Polarized Helium-3 Target

Bill Henry

(With slides stolen from Murchhana R., Mingyu C., Gordon C, Arun T, Hunter P., Junhao)

Thursday, August 10, 2023

Polarized Helium-3 Experiements @ JLab

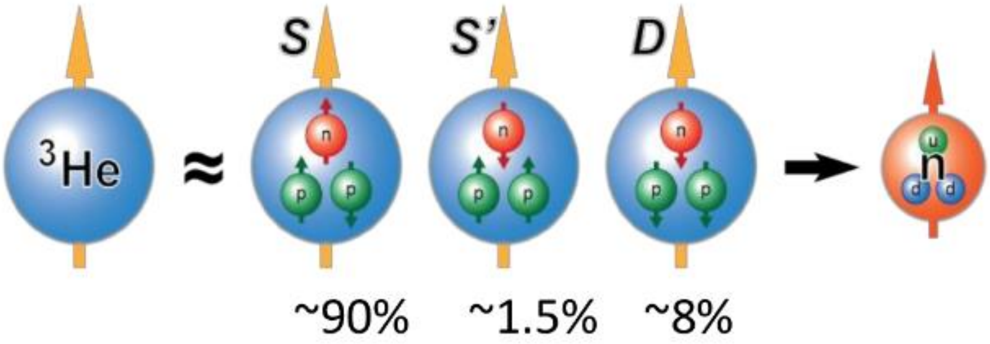
Completed Experiments:

- E94-010: Measurement of the Neutron (^{3}He) Spin Structure Function at Low Q^2; a connection between the Bjorken and GDH sum rules.
- E95-001: Transverse Asymmetry A_T from ^{3}He (e,e')at low Q.
- E99-117: $A^n{}_1$ at Large x using JLab at 6 GeV.
- E97-103: Search for Higher Twist Effects in the Neutron Spin Structure Function $g^n{}_2$.
- E01-012: Neutron (^{3}He) spin structure functiuons in the resonance region - spin duality.
- E97-110: The GDH Sum Sule and Spin Structure of ^{3}He and the Neutron Using Nearly Real Photons.
- E02-013: Neutron Electric Form Factor G_{En} at High Q^2.
- E06-010: Single Target-Spin Asymmetry in Semi-Inclusive Pion Electroproduction on a Transversely Polarized ^{3}He Target.
- E07-013: Normal Target Single-Spin Asymmetry in Inclusive n(e,e') with a Polarized ^{3}He Target.
- E06-014: Precision measurements of d_{2n}: color polarizabilities.
- E05-015: Target Single Spin Asymmetry in Quasi-Elastic ^{3}He(e, e') Reaction.
- E05-012: A_x and A_z in Quasi-Elastic ^{3}He(e, e'd) Reaction
- E08-005: Target Single-Spin Asymmetry Ay in Quasi-Elastic ^{3}He(e,e'n) Reaction

Approved 12 GeV Experiments:

- E12-06-122: A1n in the Valance Quark Region Using an 11 GeV Beam and a Polarized ^{3}He target in Hall C Completed
- E12-06-122: Neutron g2 and d2 at High Q^2 in Hall C Completed
- E12-06-122: A1n in the Valance Quark Region Using 8.8 GeV and 6.6 GeV Beam Energies and Bigbite Spectrometer in Hall A
- E12-09-018: SIDIS Pion and Kaon Electroproduction on a Transversely Polarized ^{3}He Target using the Super BigBite and Bigbite Spectrometers in Hall A 2024
- E12-09-016: GEn/GMn at High Q^2 In Progress
- E12-09-014:Target Single Spin Asymmetry in SIDIS (e,e'pi) Reaction on a Transversely Polarized ^{3}He Target at 8.8 and 11 GeV
- E12-11-007:Asymmetries in SIDIS (e,e'pi) Reactions on a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV SoLID

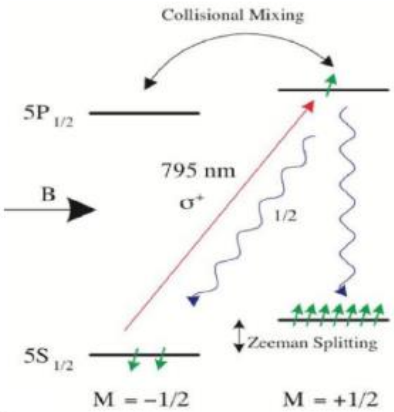
Introduction To Polarized Helium-3



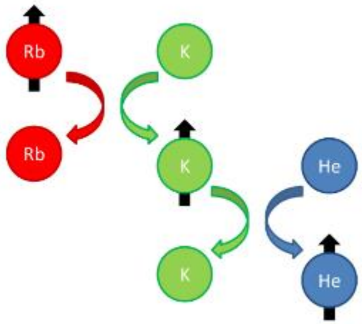
- Polarized target for study the spin structure of nucleon.
- Free neutron mean lifetime: 880.2 s.
- The unpaired neutron carries the majority of the ^{3}He nucleus polarization.
- Polarized ^{3}He is a good effective polarized neutron target.

Introduction To Polarized Helium-3

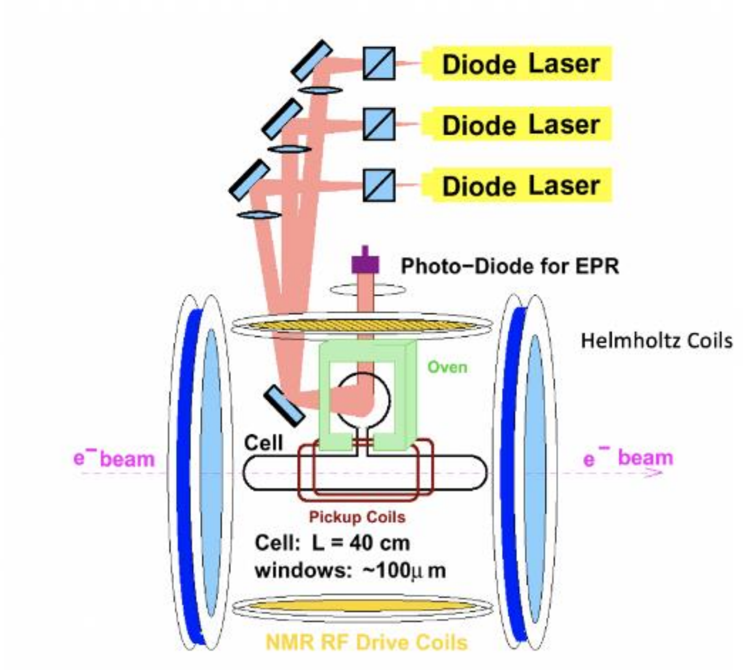
Spin Exchange Optical Pumping
(SEOP)



1. Optical Pumping



2. Spin Exchange



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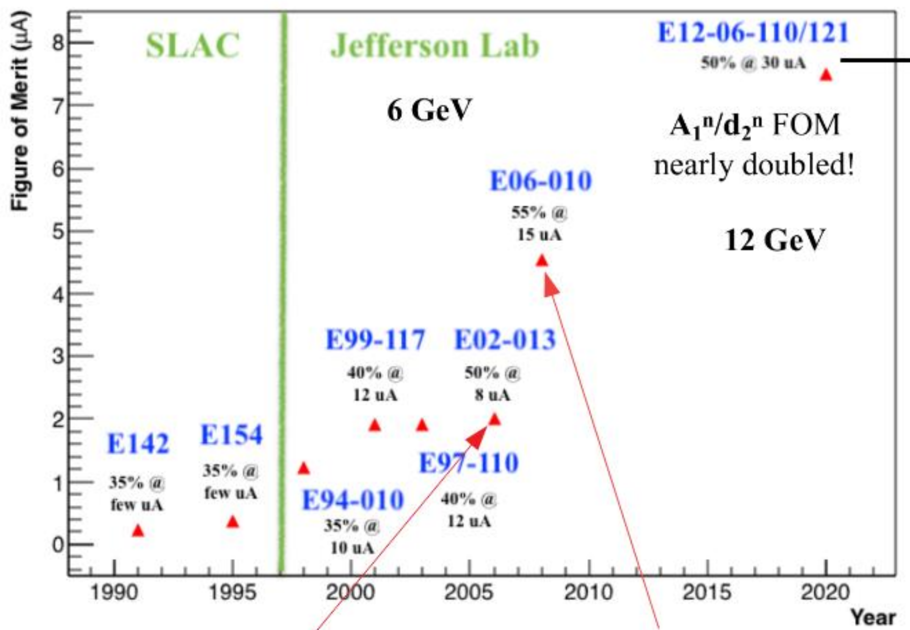
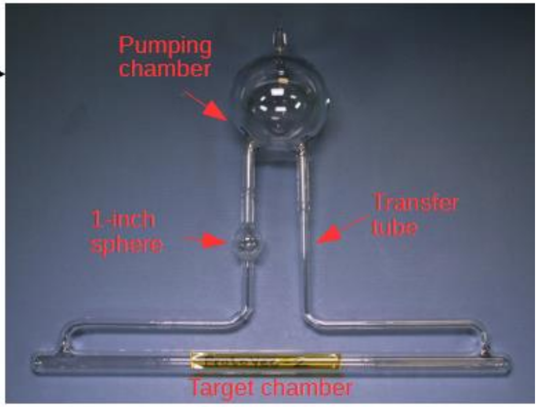
Introduction To Polarized Helium-3

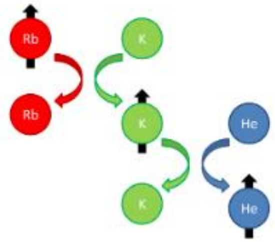
Polarized ^{3}He Targets Performance Evolution

FOM = (Target Polarization)^2 × Beam Current

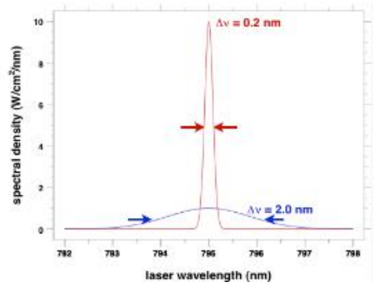




G_E^n (E02-013):
Started to use Rb/K hybrid alkali cell.



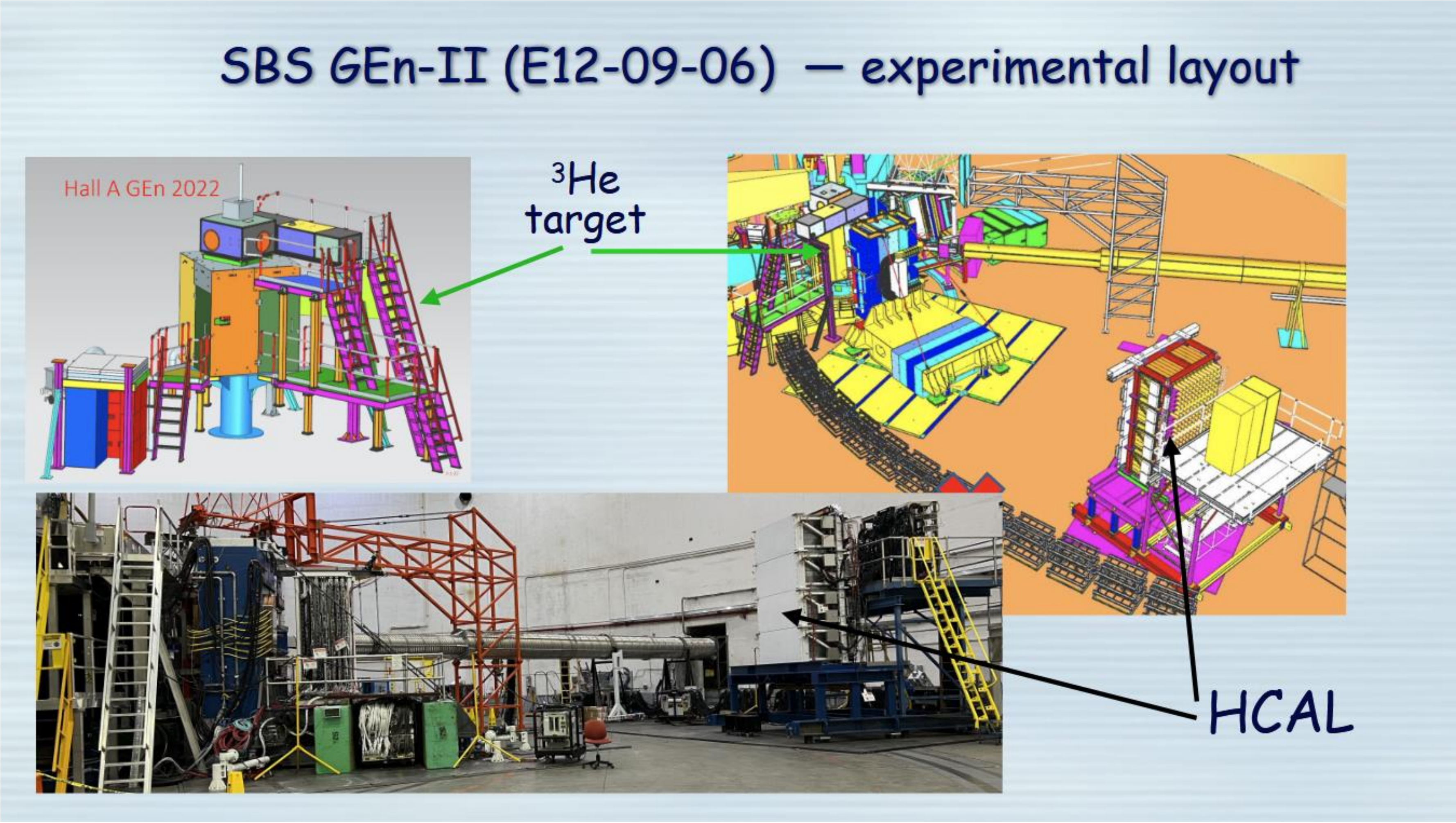
Transversity (E06-010):
Started to use narrow band laser.



- 12 GeV era Target Cell:
  Target chamber length: 40 cm
- Beam Current: 30uA
  Reached over 50% in beam polarization
  Luminosity: ~ 2.2x10^{36} cm^{-2}s^{-1}
- Convection Cell (instead of diffusion cells used in the 6 GeV era)

  → convection allows for more uniform polarization between target and pumping chamber

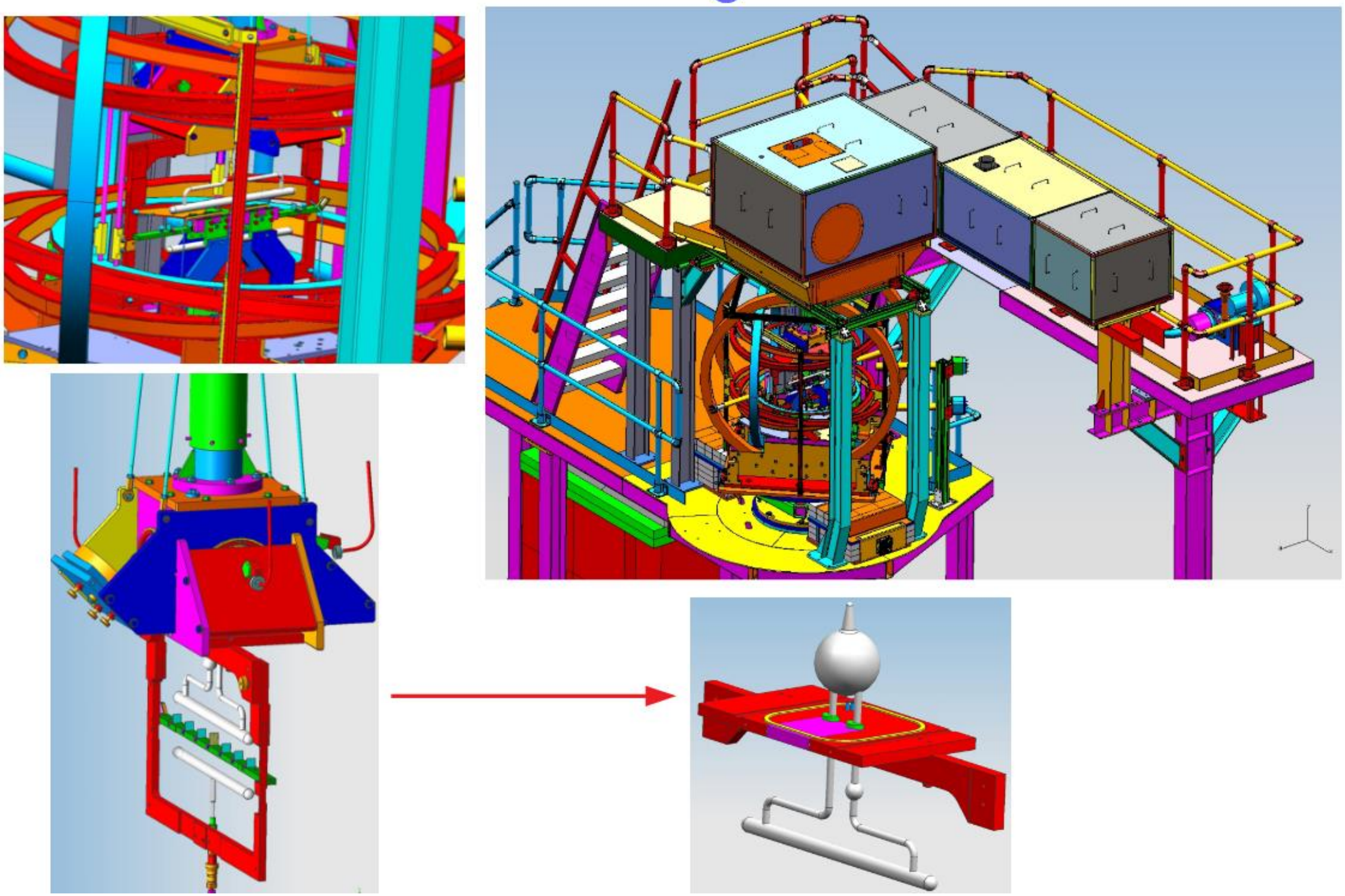
Polarized Helium-3 in Hall A



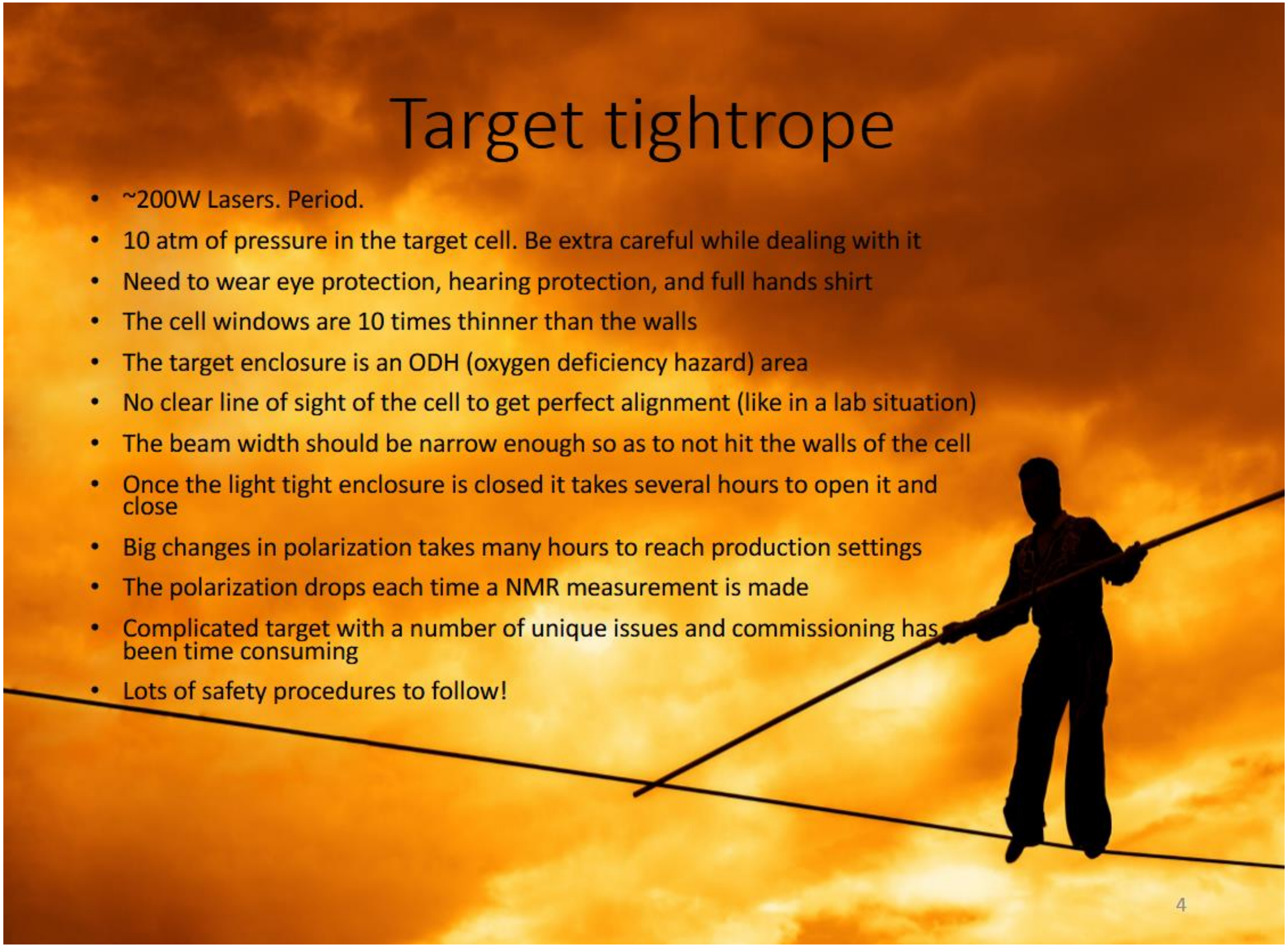
Polarized Helium-3 in Hall A

Polarized Helium-3 in Hall C

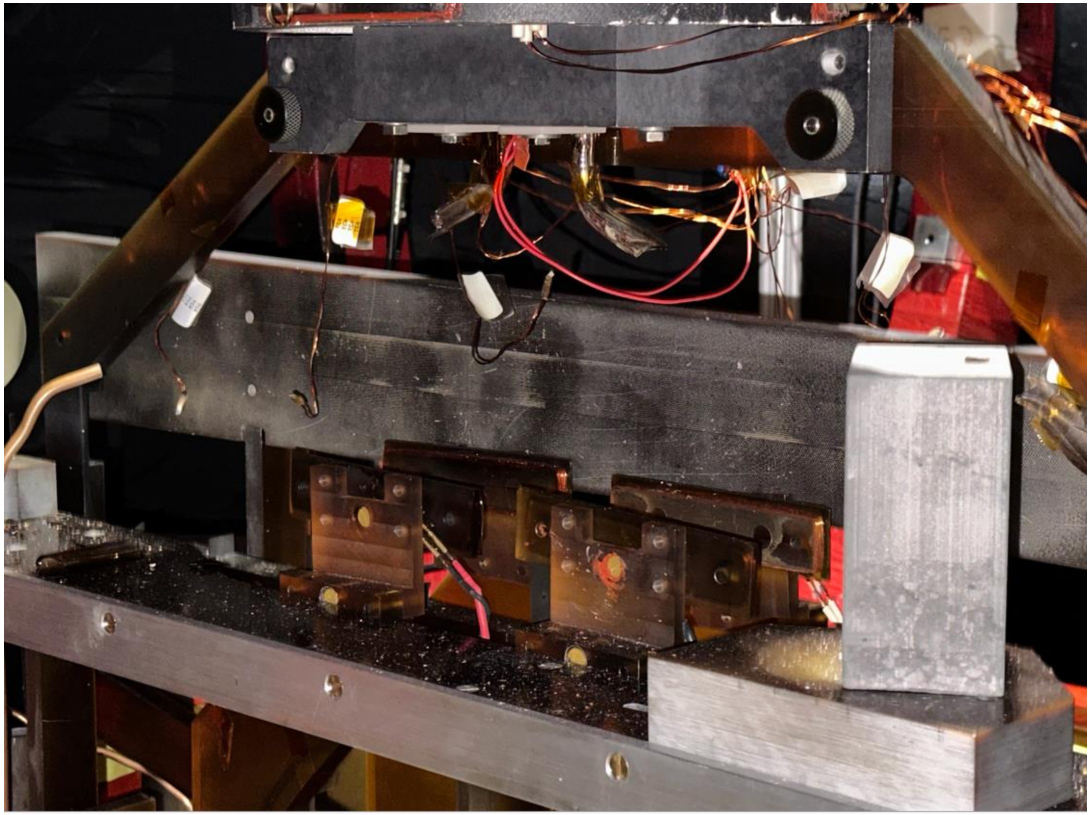
Polarized ^{3}He Target in Hall C



Helium-3 Running



Helium-3 Running

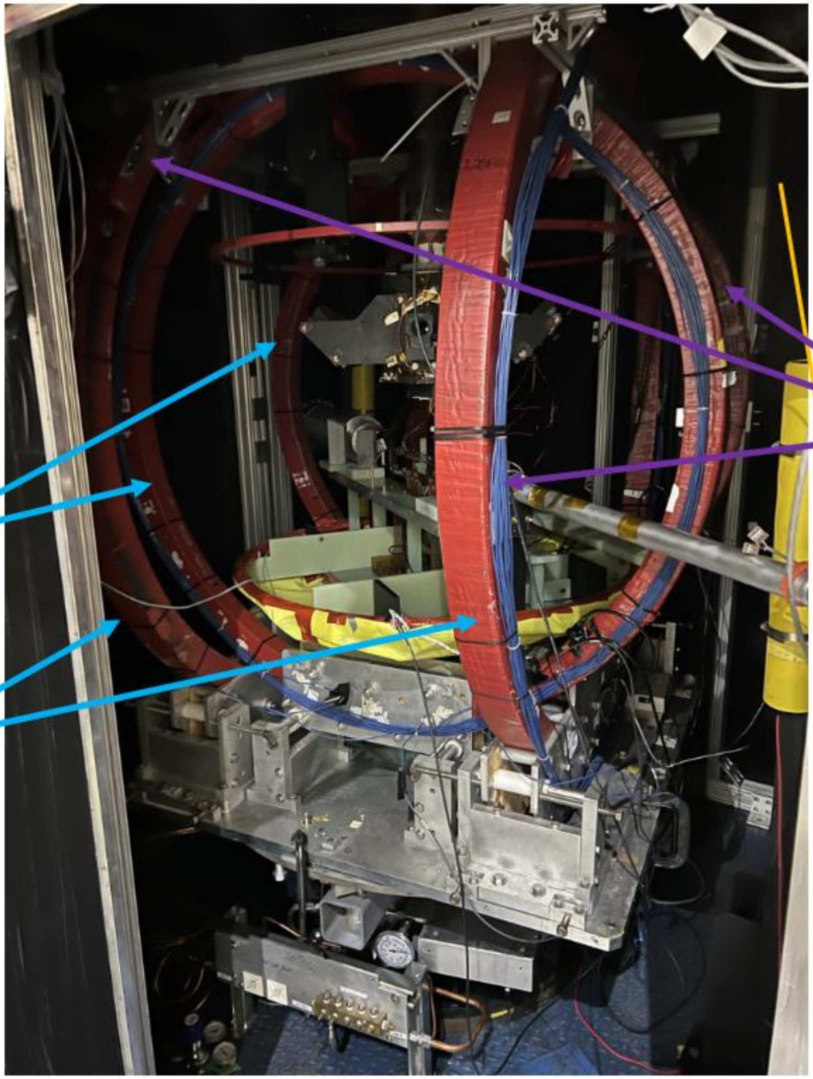


Cell Mounting

Target Holding Field

Small Helmholtz coils

Large Helmholtz coils



Horizontal correction coils (to create gradient)

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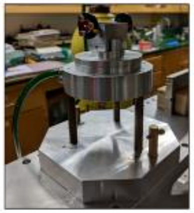
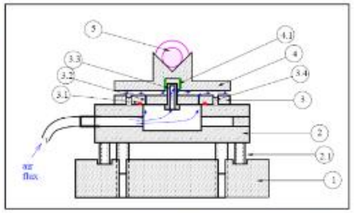
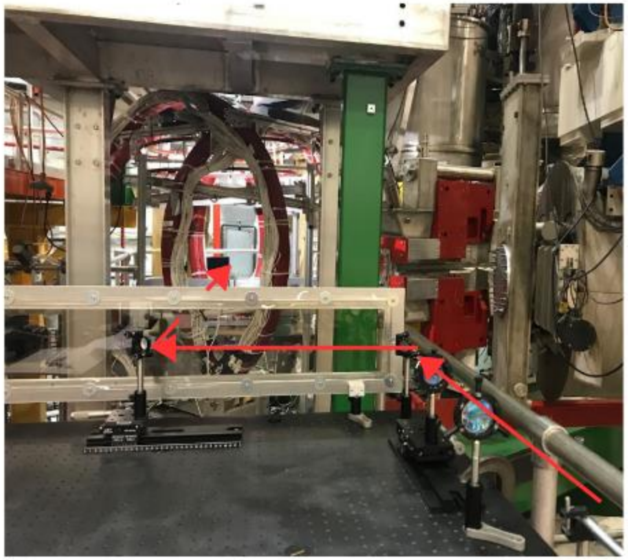
Field Measurements in Hall C

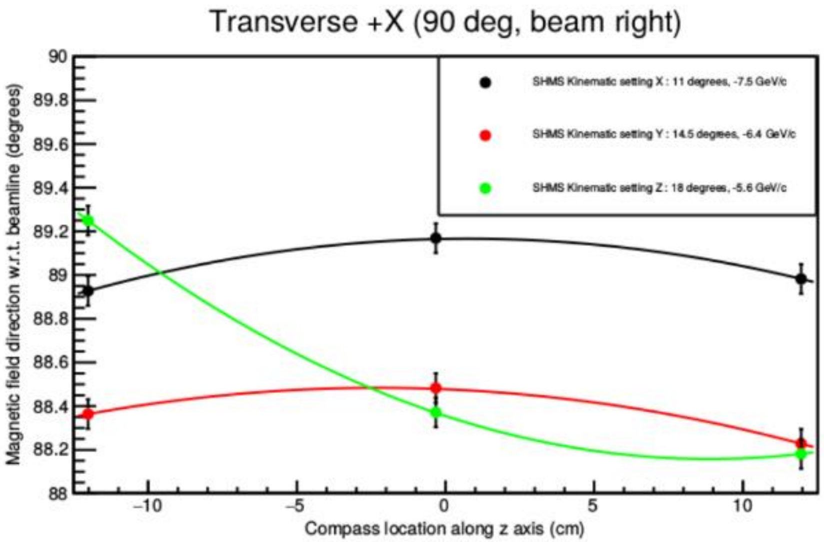
Magnetic Field Direction Measurement
(by Murchhana Roy)

- A novel air-floated compass was developed and built as the commercially available compasses cannot achieve the desired level of precision.
- The magnetic field direction was determined from the surface normal of the aligned compass mirrors by mapping incident and reflected laser beam spots on a screen.
- The points were surveyed by JLab alignment group in absolute Hall C coordinate system.









- Measured absolute direction of the target magnetic field in the Hall C coordinate system precisely to about ±0.1°.

Field Measurements in Hall C

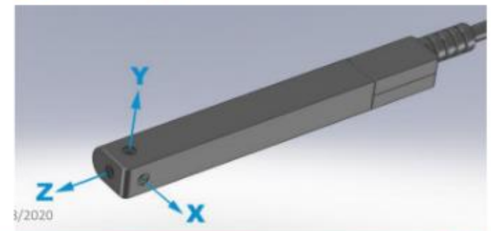
Holding Field Mapping

(by Jixie Zhang and William Henry)

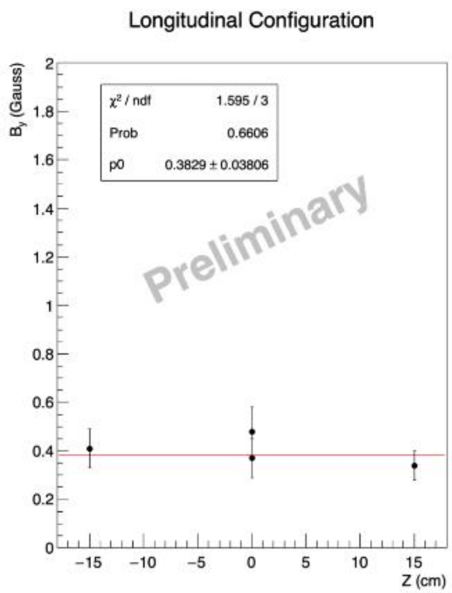
- Measure and correct the field gradient and vertical field components caused by the magnetic structures surrounding the target and fringe field of SHMS HB.
- Use 1D and 3D Hall probe mounted on a 3-axis movable slotted rack .

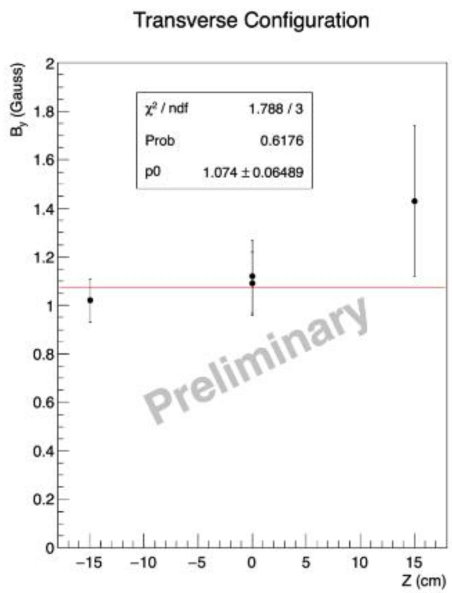
1D Probe

3D Probe



A1n Vertical Field Measurments

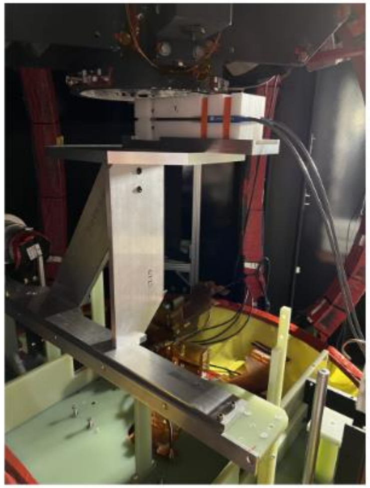


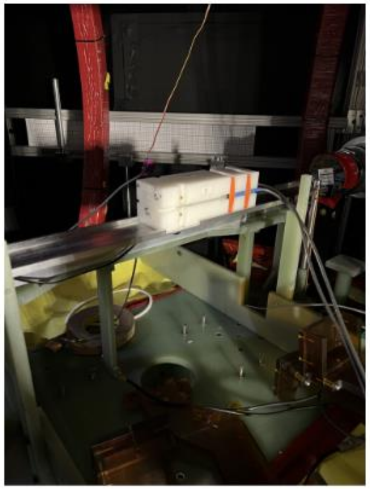


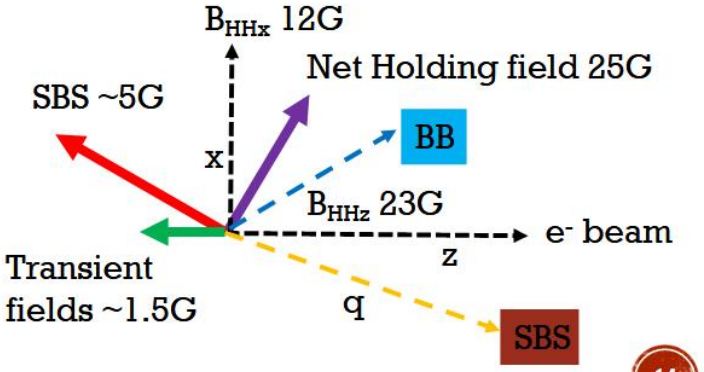
Field Measurements in Hall A

B-FIELD MEASUREMENTS

- Two methods used for field magnitude and direction - Gradient probe and a custom compass (We need the field direction to be within 2 milli radians (0.12 deg))
- Dry fit for mounting the devices and associated S/A was completed and measurement procedure established
- SBS and BB local mode operation OSP acquired in record time and plan was developed for field measurements







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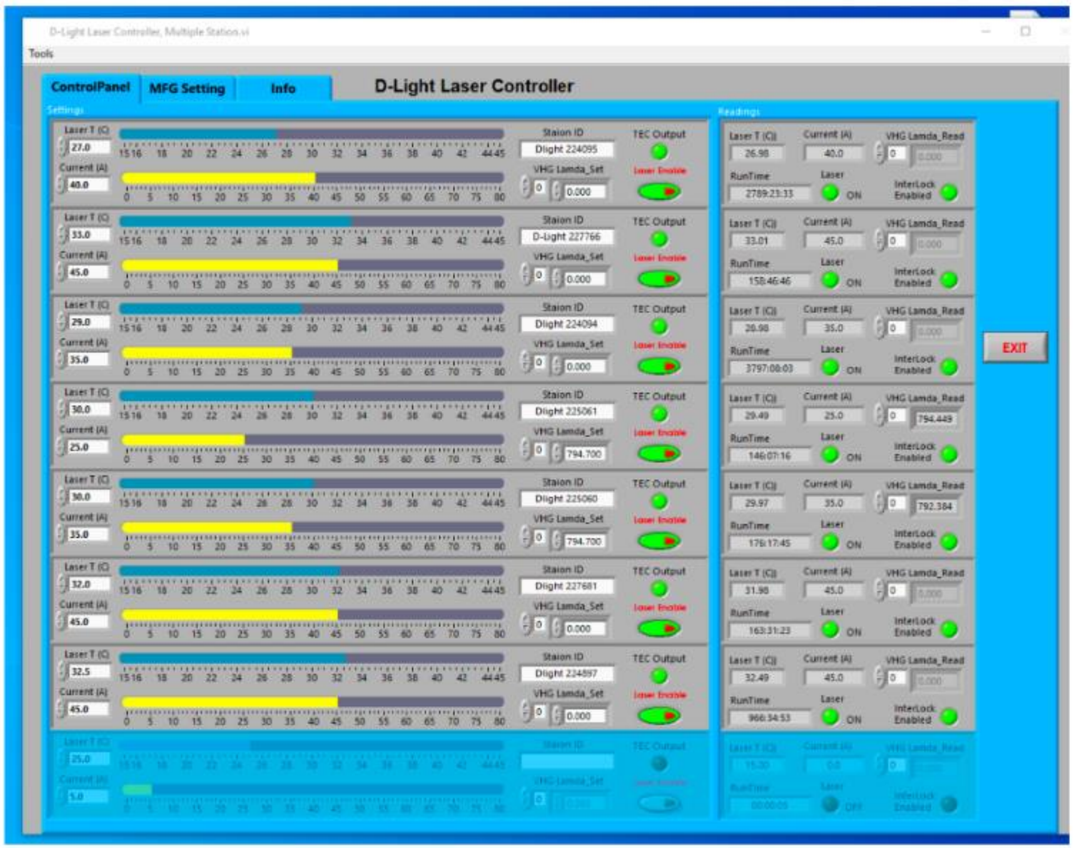
Laser System

Lasers for GEn-II

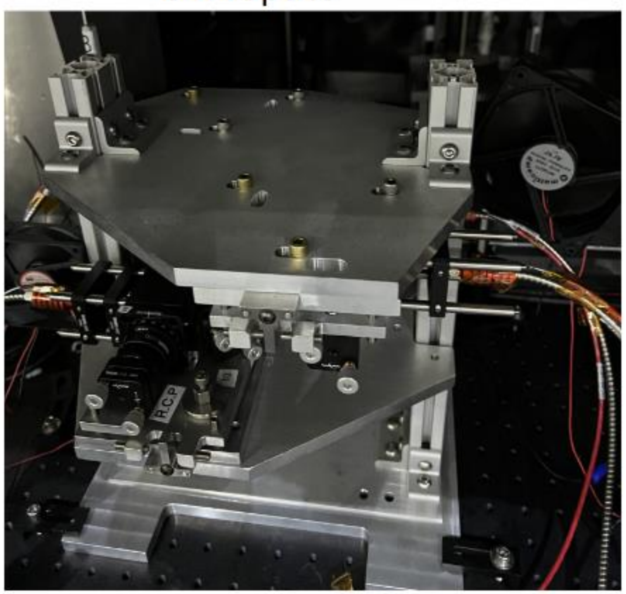


Laser System

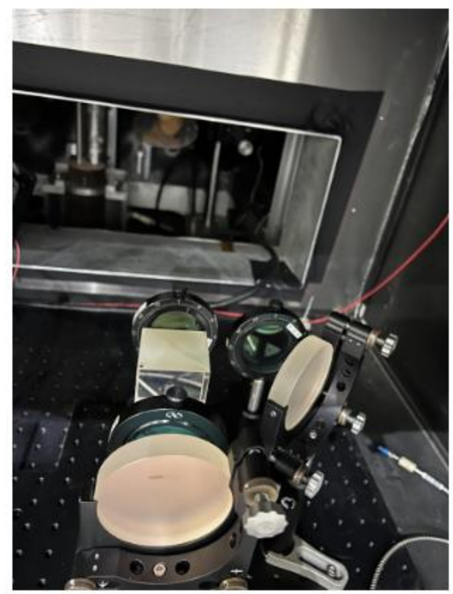
Lasers and laser optics

- The pumping of the polarized target happens from both sides of the pumping chamber (“Jlab” and “Uva” optics)

UVA optics



Jlab optics



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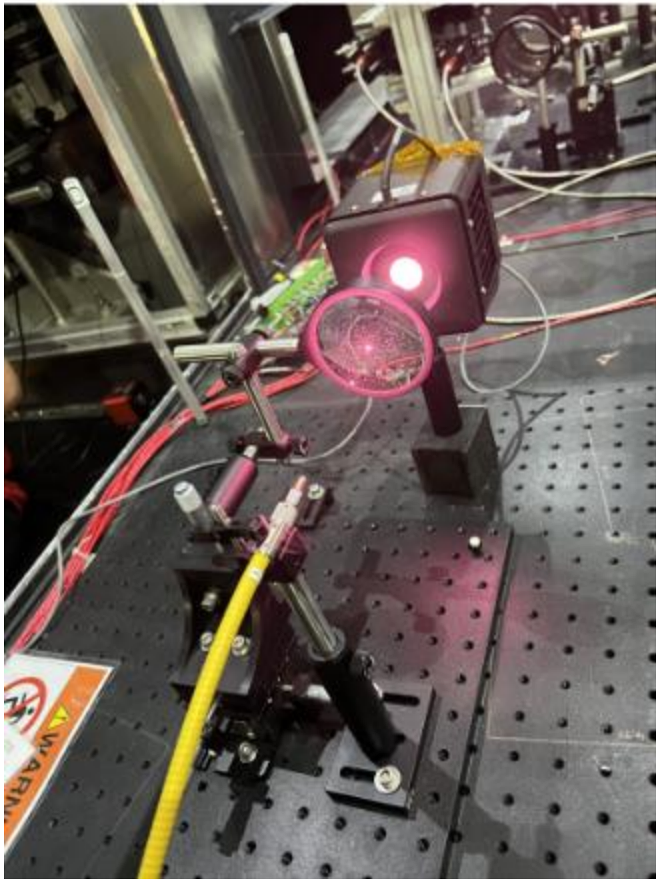
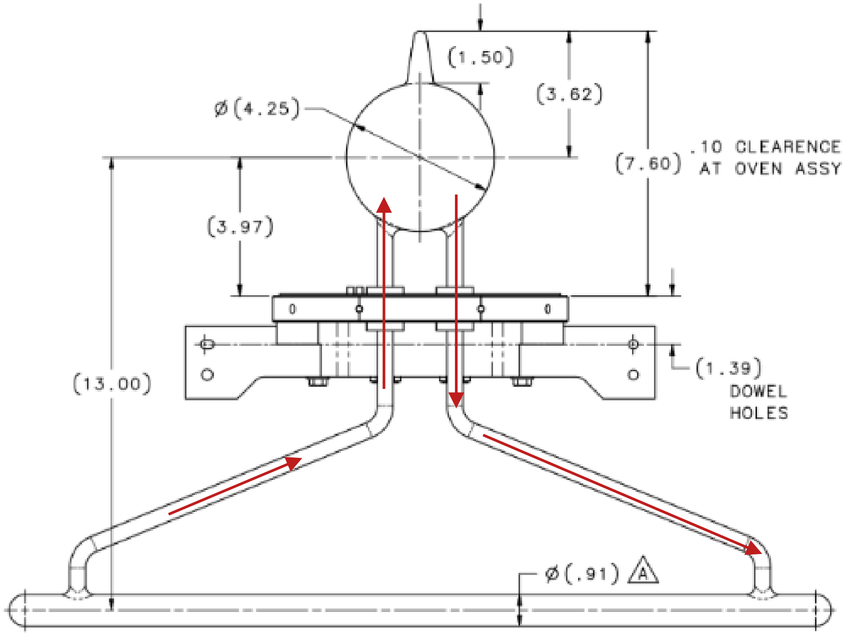
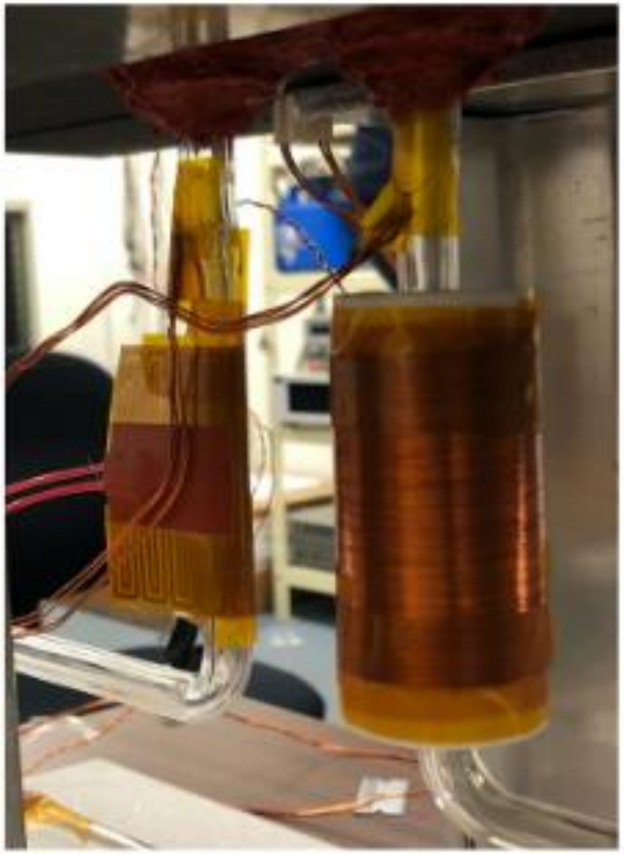
Laser System



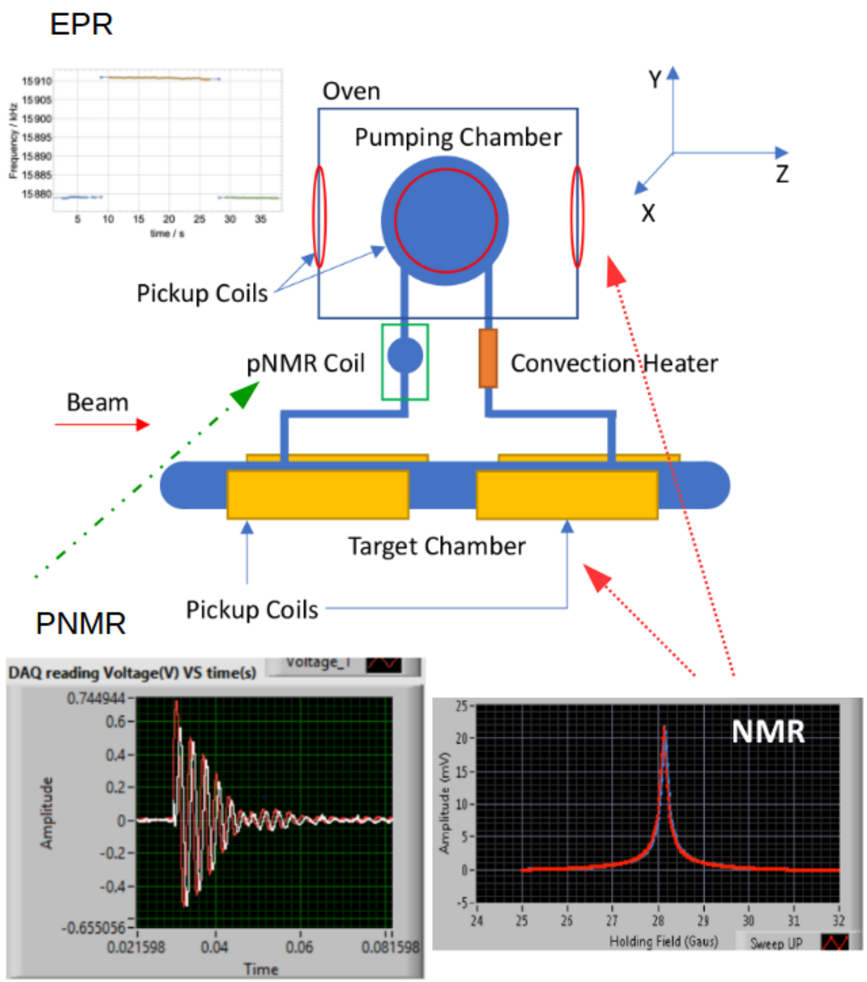
Convection Heater





Target Polarimetry

Polarimetry for ^{3}He in Target Cell



1. Adiabatic Fast Passage Nuclear Magnetic Resonance (AFP-NMR)

- Magnetic Resonance of ^{3}He Nucleus
- Sweep the holding field under AFP condition to flip the Nucleon spin direction back and forth.
- Relative measurement, calibrate with water NMR or EPR.

2. Pulse NMR

- Use resonance RF pulse at ^{3}He Larmor frequency to tilts the Nucleon spin to a certain angle.
- Relative measurement, calibrate with AFP-NMR.
- Implemented for the first time on polarized ^{3}He target.

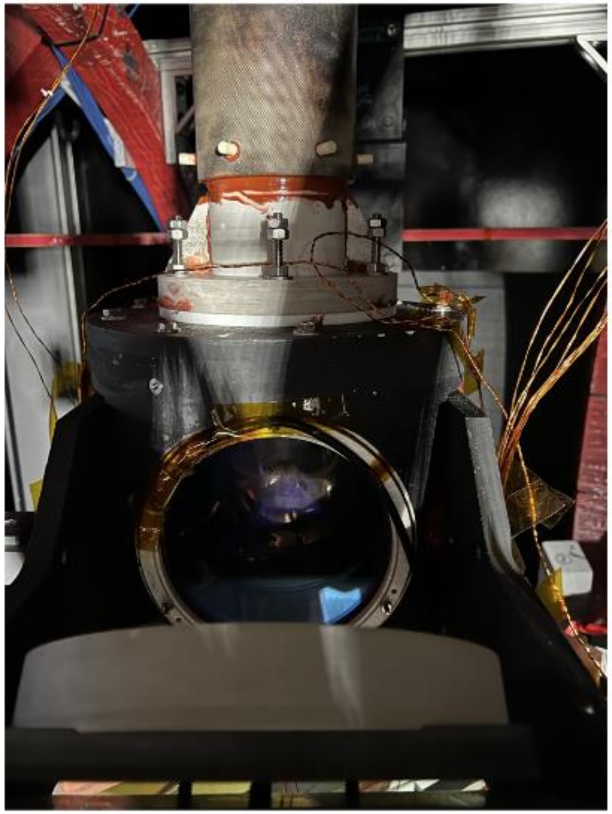
3. Electron Paramagnetic Resonance (EPR)

- Magnetic resonance of the alkali atoms
- Resonance shifted due to polarized ^{3}He, get the resonance frequency difference by flipping the ^{3}He polarization direction.
- Get ^{3}He polarization from resonance frequency difference. Absolute measurement.

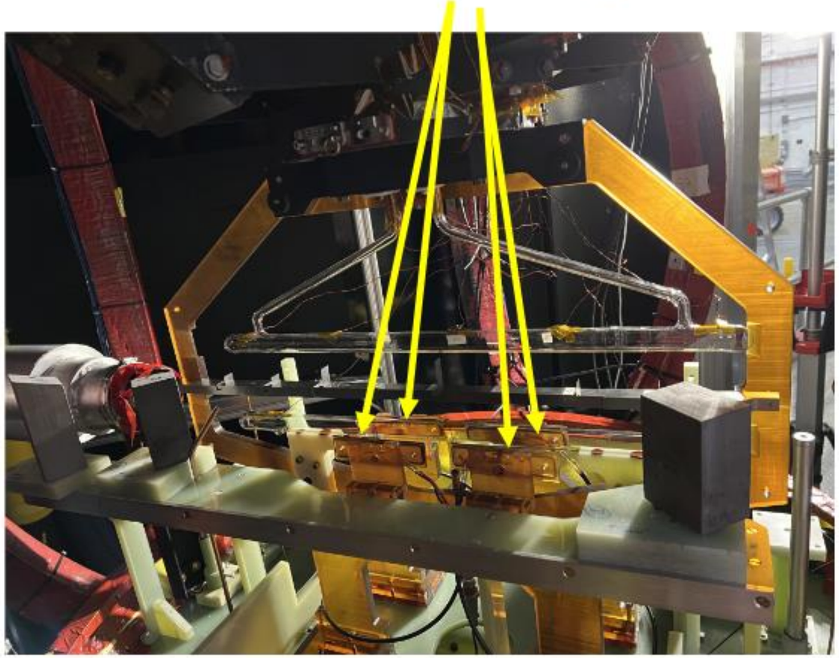
01/28/2021 Hall C Collaboration Meeting Page:7

Target Polarimetry

Pumping chamber
pick up coil



Pick up coil position:
target in between
NMR coil legs



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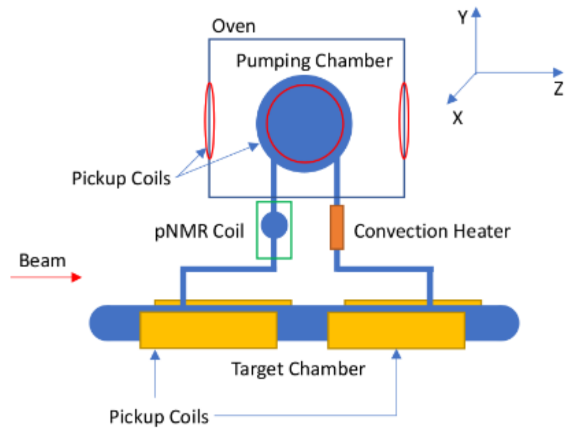
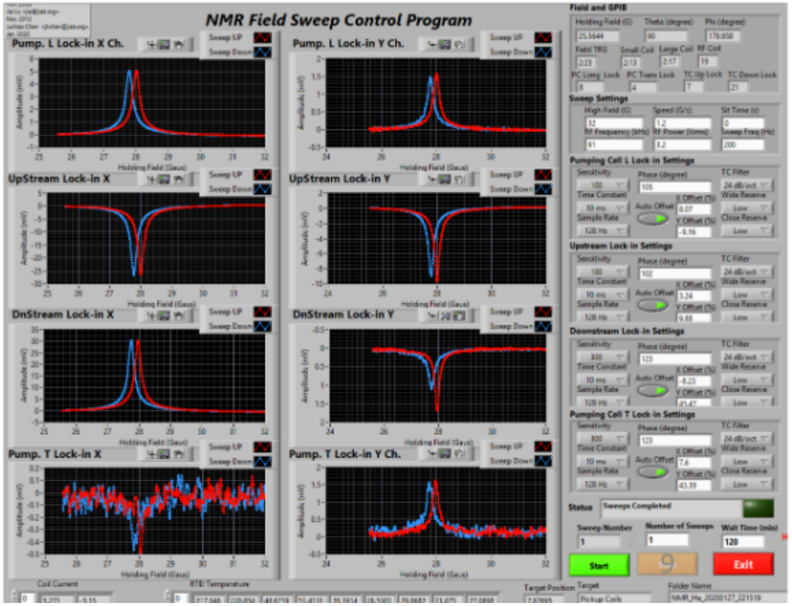
Target Polarimetry

NMR
(by Junhao Chen)

- AFP-NMR was the primary method to measure the ^{3}He target polarization during the production run.
- Two pairs of pumping chamber pickup coils: one in longitudinal direction, another one in transverse direction
- Two pairs of target chamber pickup coils: upstream and downstream
- Target chamber pickup coils are also used to study convection speed



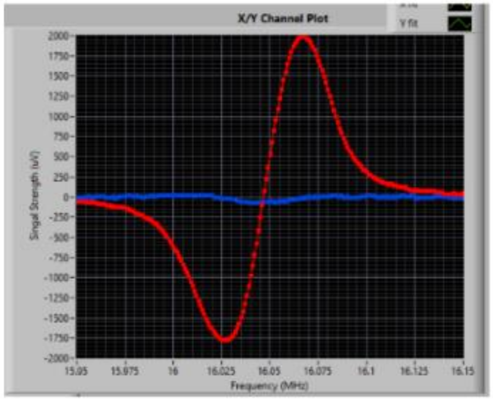


Target Polarimetry

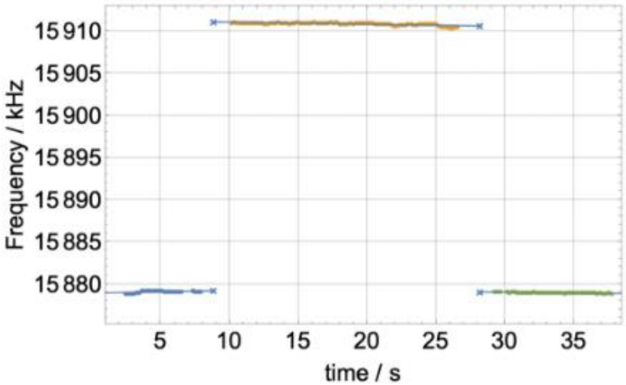
EPR System

(by Melanie Rehfuss and Junhao Chen)

- EPR provides absolute polarimetry.
- EPR polarimetry provided calibrations to NMR system.
- Used a photo diode with D_1 light filter to collect D_2 light.
- The uncertainty for target polarimetry is about ±3%.



- EPR FM Sweep



- EPR AFP Sweep

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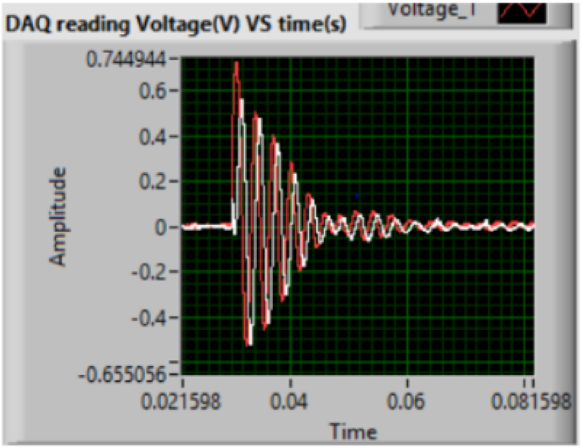
Pulse NMR

(by Mingyu Chen)

- Advantage: Took shorter time to complete measurement, less depolarization compare to AFP-NMR.
- PNMR was performed at transfer tube which was calibrated by AFP-NMR at pumping chamber.
- For most of the measurements, polarization from PNMR agrees with NMR within ±2%.
- However, the drift of holding field magnitude over time changed PNMR signal amplitude and introduce additional uncertainty.
- Still need to do detailed analysis to characterize this effect on PNMR signal and determine the systemic uncertainty for PNMR.



- Current fit for the signal by the FID fitting function to obtain PNMR amplitude A_0.

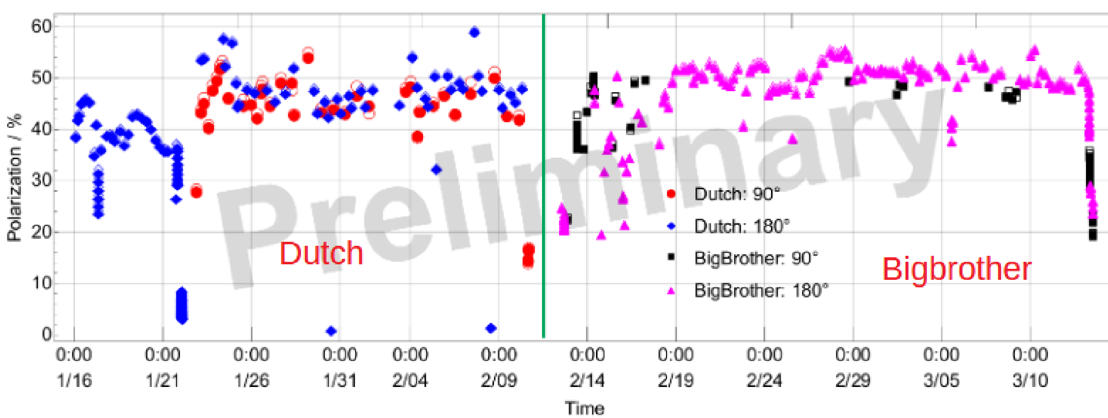
$$S(t)=FID(t)=A_0\cos(\omega t+\phi_0)e^{-t/T_2}+a*t+b$$

- Obtain $PNMR_{amp}/NMR_{amp}$ ratio in order to calibrate PNMR with NMR.

Hall C Performance

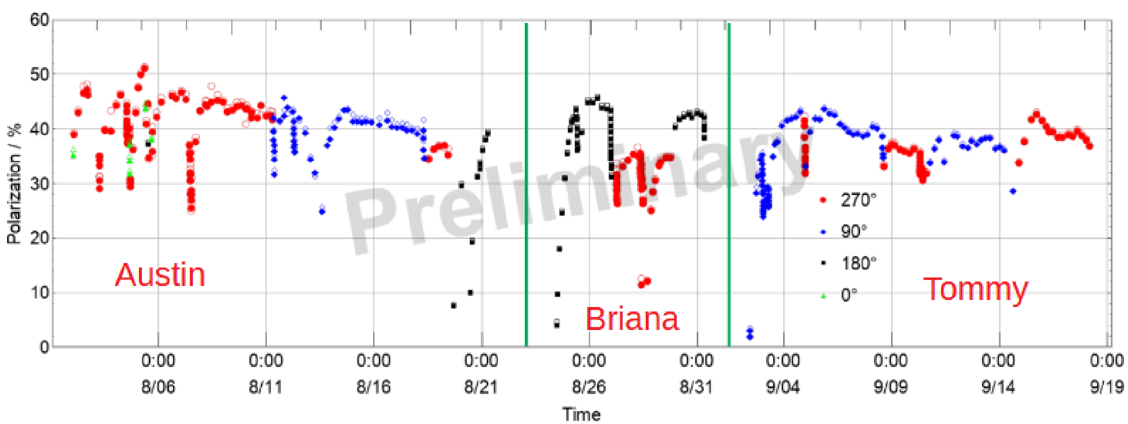
Production Cell Performance

(for A_1^n/d_2^n experiments)



- Target cell polarimetry was performed by AFP-NMR in pumping chamber and calibrated with EPR measurements. Reached over 50% polarization with 30 uA electron beam.

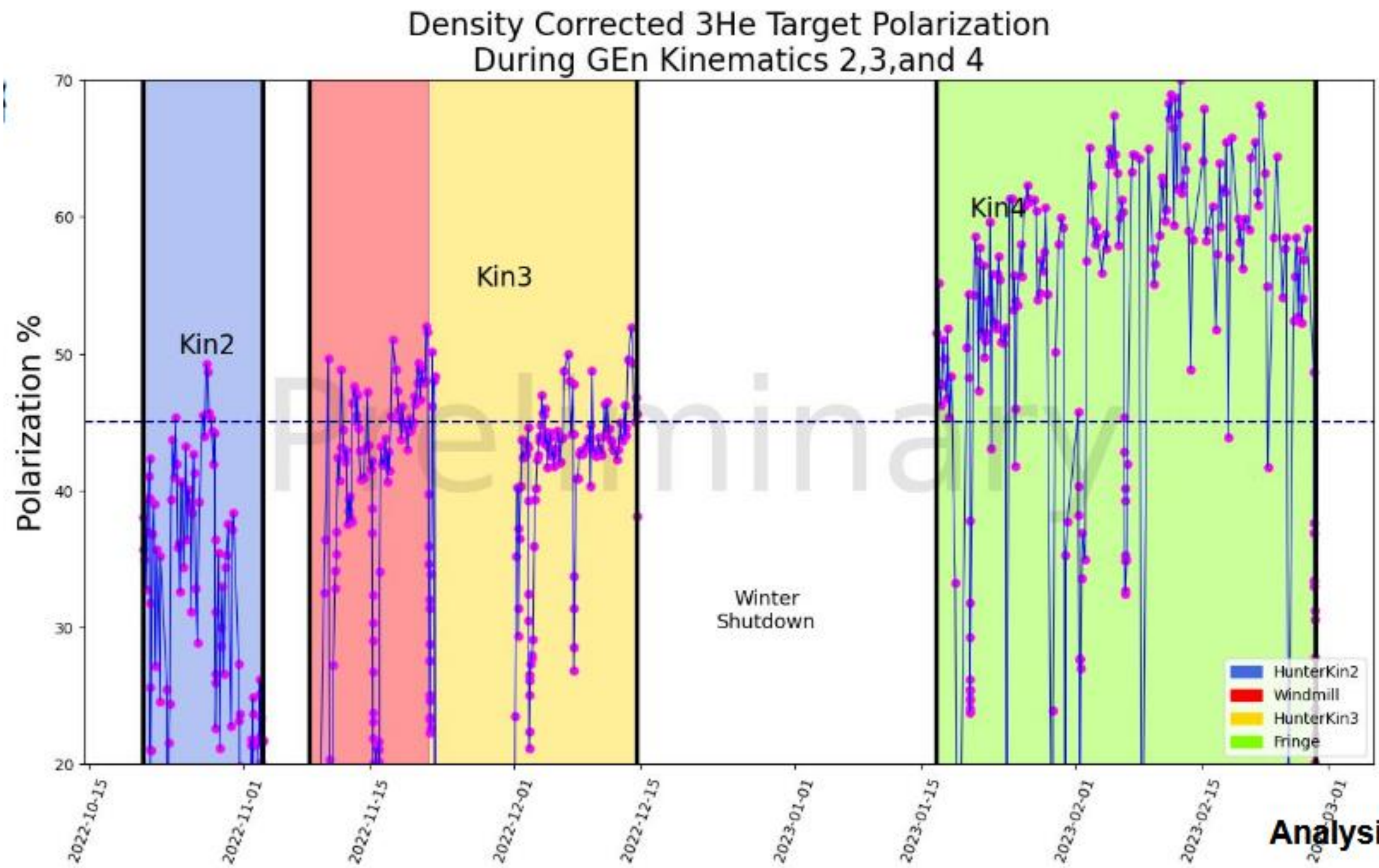
→ Polarized ^{3}He target polarization during A_1^n production running.



→ Polarized ^{3}He target polarization during d_2^n production running.

- Still need to do detailed analysis to get target polarization in target chamber with systemic uncertainties.

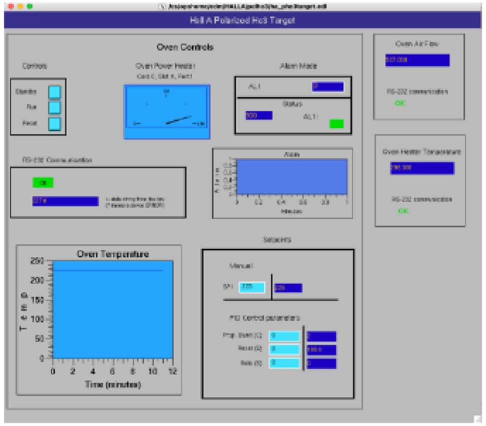
Hall A Performance



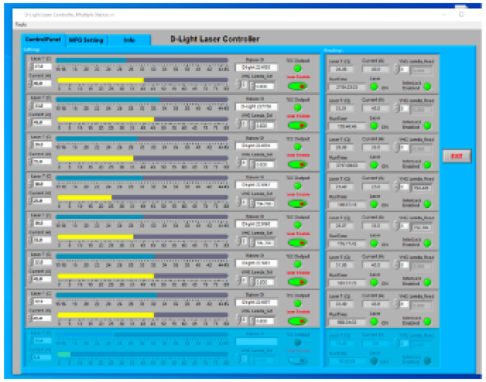
Analysis

Slow Controls

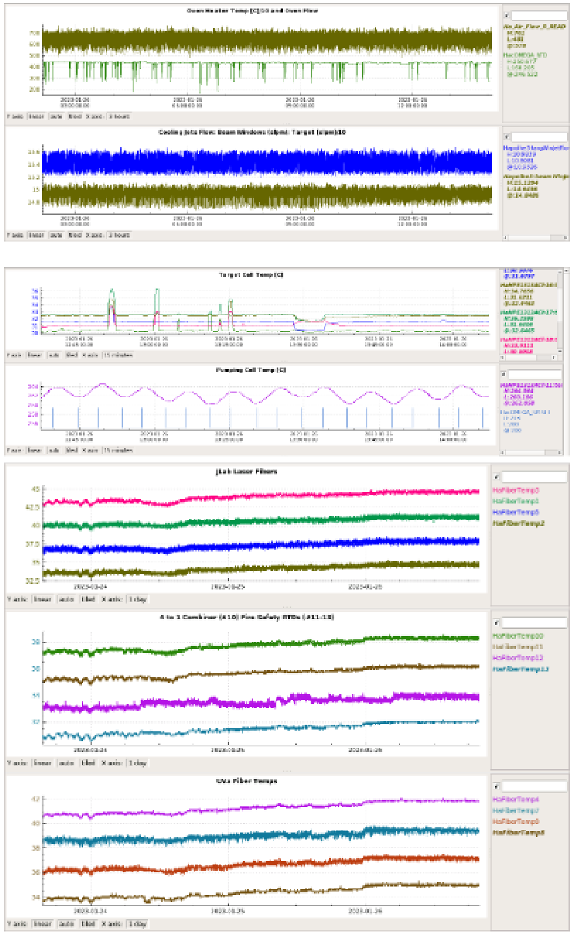
RTD monitoring

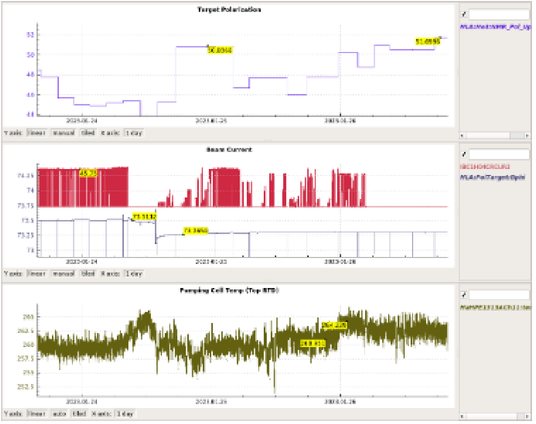


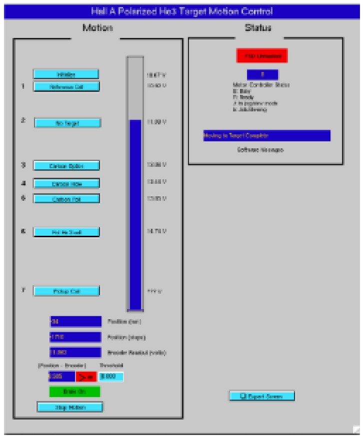
Oven control



Lasers

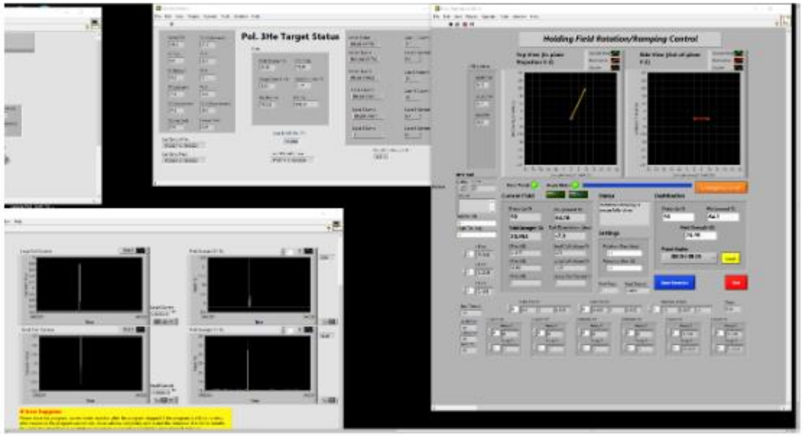






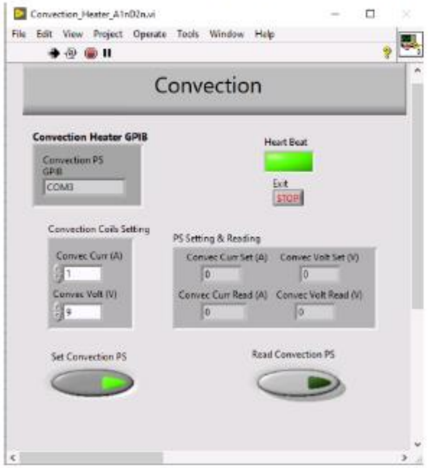
Target ladder control

Slow Controls

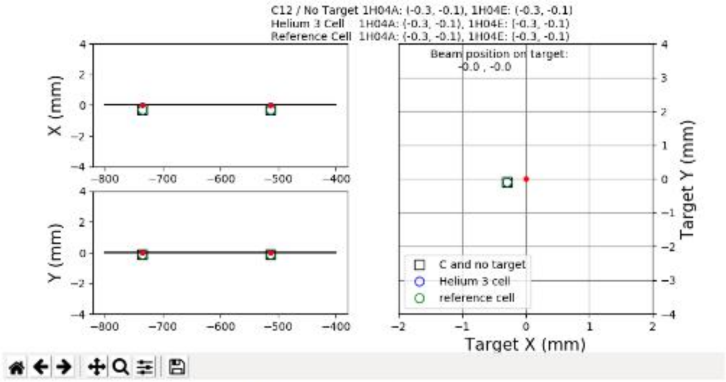


Field rotation software

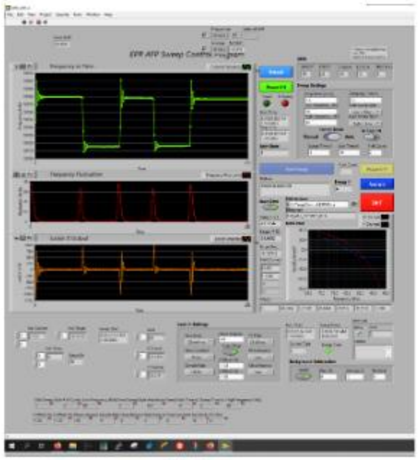
NMR polarimetry software



Convection heater



Beam position



EPR

The Hall A Team

The Hall C Team

Postdocs

A. Tadepalli, JLab

W. Henry, JLab

J. Zhang, UVA

Students

Melanie Rehfuss

Junhao Chen

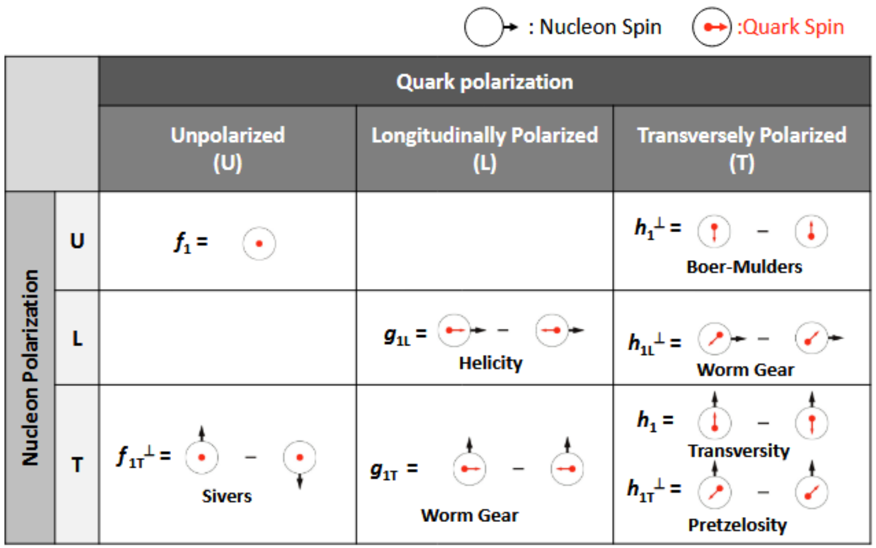
Murchhana Roy

Mingyu Chen

Summary

Sign up for shifts here !!

Polarized Helium-3 Experiments @ JLab



Asymmetries in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reactions on a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV

Abstract

We propose a measurement of single-target and double spin azimuthal asymmetries (SSAs and DSAs) in semi-inclusive electroproduction of charged pions, using the upgraded CEBAF electron beam, the Hall A polarized ^{3}He target as an effective polarized neutron target, and the newly approved SoLID spectrometer. The hardware setup is similar to that of experiment E12-10-006, with additional requirements of a longitudinally polarized target and a polarized beam. We also request a high beam polarization for E12-10-006 to measure DSAs with a transversely polarized target. The SSAs and DSAs, with longitudinal and transverse target spin, respectively, are related to two "worm-gear" transverse-momentum-dependent (TMD) parton distributions of the nucleon at leading twist. Both of the "worm-gear" TMD distributions require an interference between wave function components that differ by one unit of quark orbital angular momentum (OAM), as explicitly shown in several models. In addition, the DSAs with a longitudinal target spin will constrain the flavor decomposition of the quark helicity distribution of the nucleon and provide information on their transverse momentum dependence. All asymmetries will be measured with a high precision and a large kinematic coverage in a 4-D phase space of x, z, $P_{h\perp}$ and Q^2. The systematic uncertainties are improved by fast target spin flips and a large coverage in the azimuthal angles. We request 35 PAC days of data taking on the longitudinally polarized ^{3}He target.

2. PHYSICS MOTIVATION

2.1. "Worm-gear" functions, g_{1T} and $h_{1L}^{\perp}$

The main physics goal of this proposal is to provide direct experimental information for both "worm-gear" functions, g_{1T} and $h_{1L}^{\perp}$. They can be accessed through the double spin asymmetries $A_{LT}^{\cos(\phi_h-\phi_S)}$ with a transversely polarized target and the beam single spin asymmetries, $A_{UL}^{\sin 2\phi_h}$, with a longitudinally polarized target, respectively. The physics related to "worm-gear" functions, their measurement and their current experimental status will be discussed in this section.

https://www.jlab.org/exp_prog/proposals/11/PR12-11-007.pdf

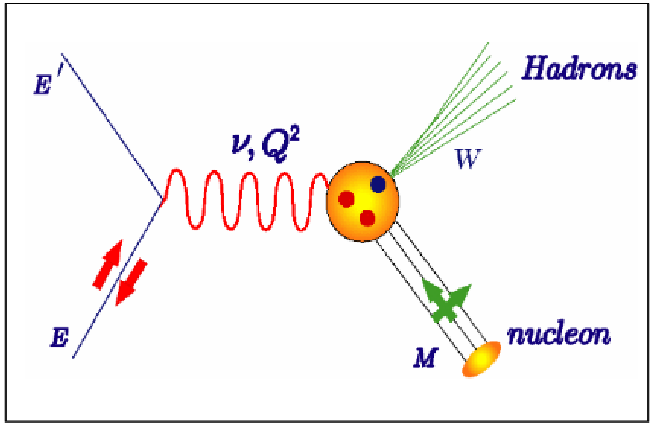
- BACK UPS

Deep Inelastic Scattering

Unpolarized cross section:

$$\frac{d^2\sigma}{d\Omega\, dE'} = \frac{\alpha^2}{4E^2 \sin^4\frac{\theta}{2}} \left(\frac{2}{M} F_1(x,Q^2) \sin^2\frac{\theta}{2} + \frac{1}{\nu} F_2(x,Q^2) \cos^2\frac{\theta}{2} \right)$$

- Unpolarized structure functions F_1 and F_2 contain information about the momentum structure of the target nucleon.



Polarized cross section:

$$\frac{d^2\sigma}{dE'\, d\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2 E'}{M Q^2 \nu E}\left[(E + E'\cos\theta) g_1(x,Q^2) - \frac{Q^2}{\nu} g_2(x,Q^2)\right] = \Delta\sigma_{\parallel}$$

$$\frac{d^2\sigma}{dE'\, d\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin\theta\, E'^2}{M Q^2 \nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right] = \Delta\sigma_{\perp}$$

- Polarized structure functions g_1 and g_2 encode information about the spin structure of the target nucleon.

Q^2 = 4-momentum transfer squared of the virtual photon

ν = E-E' = energy transfer

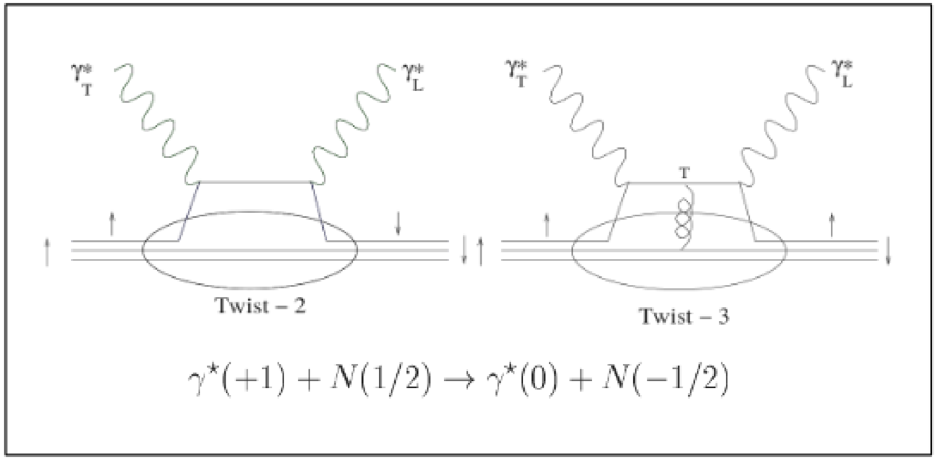
θ = scattering angle

x = Fraction of nucleon momentum carried by the struck quark

g_2 and Quark-Gluon Correlations

- g_2 has no interpretation in naive quark parton model, provides information on quark-gluon correlation.

- g_2 is among the cleanest higher twist observables – contributes to leading order (twist-2 is leading twist) at the transverse spin asymmetry.



$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- Twist-2 term (*Wandzura & Wilczek*).

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)}{y} dy$$

- Twist-3 term with a suppressed twist-2 piece (*Cortes, Pire & Ralston*).

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M} h_T(y,Q^2) - \xi(y,Q^2)\right)\frac{dy}{y}$$

Transversity

Quark-gluon correlation

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d_2: Clean Probe of Quark-Gluon Correlations

- d_2 is a clean probe of quark-gluon correlations / higher twist effects - third moment of the linear combination of the spin structure function.

$$d_2(Q^2)=3\int_0^1 x^2[2g_1(x,Q^2)+3g_2(x,Q^2)]dx=3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$

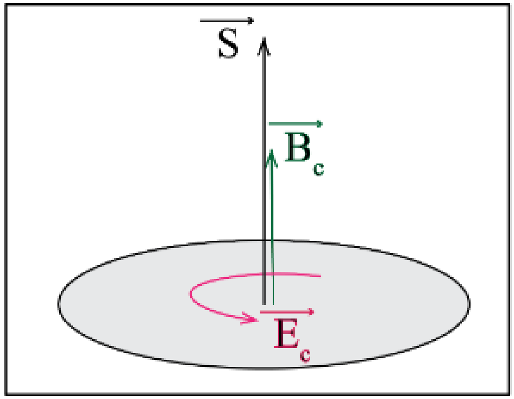
- Related to matrix element in OPE, which represents average transverse color Lorentz force on the struck quark due to the remnant system and it is cleanly computable using Lattice QCD.

- Connected to "color polarizability".

$$\chi_E=\frac{(4d_2+2f_2)}{3} \qquad \chi_B=\frac{(4d_2-f_2)}{3}$$

- f_2 is a twist-4 contribution can be extracted from the first moment of g_1.

$$\Gamma_1=\int_0^1 g_1 dx=\mu_2+\frac{M^2}{9Q^2}(a_2+4d_2+4f_2)+O\left(\frac{\mu^6}{Q^4}\right)$$



Response of the color $\vec{B}$ and 5
$\vec{E}$ field to the nucleon polarization