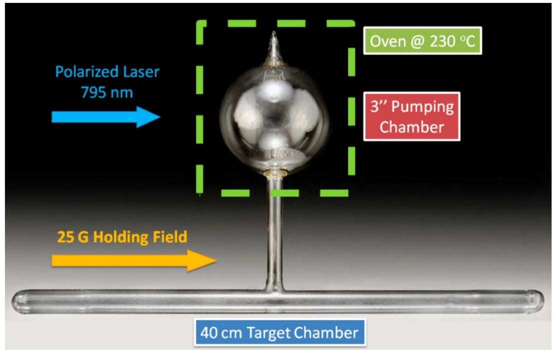
Polarized ^{3}He Targets at Jefferson Lab Hall A

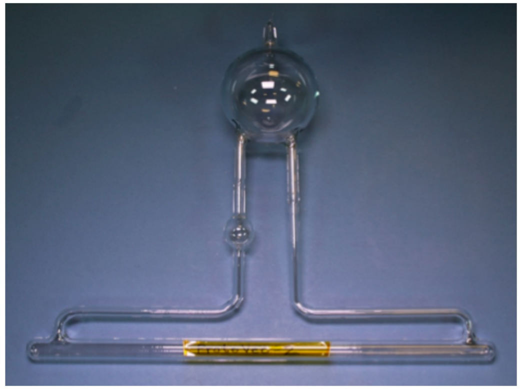


J. Alcorn et al., NIM-A 522, 294 (2004)







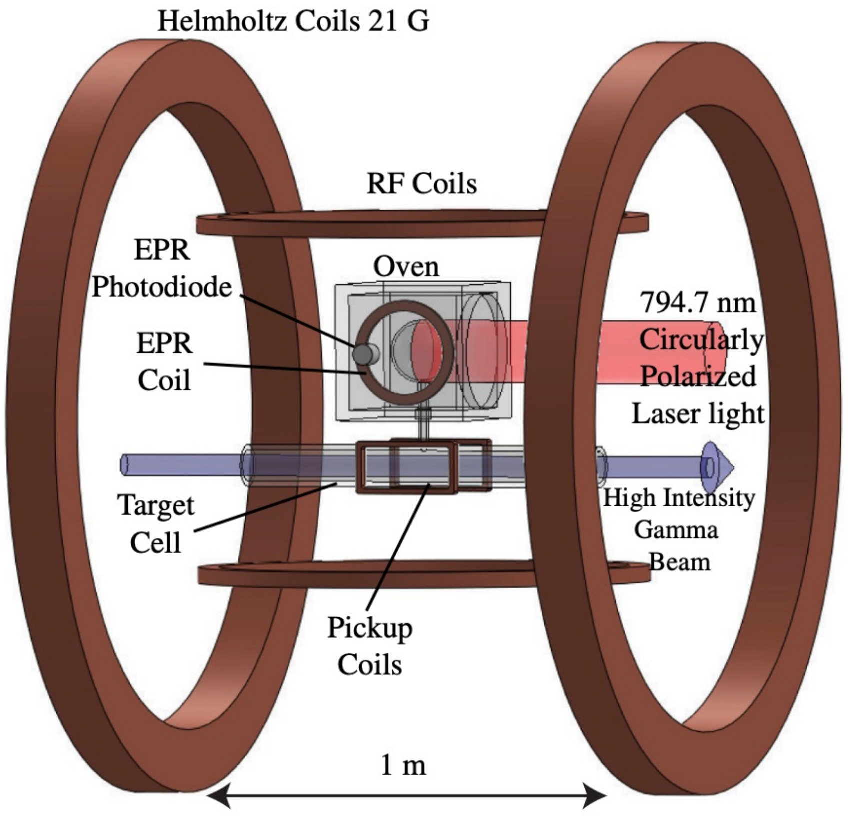


^{3}He nuclear polarization: 30-55%

Target thickness: 10^{22} nucl./cm^2 @ 40 cm, 10 bar

Polarimetry Methods for SEOP

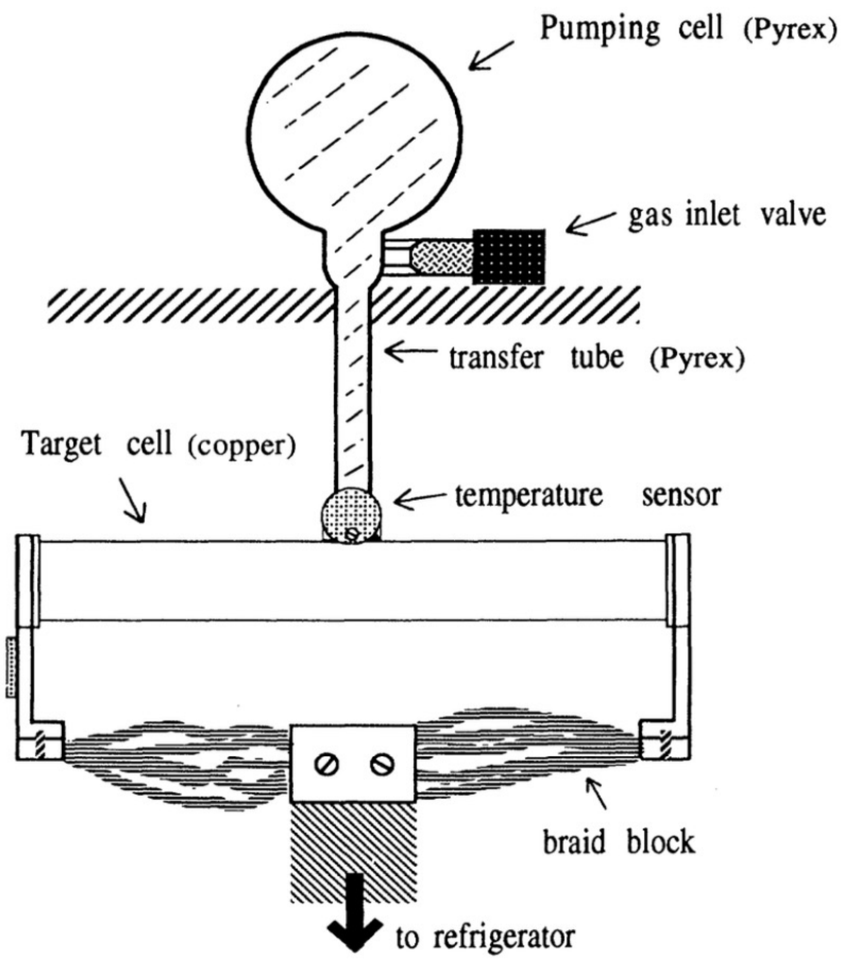
- Nuclear Magnetic Resonance (NMR)
  - Adiabatic Fast Passage
    - transverse RF signal with swept frequency
    - ^{3}He spin flipped at Larmar frequency
    - pick up the spin precessing signal
  - Free Induction Decay
    - transverse RF pulse at Larmar frequency
    - ^{3}He spin tilted by a small 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 Target for MIT-Bates 88-02 Experiment

- First laser-driven MEOP polarized ^{3}He target



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

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

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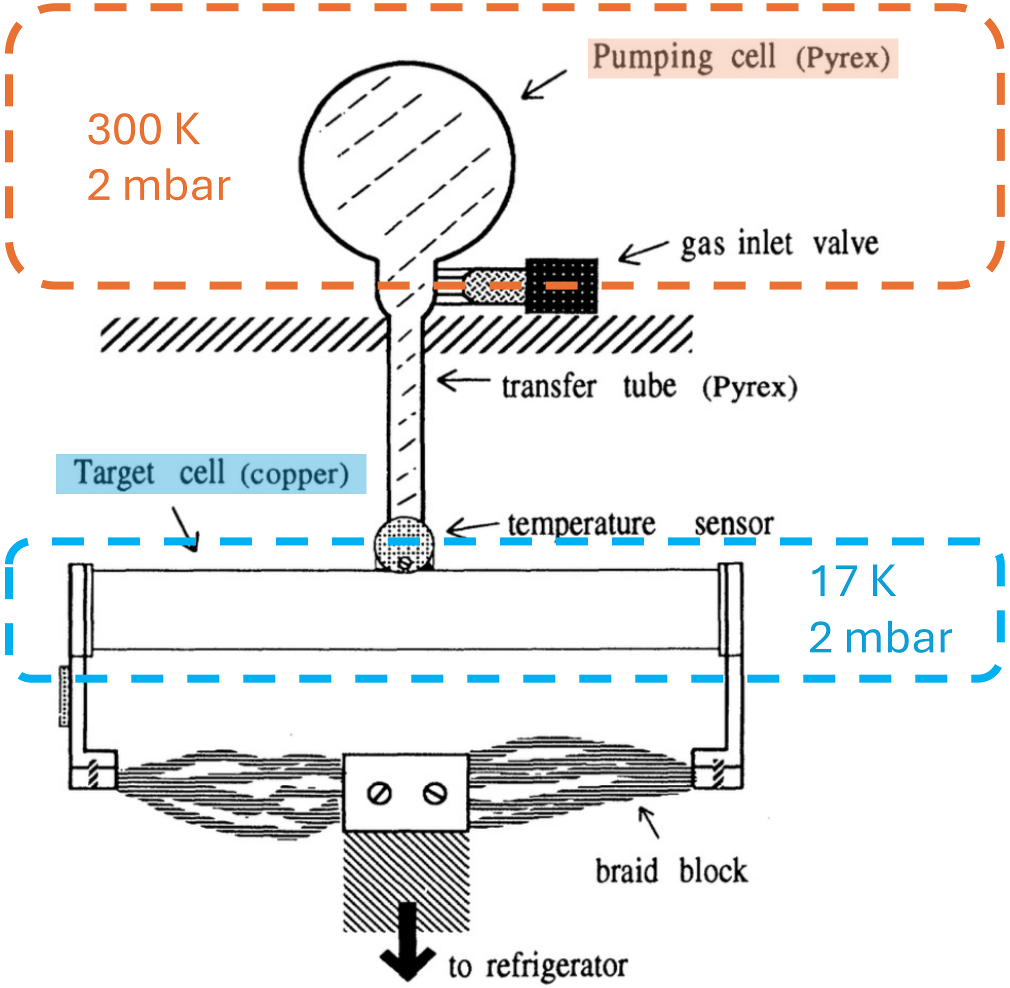
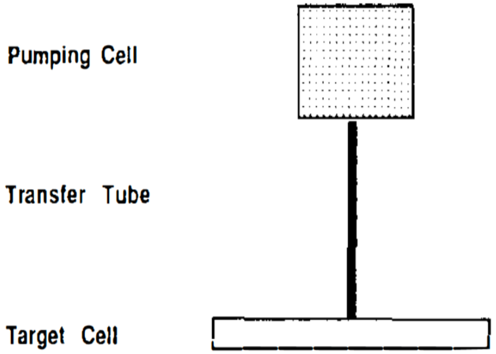
- **Double-cell** design



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

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

- First laser-driven MEOP polarized ^{3}He target
- **Double-cell** design
- **Polarization measured from pumping cell** and well inferred for target cell
  - ~40% in-beam polarization achieved

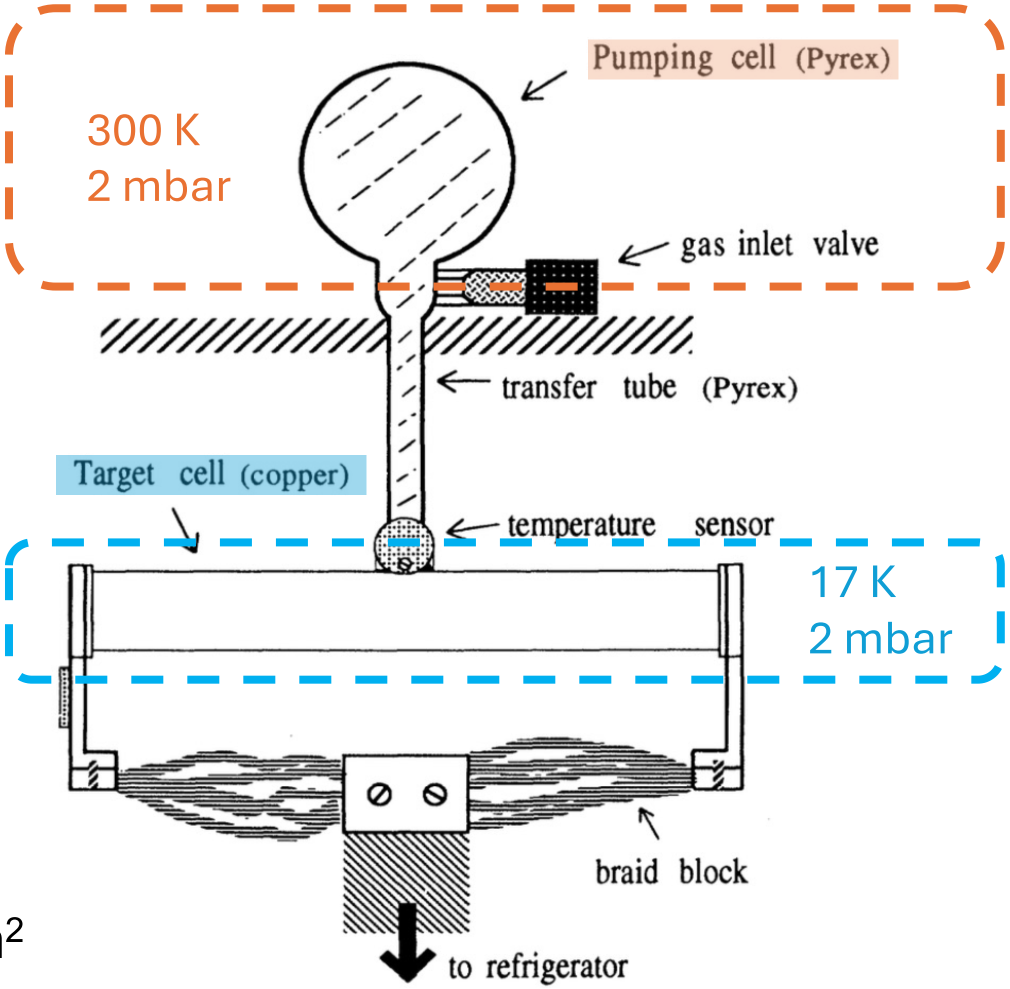


$$\frac{dP_p(t)}{dt} = -\frac{P_p(t)}{\tau_p} + \frac{P_t(t) - P_p(t)}{t_p}$$

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

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

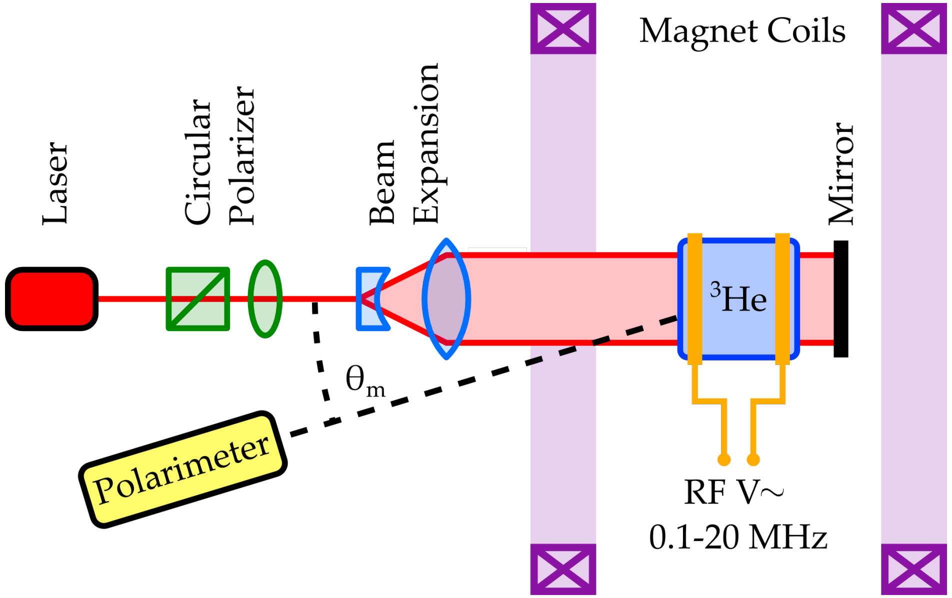
  - 10 cm target cell, target thickness ~10^{19} nuclei/cm^2



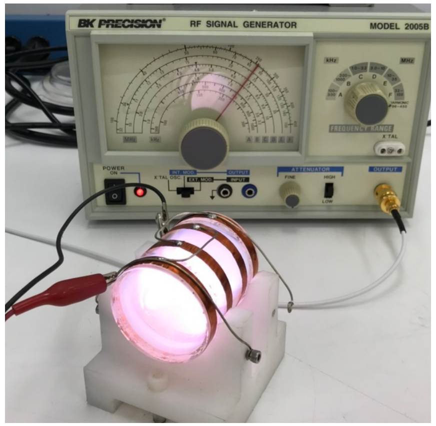
C.E. Jones et al., PRC 47, 110 (1993); PRL 65, 698 (1990)

Polarimetry for MEOP (Traditional)

- 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

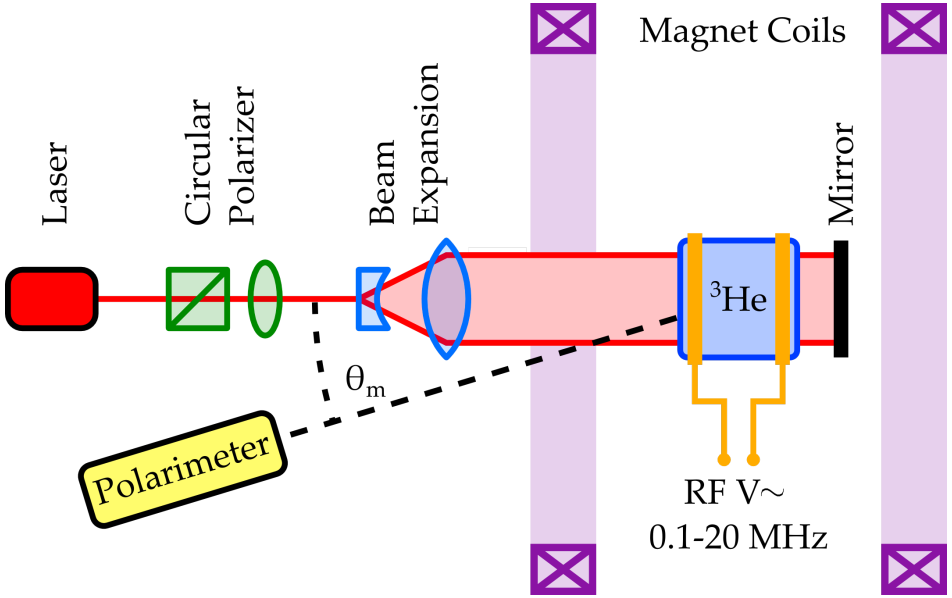


J.D. Maxwell et al., NIM-A 764, 215 (2014)



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
- **Work for low magnetic fields only**



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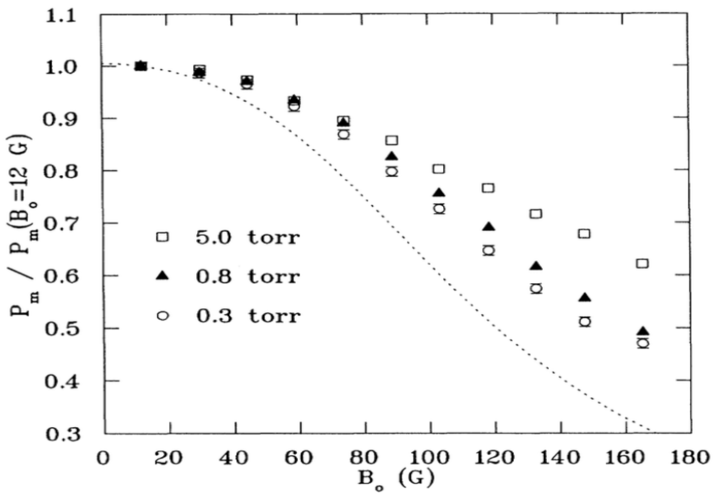
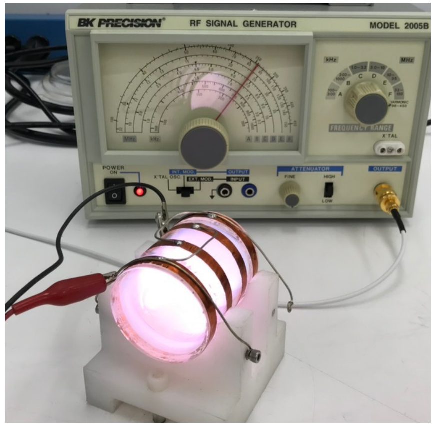
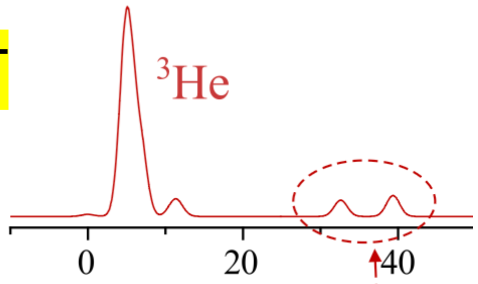


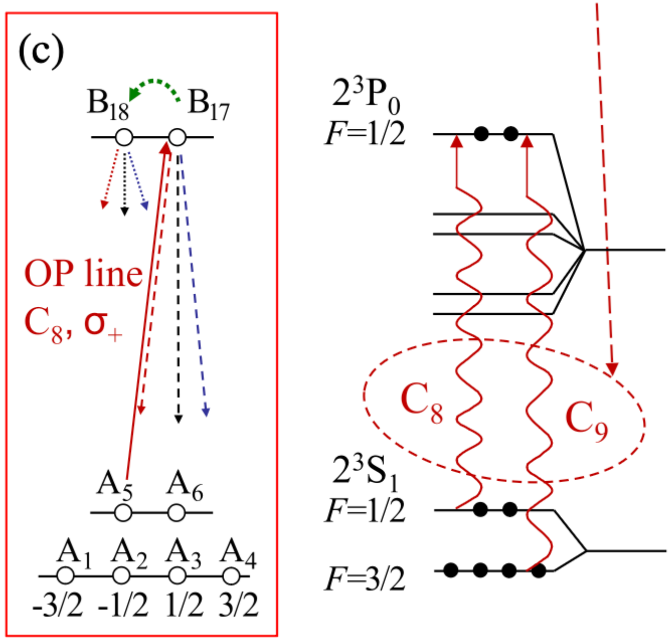
W. Lorenzon et al., Phys. Rev. A 47, 468 (1993)



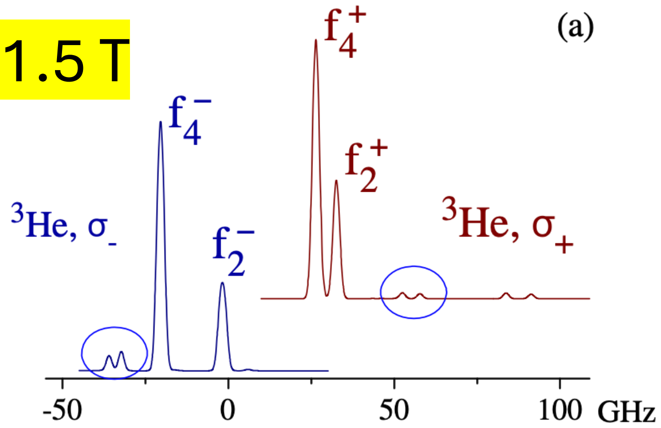
Low Field vs. High Field MEOP

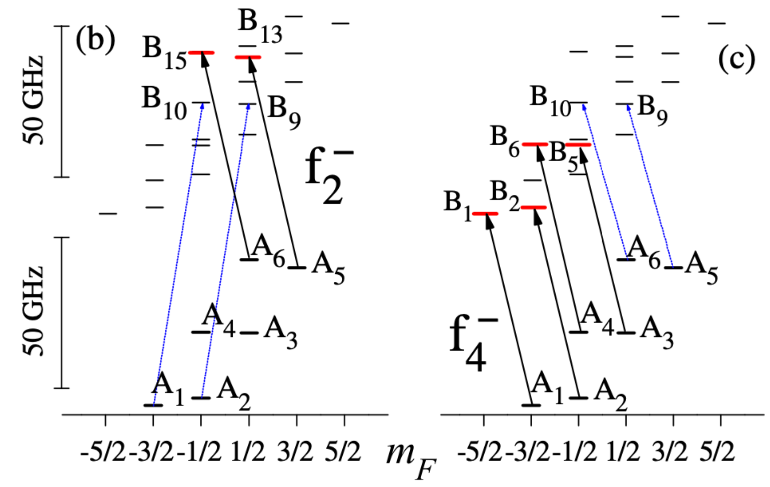
B = 0.001 T





B = 1.5 T

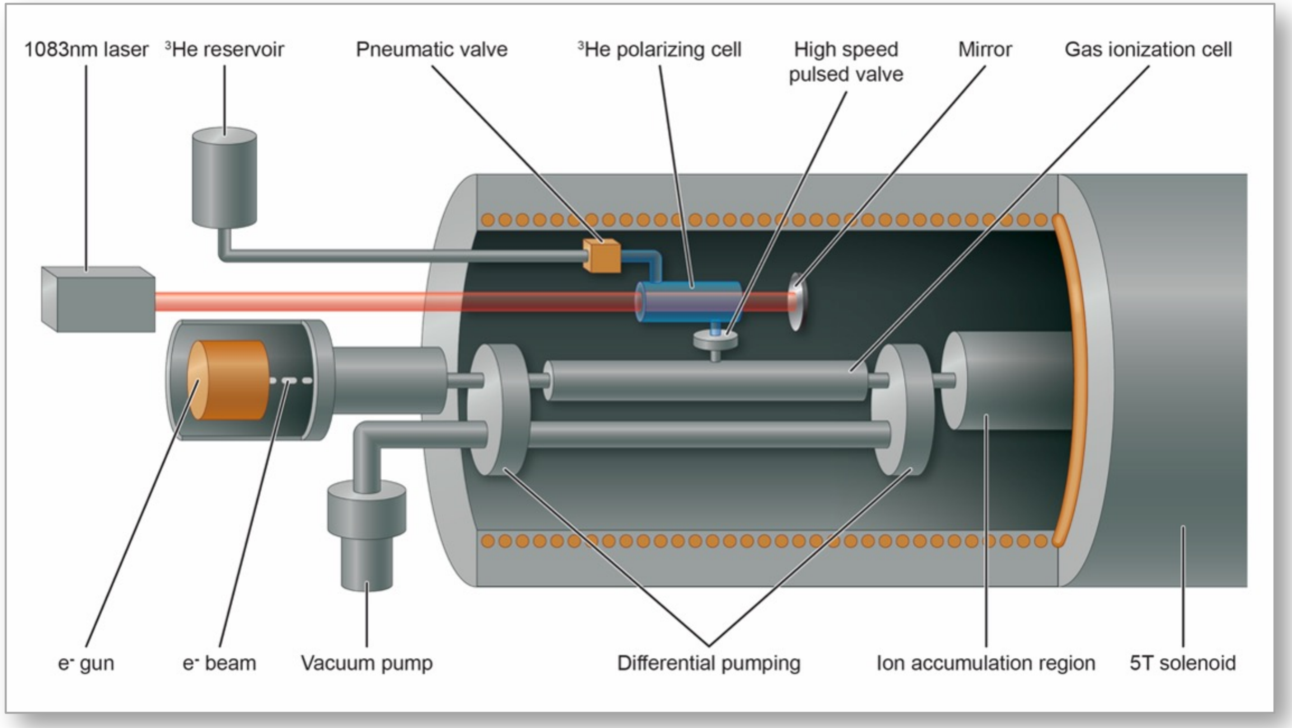




T.R. Gentile et al., Rev. Modern Phys. 89, 045004 (2017)

Polarized $^3He^{++}$ Source at BNL for EIC

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



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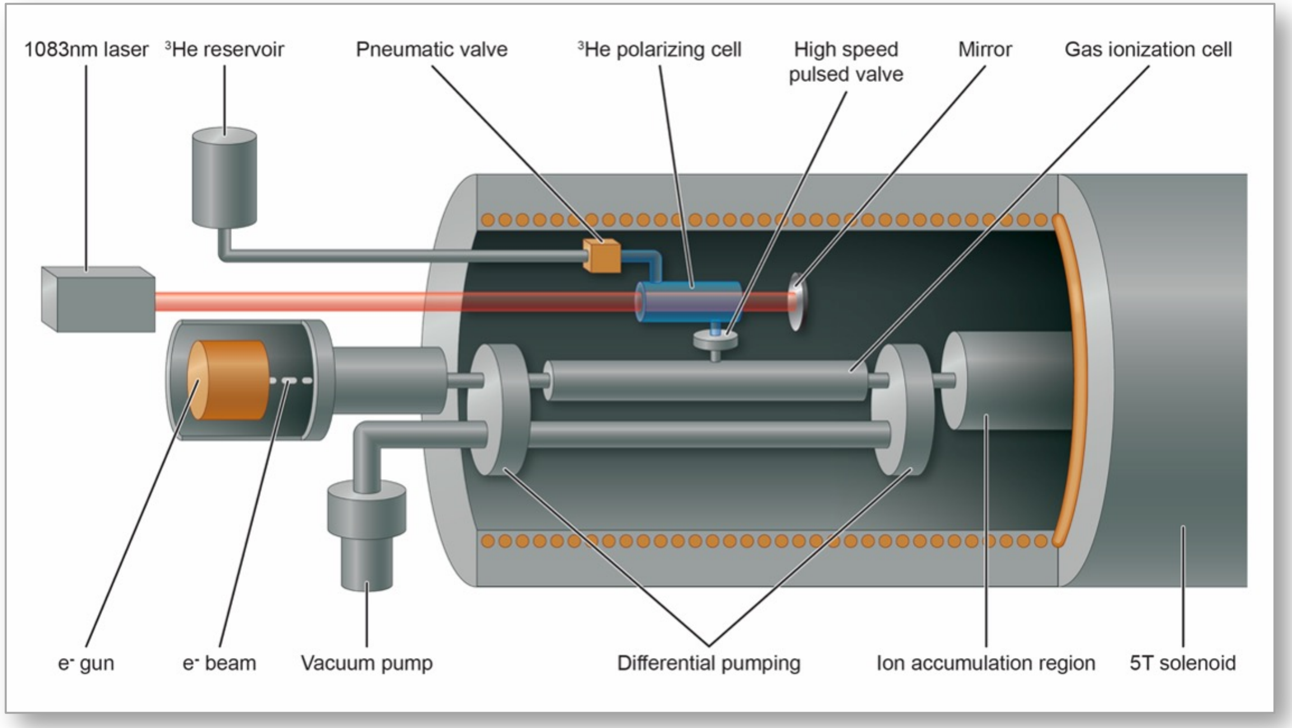
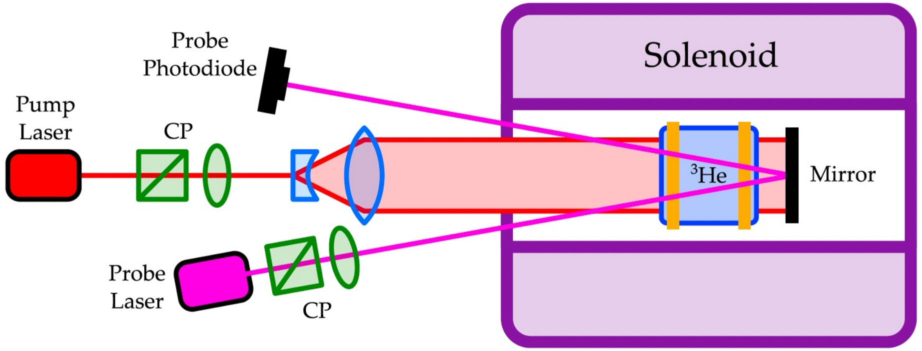
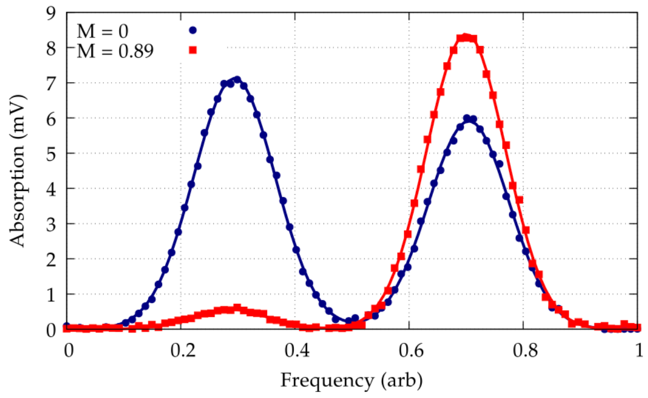


- High-field polarimetry method for MEOP



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



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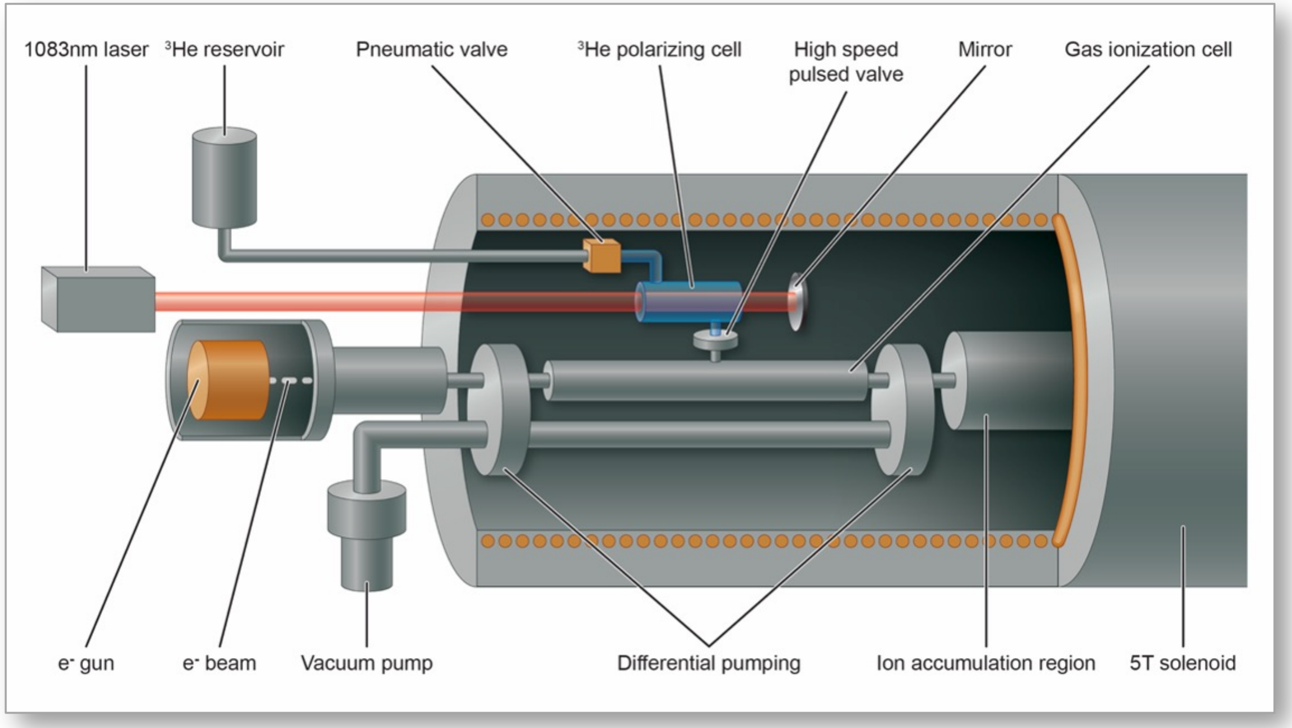

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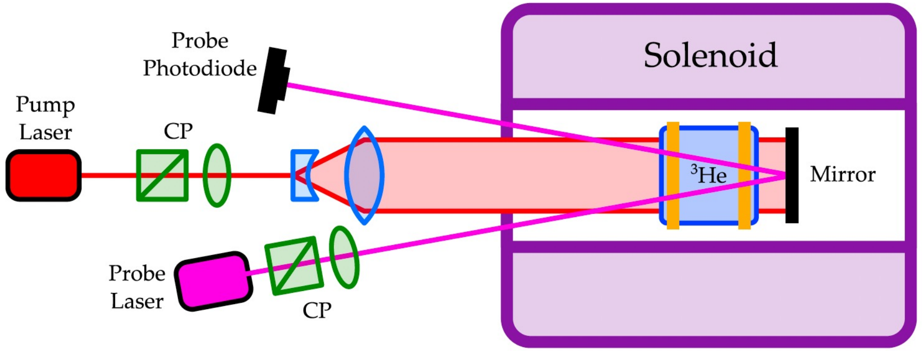

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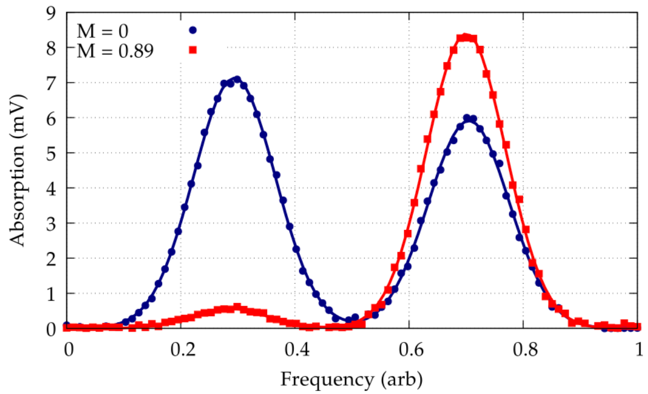


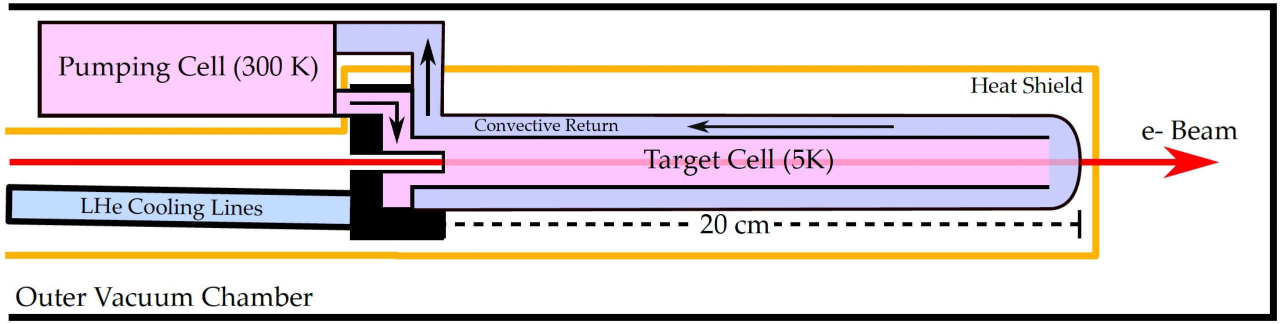
- 1^{st} high-field MEOP for fundamental physics research
- Ongoing effort by BNL-MIT collaboration

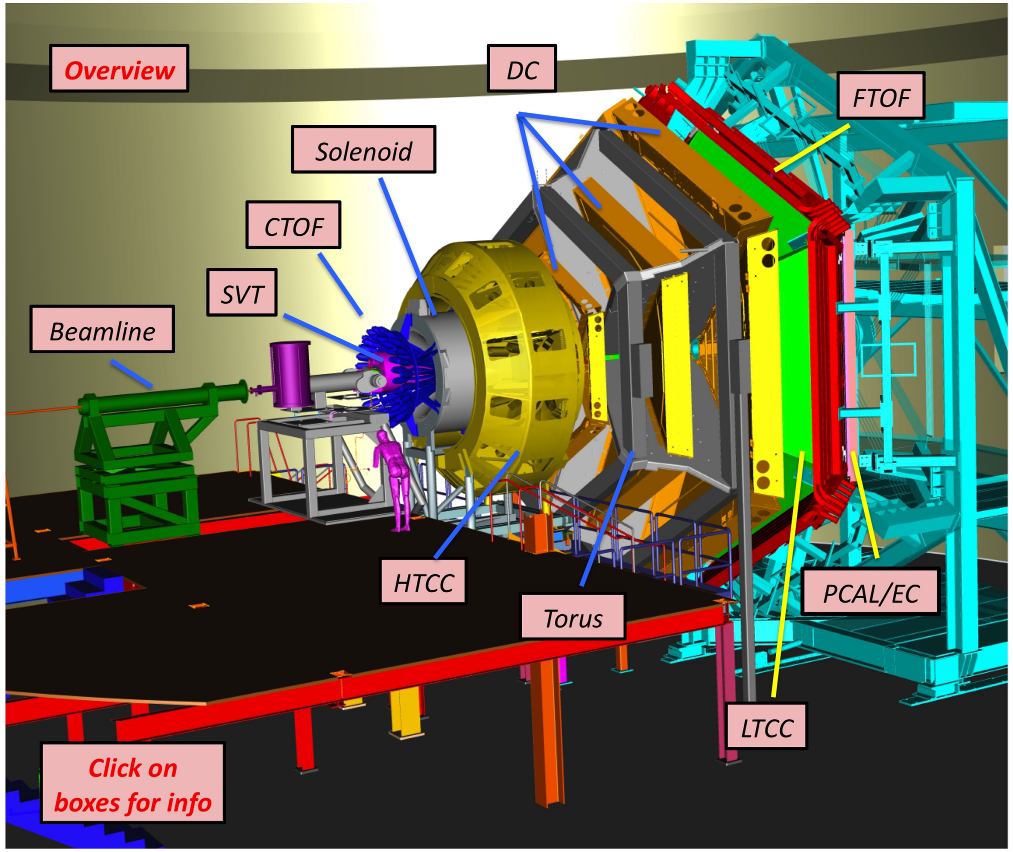
NIM-A 1055, 168494 (2023)

Novel Polarized ^{3}He Target at CLAS12 JLab

- First high-field polarized ^{3}He target
- Accomodate to 5-T solenoid of CLAS12
- Ongoing target R&D by JLab-MIT-UTK-SDU

Target Conceptual Design



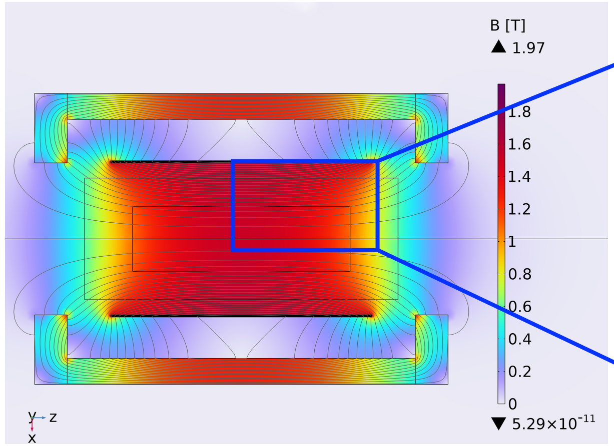


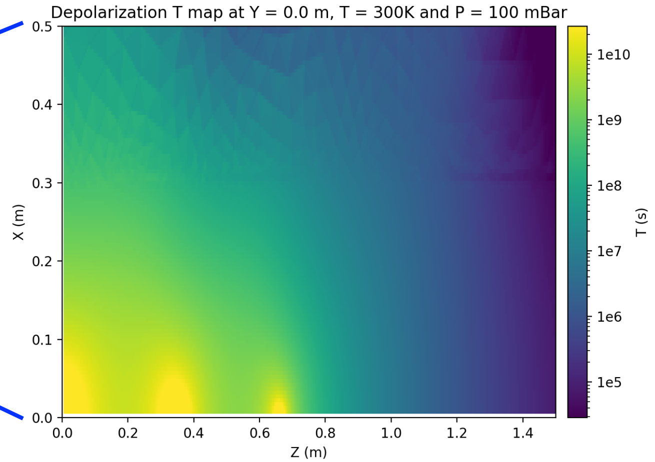
Pumping cell:
- Borosilicate glass cell
- 60% polarization at room temperature

Target cell:
- Aluminum cell
- Target thickness >10^{21} ^{3}He/cm^2 compariable to SEOP target

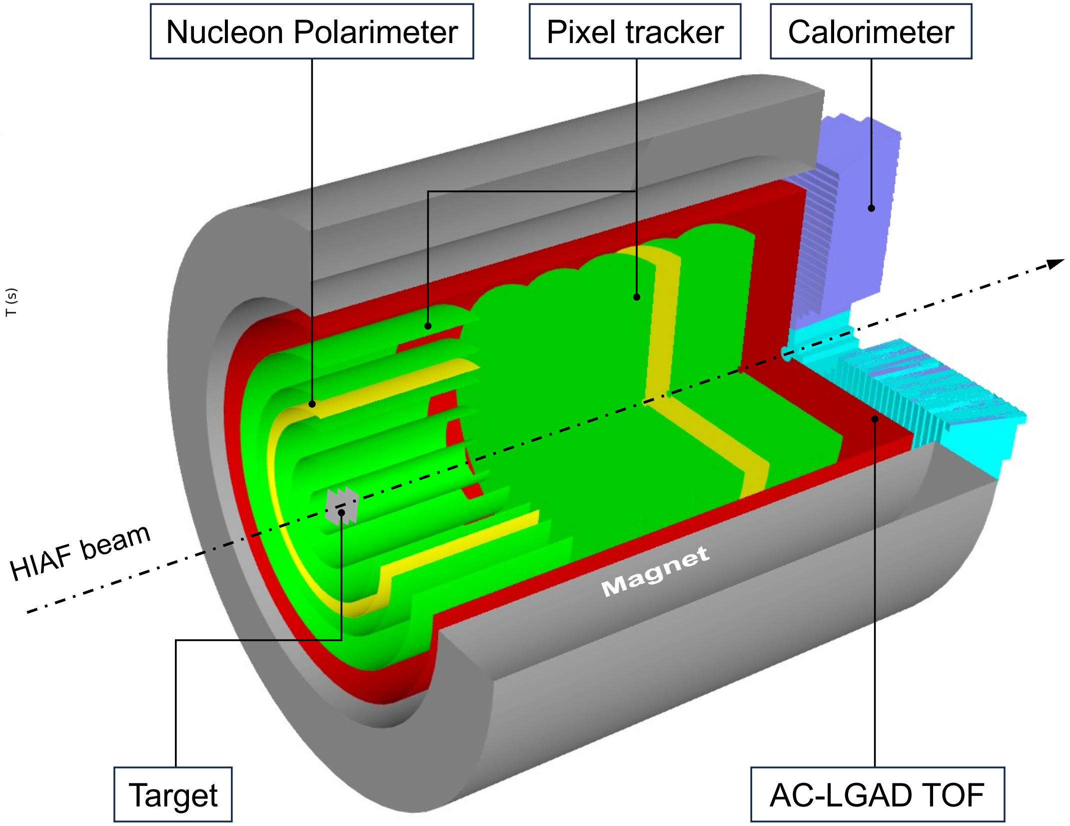
High-Field Polarized ³He Target at H-NS

- Opimize target location according to B field map





- Target thickness request: 0.02 g/cm^2
  - 0.002 g/cm^2 @ 20 cm target length, 1 bar, 300 K
- Need cryogenic or compression techniques to achieve desired target thickness



Path towards Polarized $^3He^{++}$ Source in China

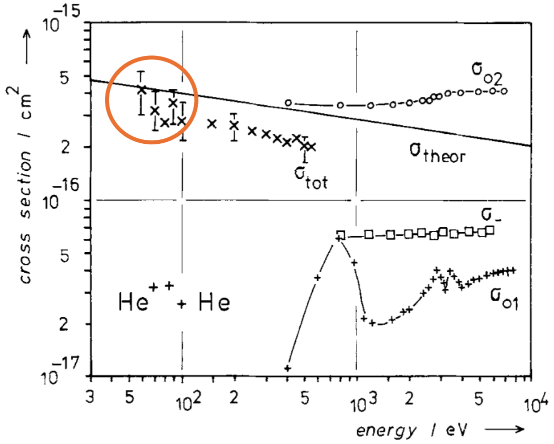
Challenges:

- Novel approach to couple ^3He polarizer and ionizer
- Achieve high current and high polarization

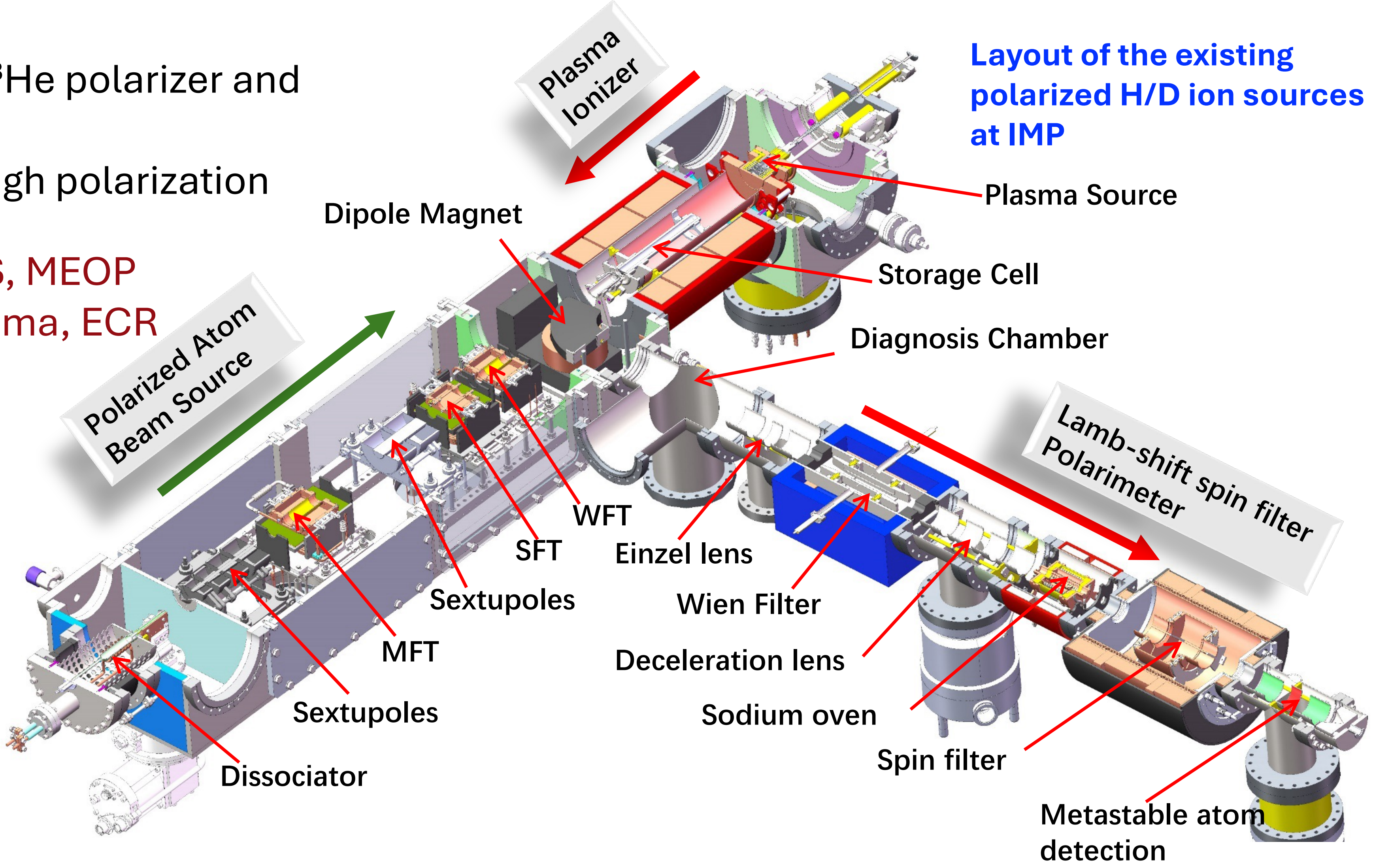
➢ ^3He polarizer options: ABS, MEOP

➢ Ionizer options: $^4He^{2+}$ plasma, ECR

$$^4He^{2+} + {}^3He \rightarrow {}^4He + {}^3He^{2+}.$$



A.S. Belov, NIM A 402, 205 (1998)



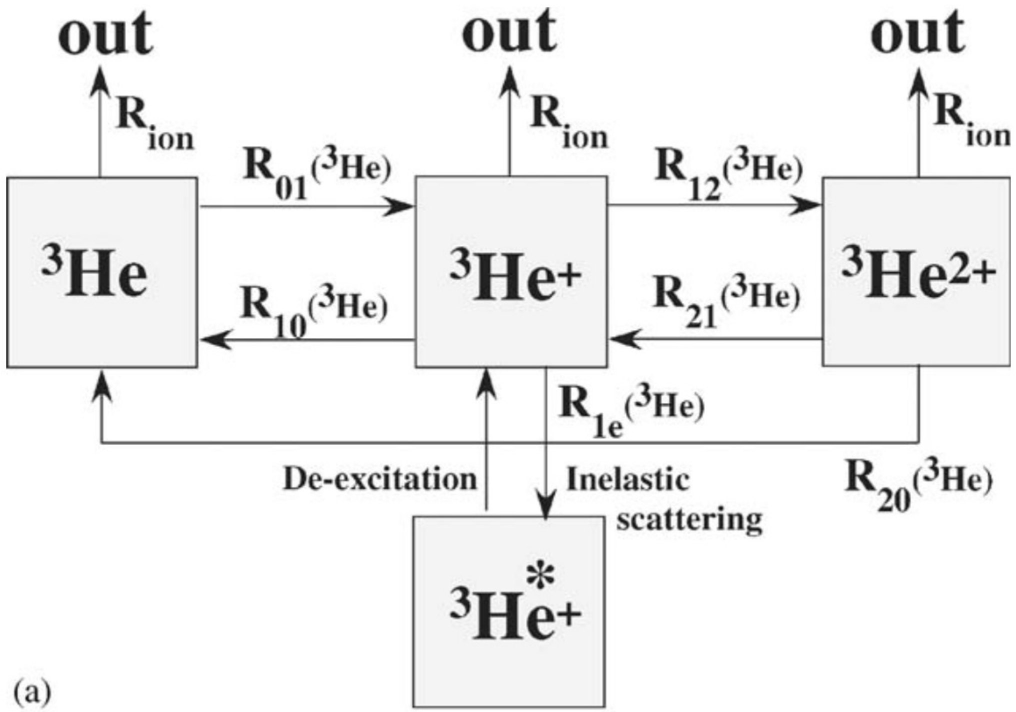
Layout of the existing polarized H/D ion sources at IMP

Path towards Polarized $^3He^{++}$ Source in China

ECR ionizer approach

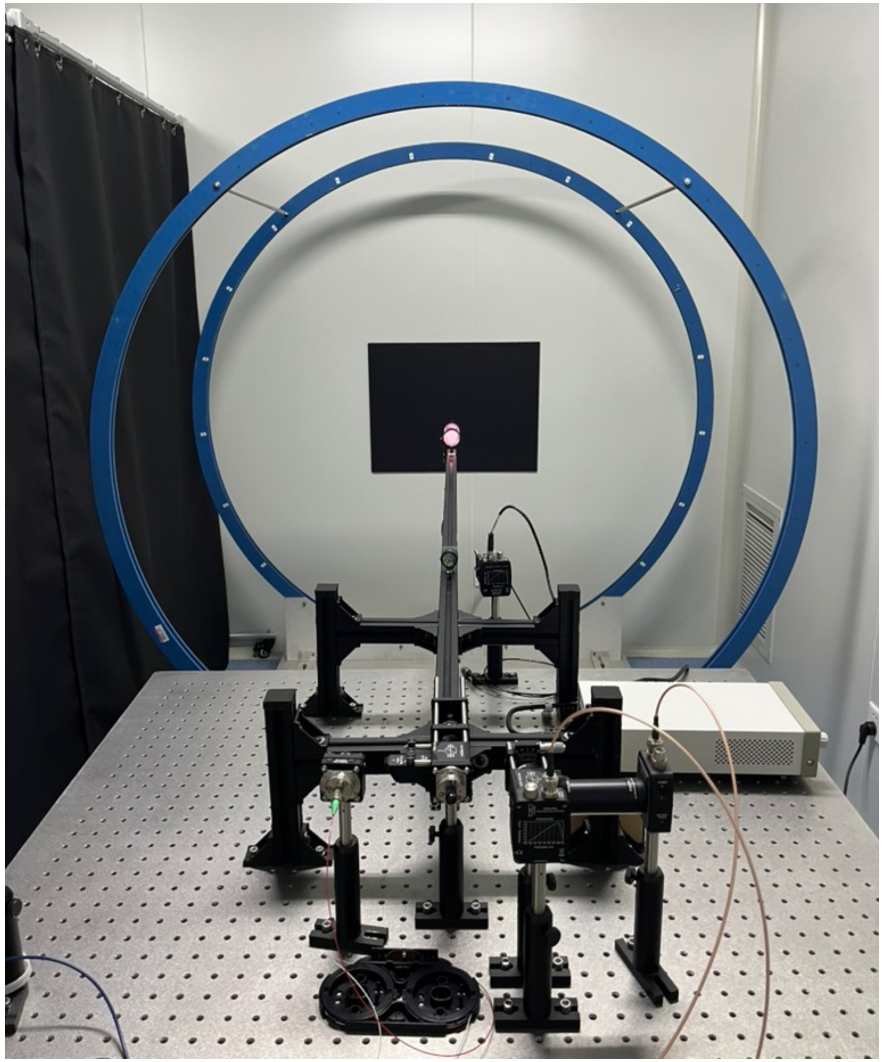
- Monte Carlo simulation for multiple ionization, inelastic scattering and de-ionization processes for ^3He, $^3He^+$ and $^3He^{++}$ in ECR plasma
- Polarization 10-20% expected in the 2004 work
- New simulation to be conducted with advanced ECR configurations

M. Tanaka et al. / Nuclear Instruments and Methods in Physics Research A 524 (2004) 46–59

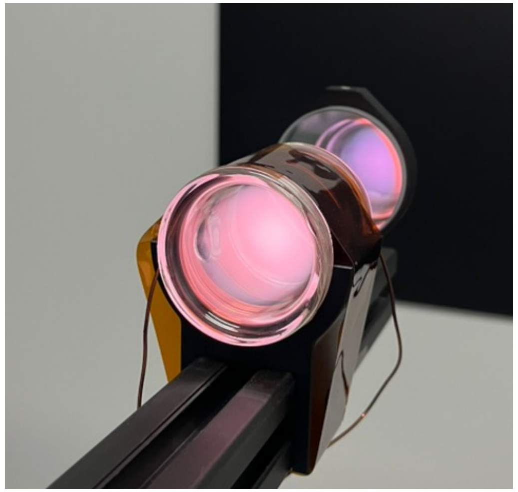


(a)

New Polarized ^{3}He Lab at Shandong University



- Establishing low field MEOP system at SDU polarized ^{3}He lab
- High field MEOP upgrading in 2027 with extended lab space on campus



1 mbar ^{3}He glass cell produced at CSNS

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, new high-field MEOP techniques enable ^{3}He nuclear polarization in 1~5 T
- Novel OP techniques open new opportunities in spin physics research
- Polarize ^{3}He lab established on SDU Qingdao campus
- Development on new ^{3}He target and ion source is underway in China

Thanks for your attention!

Backup

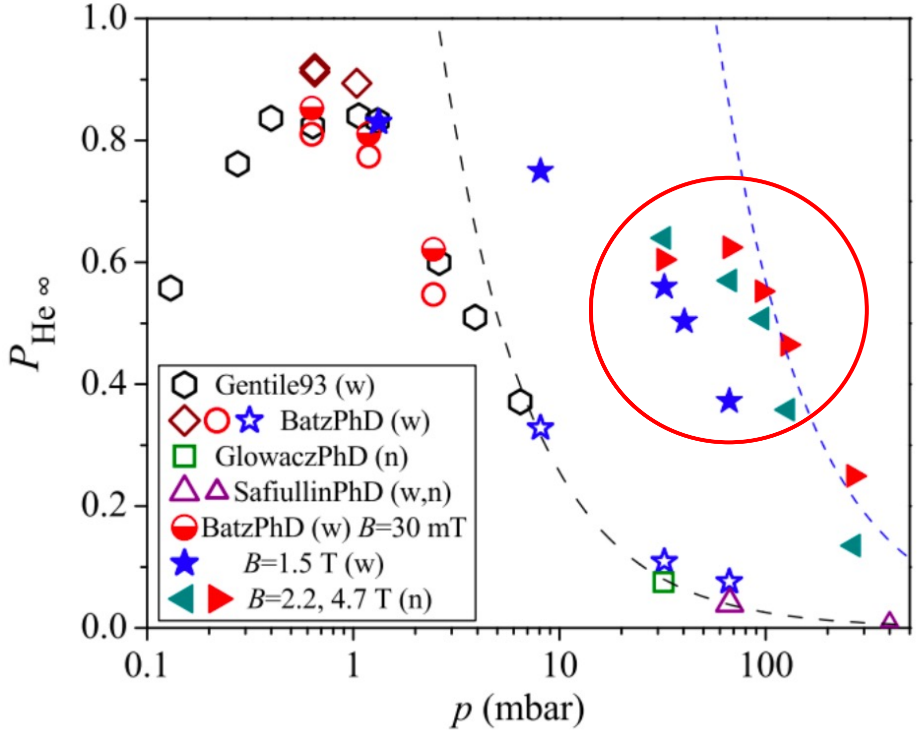
Polarized ^{3}He in High Magnetic Fields

- 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)

^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 in higher fields

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