SpinQuest (E1039) Polarized Target: An Overview

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For the UVA Spin-Physics Group

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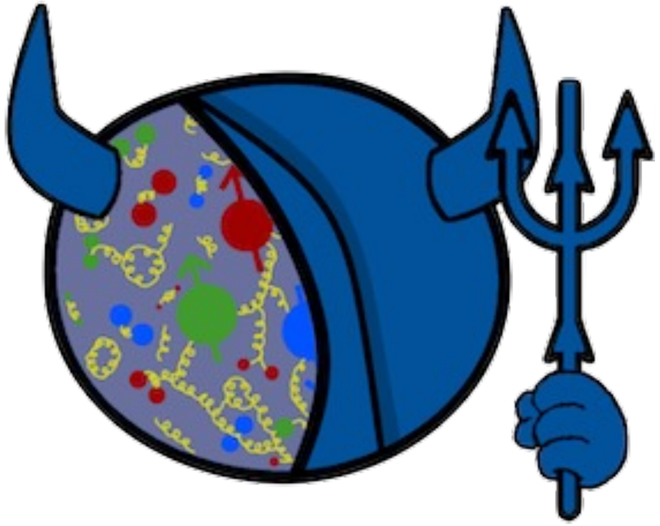


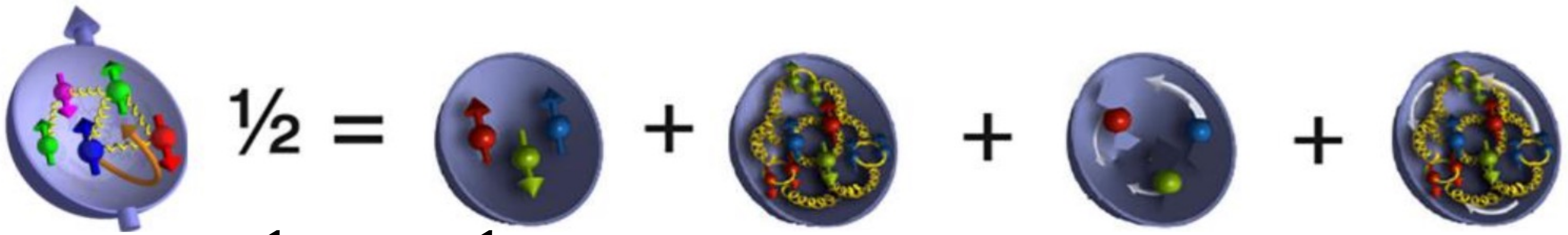
This work was supported by DOE contract *DE-FG02-96ER40950*

Outlines of the talk

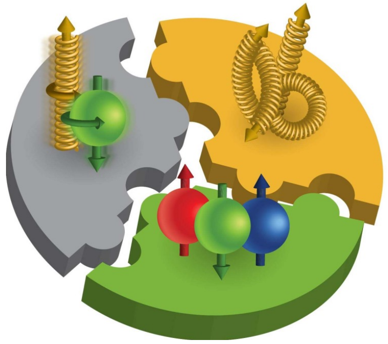
- Physics motivation
- SpinQuest (E1039) experiment setup at Fermilab
- Cryoplatform at NM4 and Polarized target at NM3
- Dynamic Nuclear Polarization (DNP) Method
- Microwave System
- Target materials
- Superconducting Magnet system
- NMR (Nuclear Magnetic Resonance)
- Evaporation Fridge
- Summary

Physics Motivation

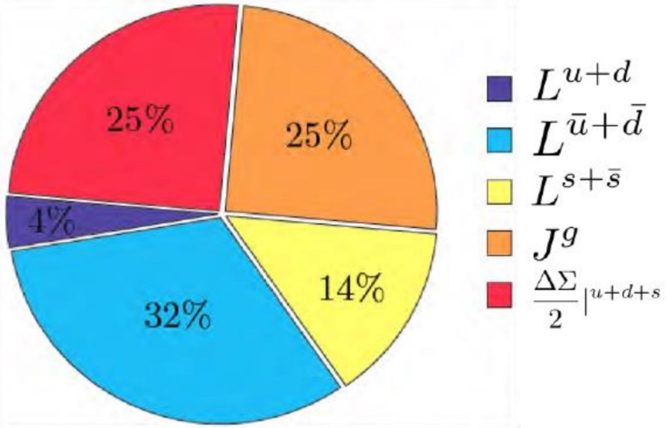
- **Spin crises:** **70%** of the nucleon spin is missing!



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_{\bar{q}} + L_g$$



K.F. Liu *et al* arXiv: 1203.6388

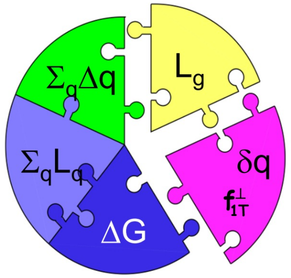


$\Delta\Sigma_q \approx 25\%$

$L_u \approx -L_d$

$2L_q \approx 46\% \left(0\%(valence) + 46\%(sea)\right)$

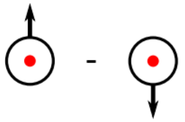
$J_g \approx 25\%$



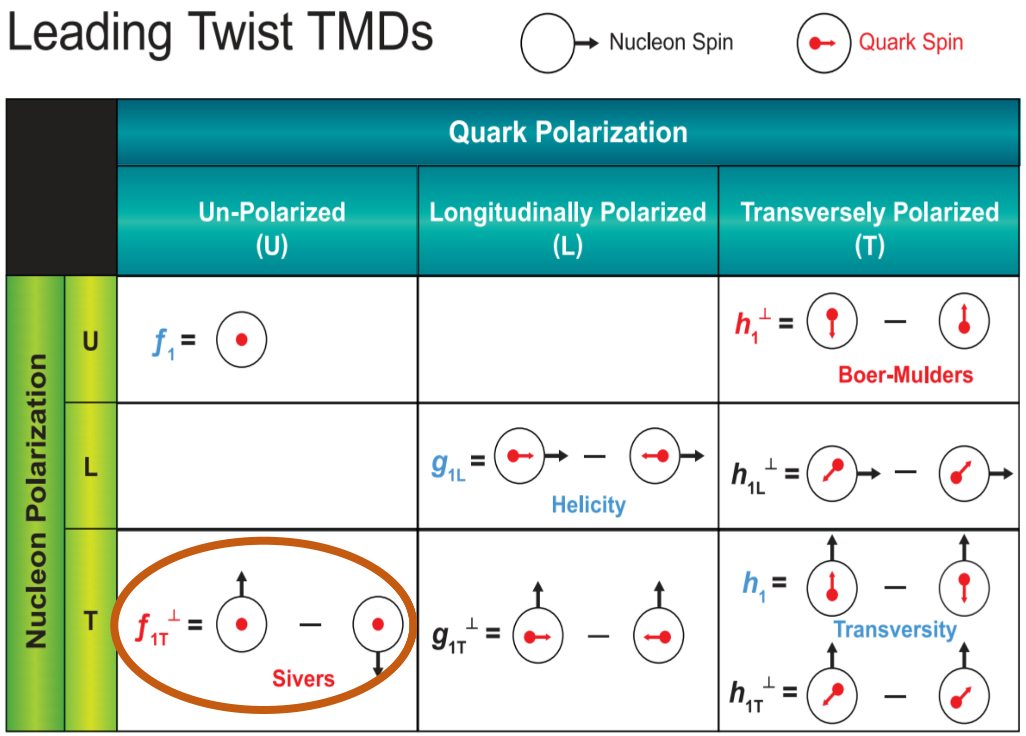
OAM from sea quarks could contribute up-to half of the proton's spin

SpinQuest Goals

- **Sivers function**: The Sivers function describes the correlation between the momentum of the struck quark and the spin of its parent nucleon.

$$f_{1T}^{\perp}(x, k_T) =$$ 

- A non-vanishing Sivers function for the sea quarks is evidence there is sea quark orbital angular momentum (OAM).
- If sea-quark Sivers asymmetry is non-zero, then sea quarks have non-zero OAM.
- A non-zero Sivers asymmetry from SpinQuest is "smoking gun" evidence for sea quark OAM.
- SpinQuest will measure the correlation between the angular distribution of the di-muons and the proton spin. If this is non-zero, then the antiquarks must have some orbital angular momentum.



SpinQuest Goals

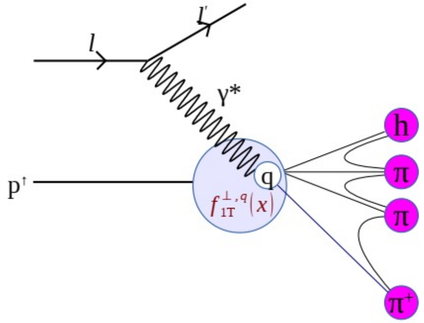
- Separately measure the Sivers function for the sea quarks
- Measure Sign and Magnitude

$$f_{1T}^{\perp}|_{SIDIS} = -f_{1T}^{\perp}|_{DY}$$

- Measurement of Sivers function for gluons (J/ψ SSA)
- Polarized $\bar{u}$ to $\bar{d}$ ratio
- Extensions: transversely, tensor charge, tensor polarized observables, dark sector, polarized proton beam, ….

$$e + p^{\uparrow} \rightarrow e'\pi X$$

- Polarized Semi-Inclusive DIS

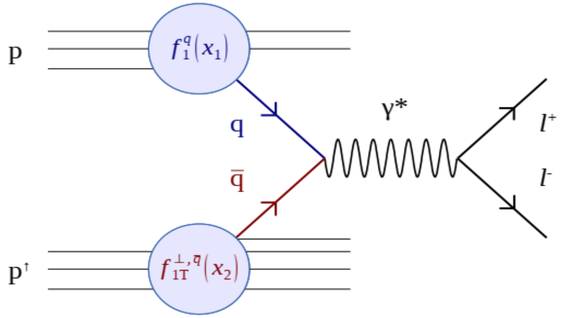


- L-R asymmetry in hadron production
- Quark to hadron fragmentation function
- Valence-sea quark: mixed

$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

$$p + p^{\uparrow} \rightarrow \mu^+\mu^- X$$

- Polarized Drell-Yan



- L-R asymmetry in Drell-Yan production
- No fragmentation function
- Valence-sea quark: isolated

$$A_N^{DY} \propto \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}$$

FERMILAB (E1039) EXPERIMENT

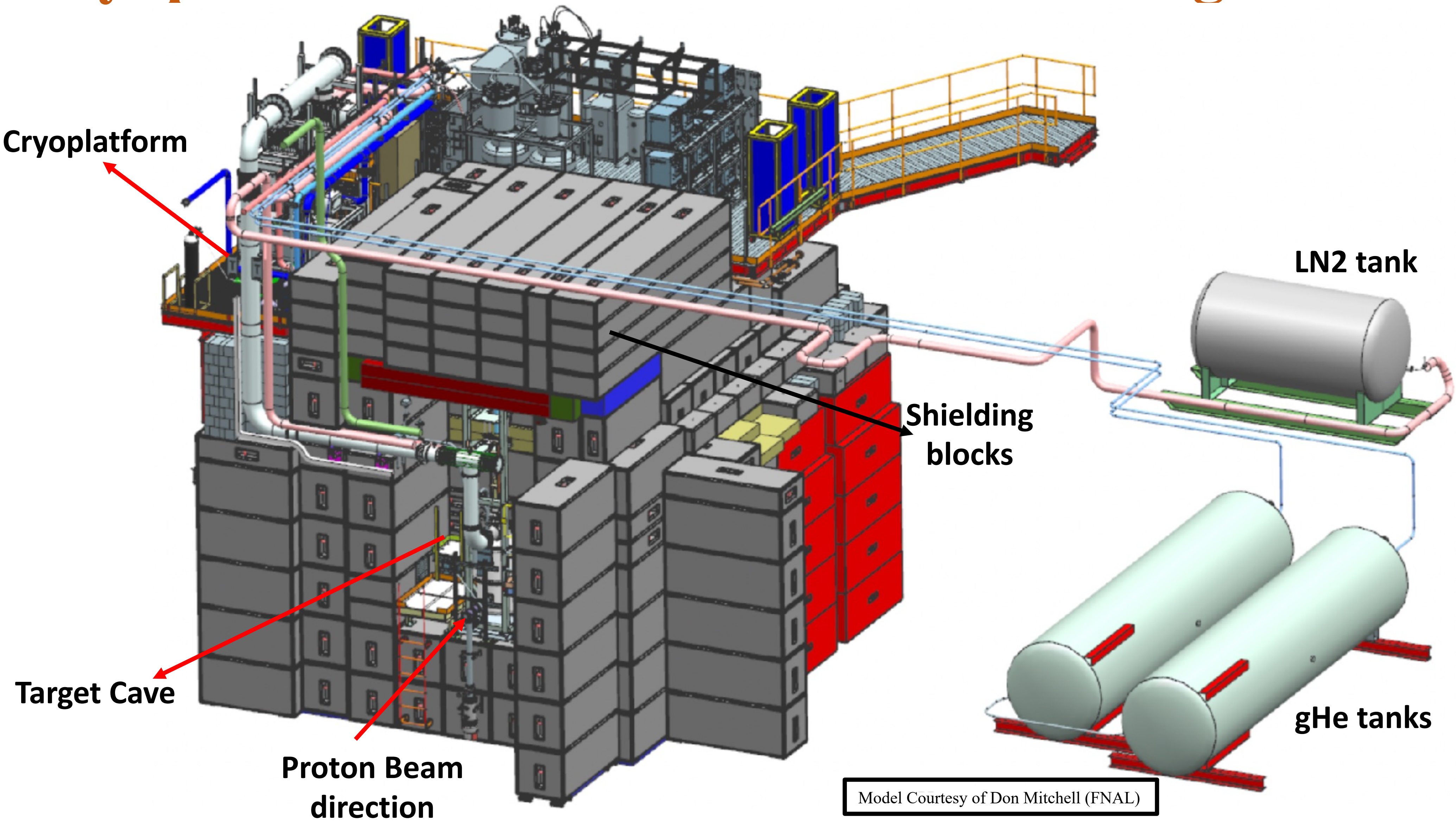
(Un)Polarized Drell-Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity $(cm^{-2}s^{-1})$	$A_T^{sin\emptyset_s}$	P_b or P_t (f)	$rFOM^{\#}$	Timeline
COMPASS (CERN)	$\pi^- + p^\uparrow$	190 $\sqrt{s} = 17.4$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f=0.22	1.1×10^{-3}	2015, 2018
PANDA (GSI)	$\bar{p} + p^\uparrow$	15 $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	2×10^{32}	0.07	$P_t = 90\%$ f=0.22	1.1×10^{-4}	2032
PAX (GSI)	$p^\uparrow + \bar{p}$	Collider $\sqrt{s} = 14$	$x_b = 0.1 - 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	?
NICA (JINR) SPD	$p^\uparrow + p^\uparrow$	Collider $\sqrt{s} = 27$	$x_b = 0.02 - 0.9$	1×10^{32}	0.04	$P_b = 70\%$	6.8×10^{-5}	2028
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	Collider $\sqrt{s} = 510$	$x_b = 0.05 - 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	2000-2016
sPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	2023-2025
SeaQuest (FNAL: E-906)	$p + p$	120 $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$ $x_b = 0.35 - 0.85$	3.4×10^{35}	.....	.....	......	2012-2017
SpinQuest ‡ (FNAL: E-1039)	$p + p^\uparrow$	120 $\sqrt{s} = 15$	$x_t = 0.1 - 0.5$	5×10^{35}	0-0.2*	$P_t = 80\%$ f=0.176	0.15 or 0.09	2024-2025
SpinQuest ± (Transversity)	$p + p^\uparrow$	120 $\sqrt{s} = 15$	$x_b = 0.1 - 0.5$	5×10^{35}	0-0.2*	$P_t = 80\%$ f=0.176	0.15 or 0.09	2026-2029

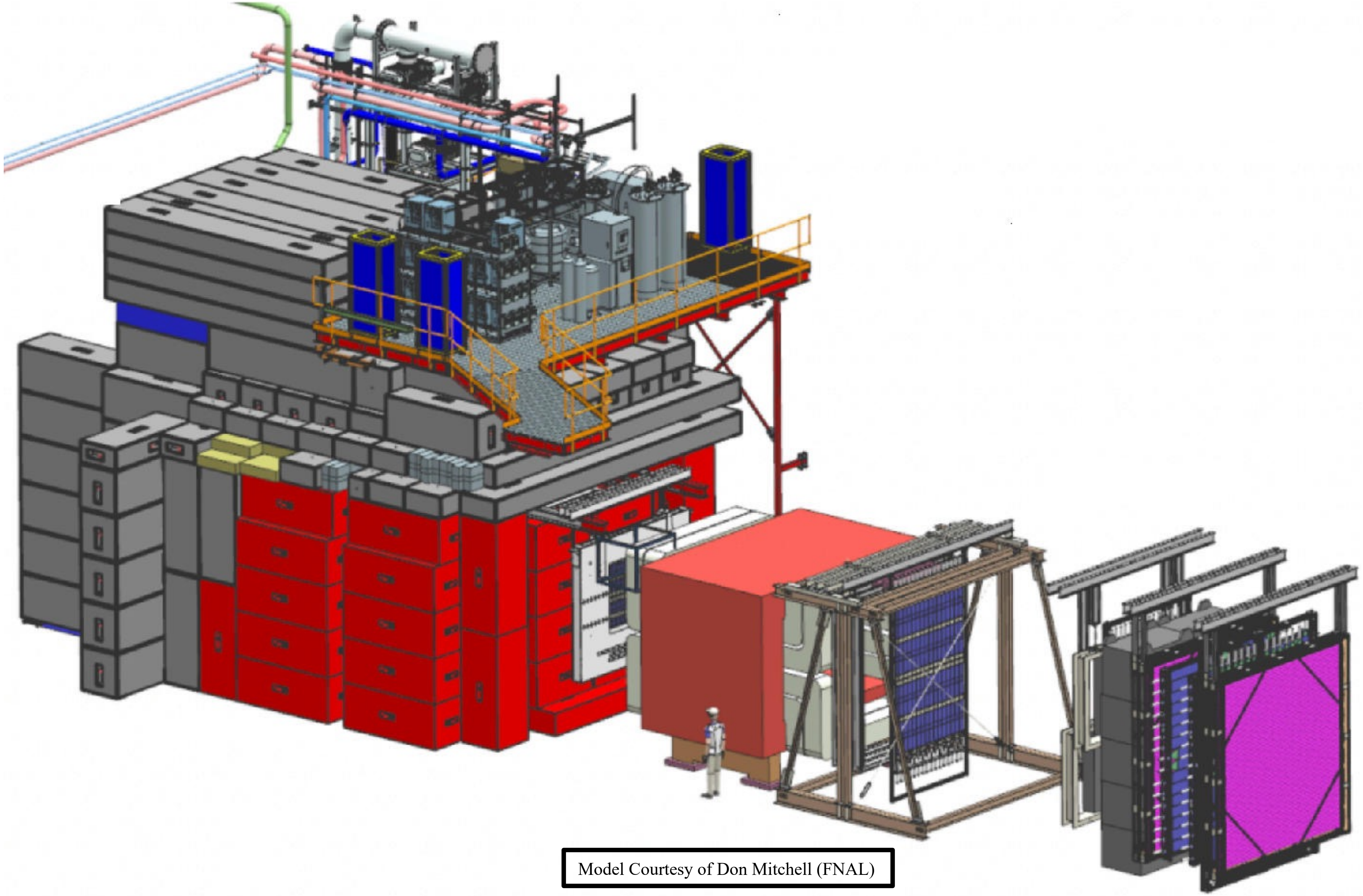
‡ 8 cm ammonia target / $L = 10^{36} cm^{-2}s^{-1}$, ±(Tensor Polarized Spin-1 target) / $L = 10^{36} cm^{-2}s^{-1}$

*not constrained by SIDIS data / #rFOM = relative lumi * P^2 * f^2 w.r.t E-1027 (f=1 for pol. P beams, f=0.02 for π^- beam on NH_3)

Cryoplatform at NM4 and Polarized Target in NM3



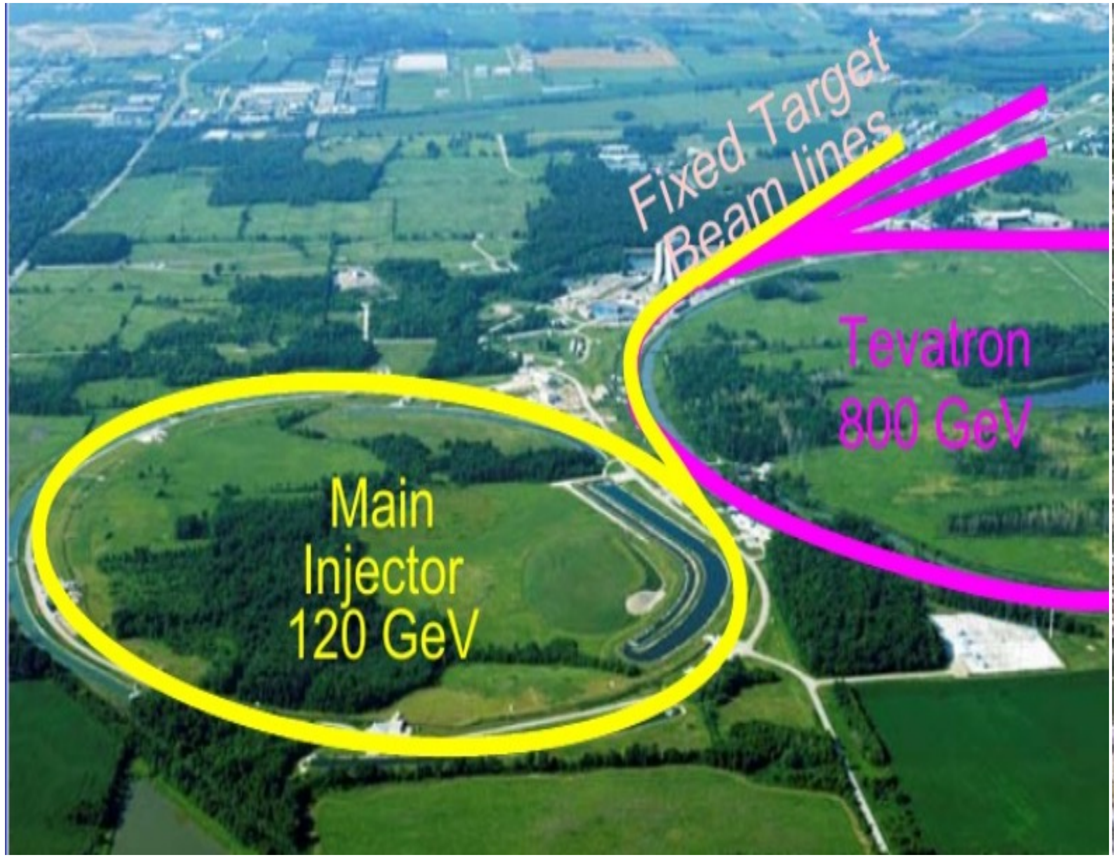
Cryoplatform at NM4 and Polarized Target in NM3

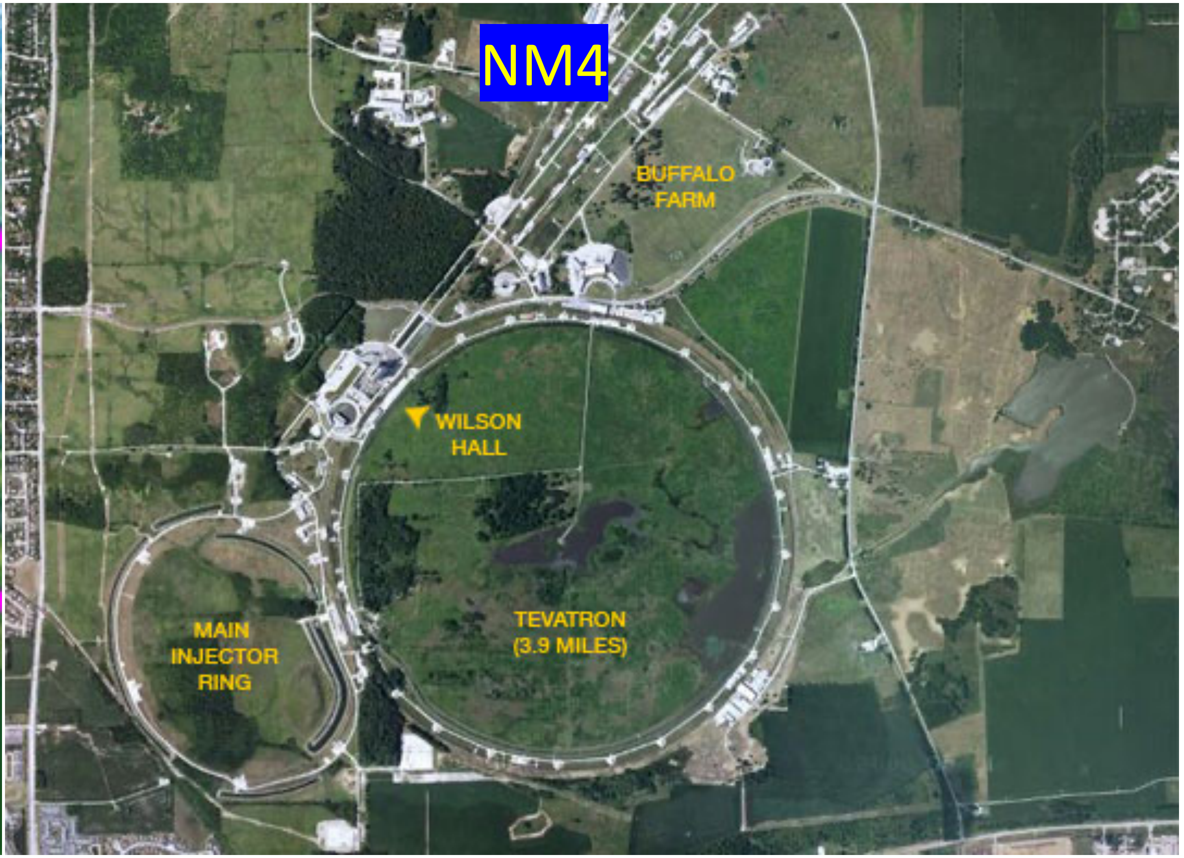


Model Courtesy of Don Mitchell (FNAL)

SpinQuest/E1039 Experiment Setup @ FNAL

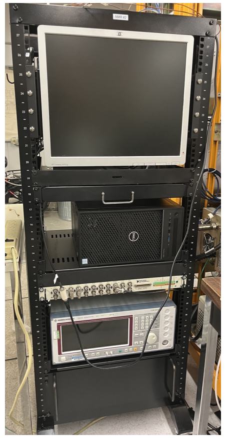
- **FNAL 120 GeV proton beam**
  - $\sqrt{s} = 15.5$ GeV
  - (5×10^{12}) protons/spill with 4.4 sec/min
  - 7.7×10^{17} protons on target/year



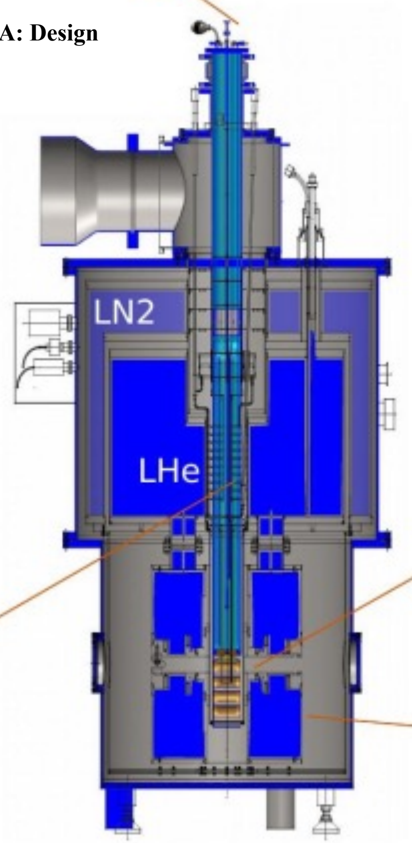


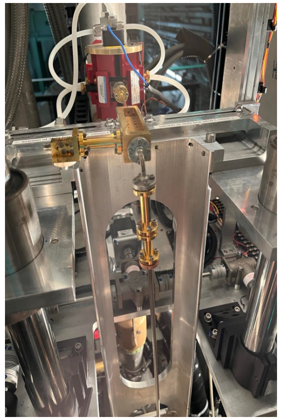
Polarized Target System

Will use Liverpool cold NMR, UVA AI w/ Q-meter, and LANL Q-meter for systematic measurements of polarization



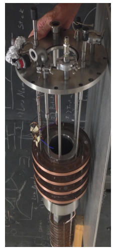
UVA: Design





UVA: Tune System and Automation

17,000 m^3/h providing the highest cooling power for 1K system
Owned by LANL



UVA: Configure Fridge and Insert, Commission for Optimal running, Setup with Actuator

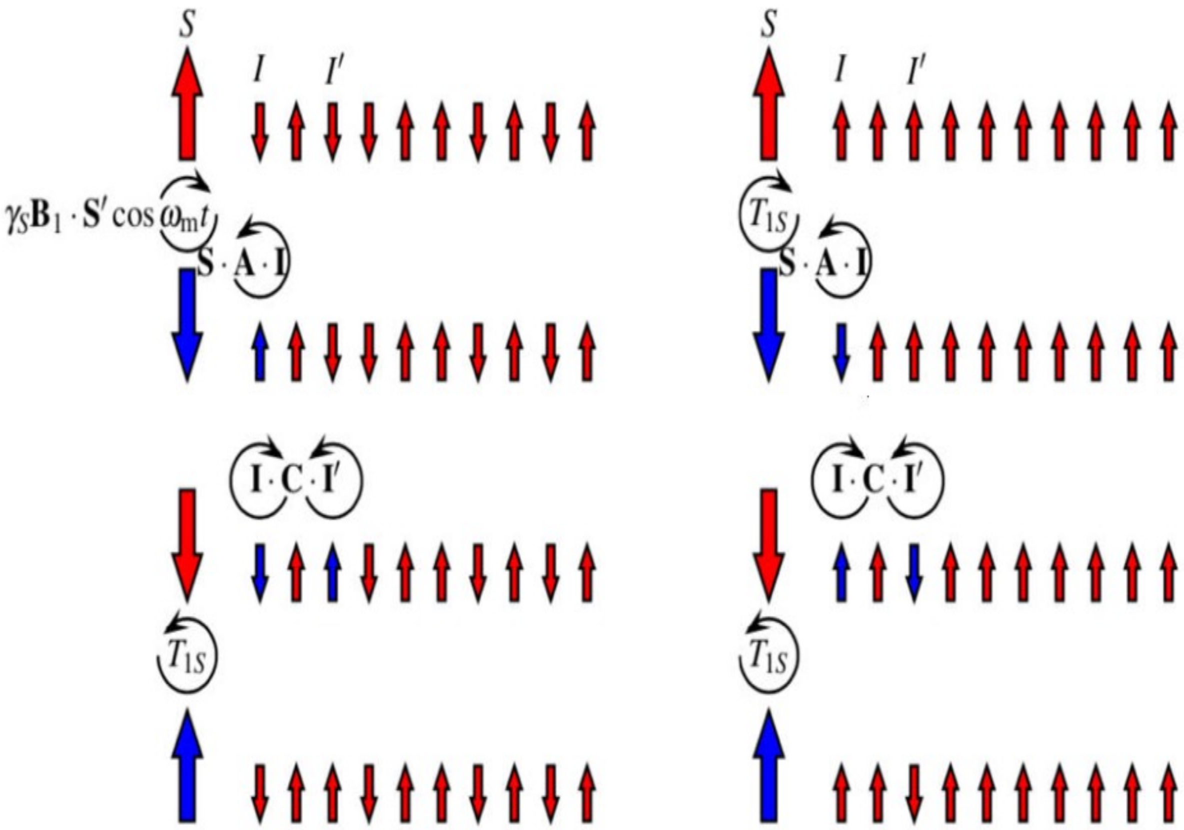
UVA: Target Insert with longest cell at 8 cm for 5T

Assembled, Commissioned and Operated by UVA

Owned by LANL and modified by Oxford to be optimized for transverse polarization

Dynamic Nuclear Polarization (DNP)

- Transfer of spin polarization from electrons to nuclei using RF irradiation in an external magnetic field
- The $(\mu_e = 660\mu_P)$. Whereas the polarization at 5T and 1K of electrons is 98% and protons is 0.5%.
- Dipole-dipole interaction between electron and proton provides contact between spin species.
- By applying RF-field at 140 GHz very close to electron ESR frequency electron high polarization can be transferred to proton.
- One electron transition/millisecond
- One proton transition/minute
- The model is valid if the ESR spectrum is narrow.

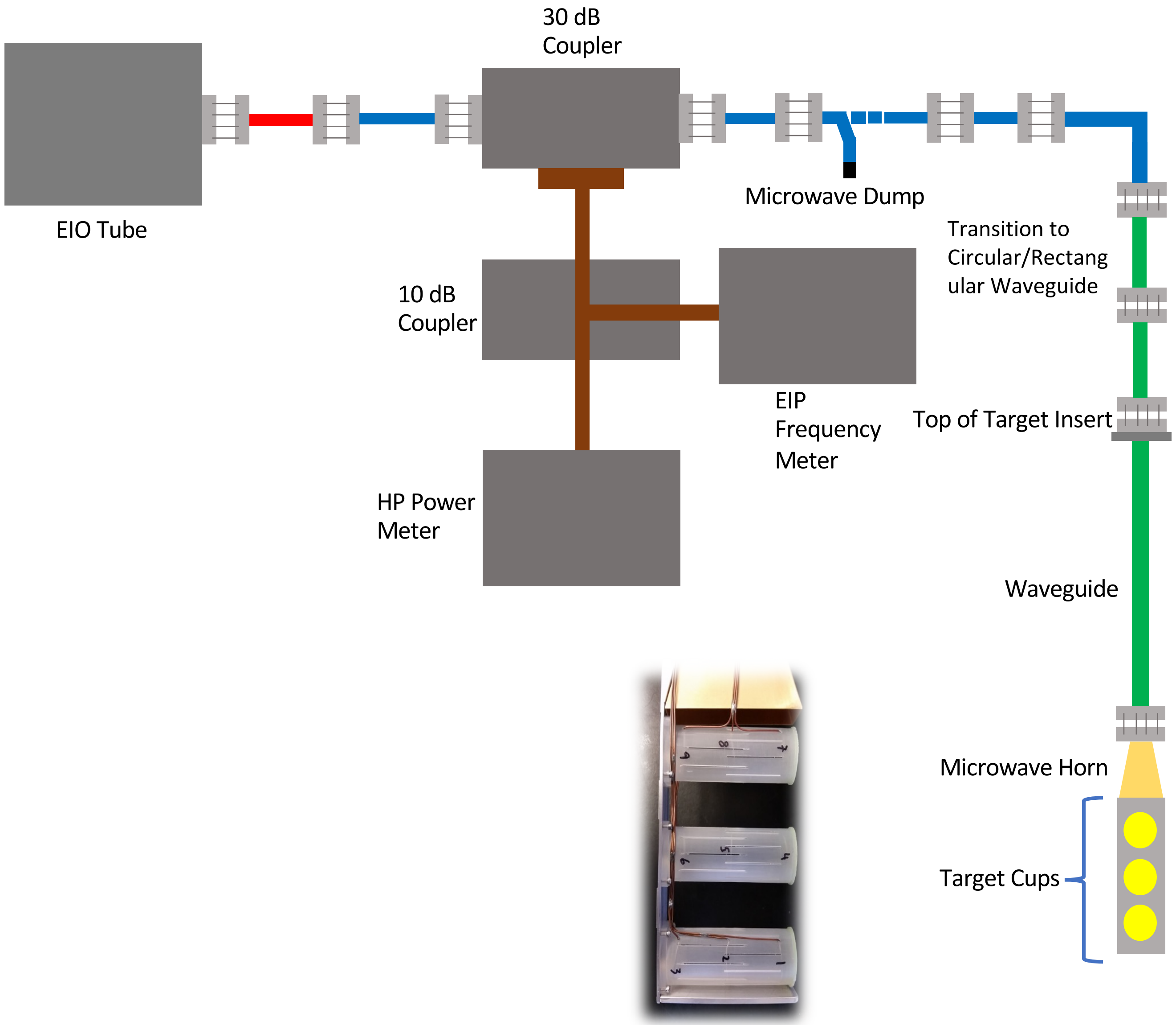


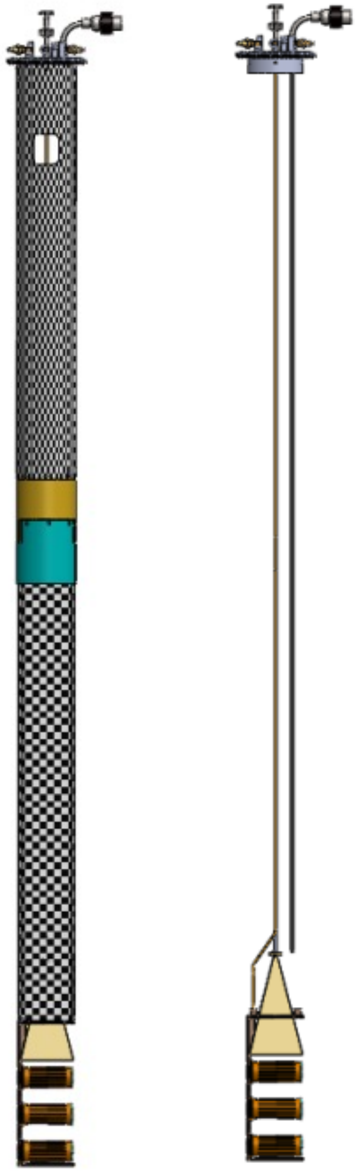
Solid State Effect (SSE)

Microwave System

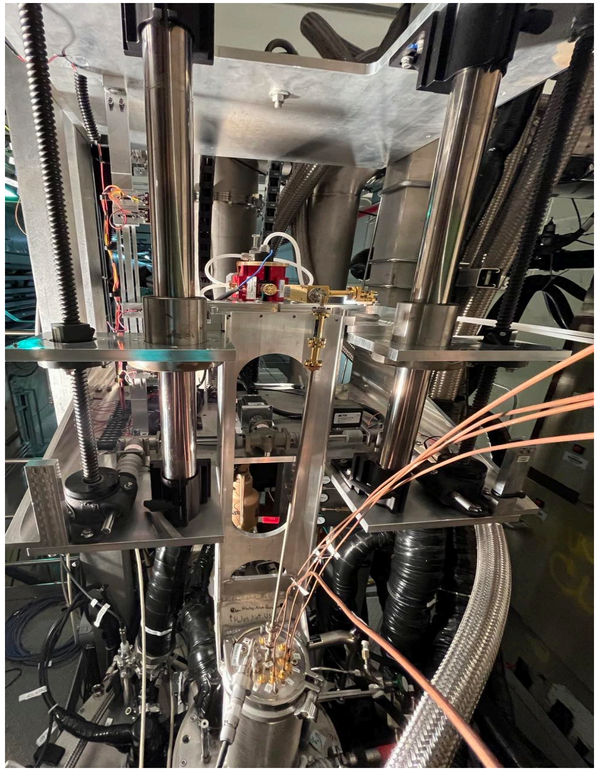
- 140 GHz RF signal is generated by Extended-Interaction Oscillator (EIO) through interaction between electron beam (produced from ~kV of cathode/anode) and resonant cavities
- The optimal frequency changes as we flip the spin direction
- The optimal frequency also changes as the target accumulates radiation damage from the beam
- The variation of the beam voltage allows up to 0.4% frequency tuning
- Cavity size adjustment using a stepper motor allows an additional 1.5%

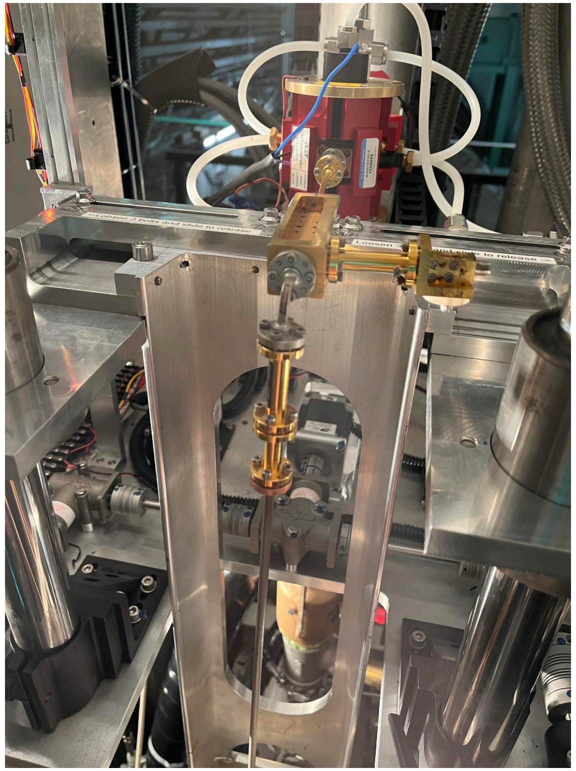
Microwave System





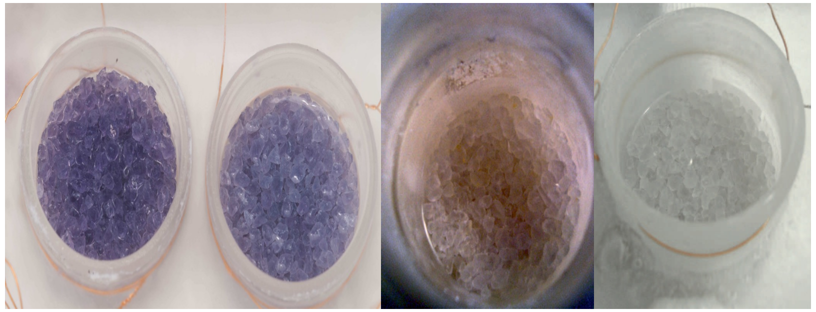
Microwave System

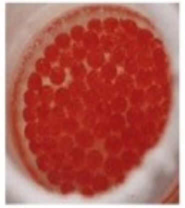




Target Material

- A successful target material candidates for the DNP can be characterized by:
  - Maximum achievable polarization
  - Dilution factor → total nuclear content
  - Resistance to ionization radiation
- Paramagnetic centers can be doped into bulk target material (chemical or by radiation doping)
- The target consists of an 8cm long PTFE target cells containing ammonia beads immersed in LHe
- Target material NH_3/ND_3 are doped with paramagnetic free-radical by being irradiated at NIST
- The polarization decays over time due to the radiation damage and restored by annealing process (target is heated at 70-100K)
- Also form color centers that correlates to the dose



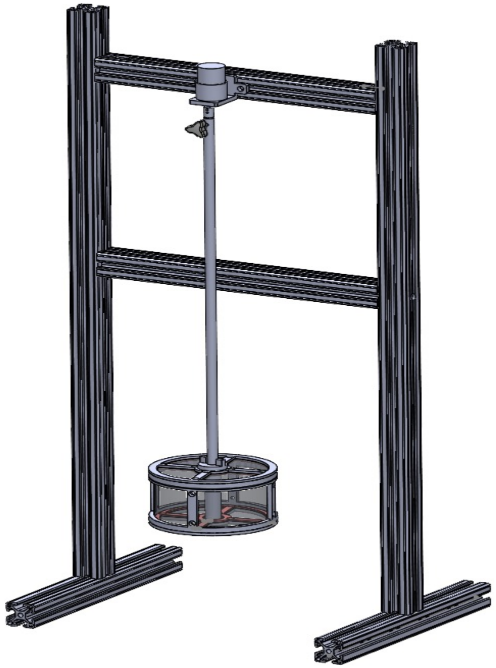
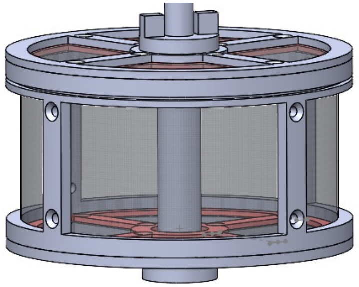
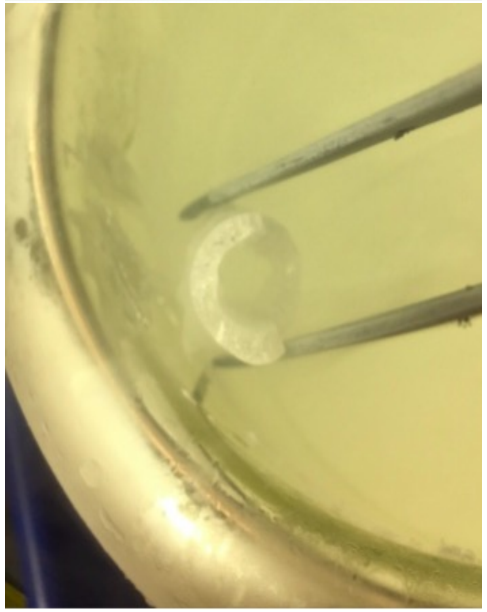


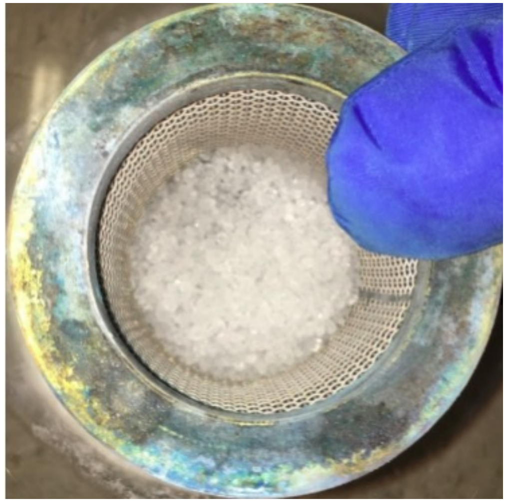
Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	very high
Comments	*Easy to produce and handle*	*Works well at 5T/1K*	*Slow polarization, but long T_1*

Preparation of Solid Ammonia

- The following pictures and CAD model depict the preparation of Solid Ammonia at NIST.



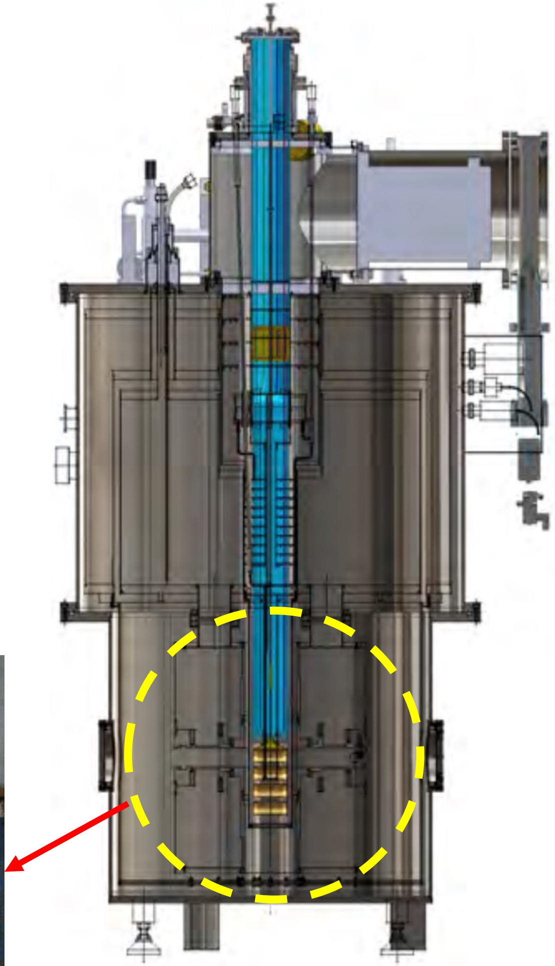






Superconducting Magnet

- The superconducting magnet coils provide Magnetic Field (transverse to the beam): **B=5 T** with uniformity $dB/B < 10^{-4}$ over 8cm
- The magnet consist of NbTi coils which are impregnated in epoxy to prevent them from moving during when the magnet is energized; and the coils are held in place by stainless steel (type: 316)
- Originally used by LANL with axial field in a neutron beam, Oxford Instruments rebuild for transverse polarization, then commissioned and tested at UVA and finally send to FNAL and reassembled.

Coil



Superconducting Magnet

Superconducting Magnet

UVA target group and FNAL technicians installed

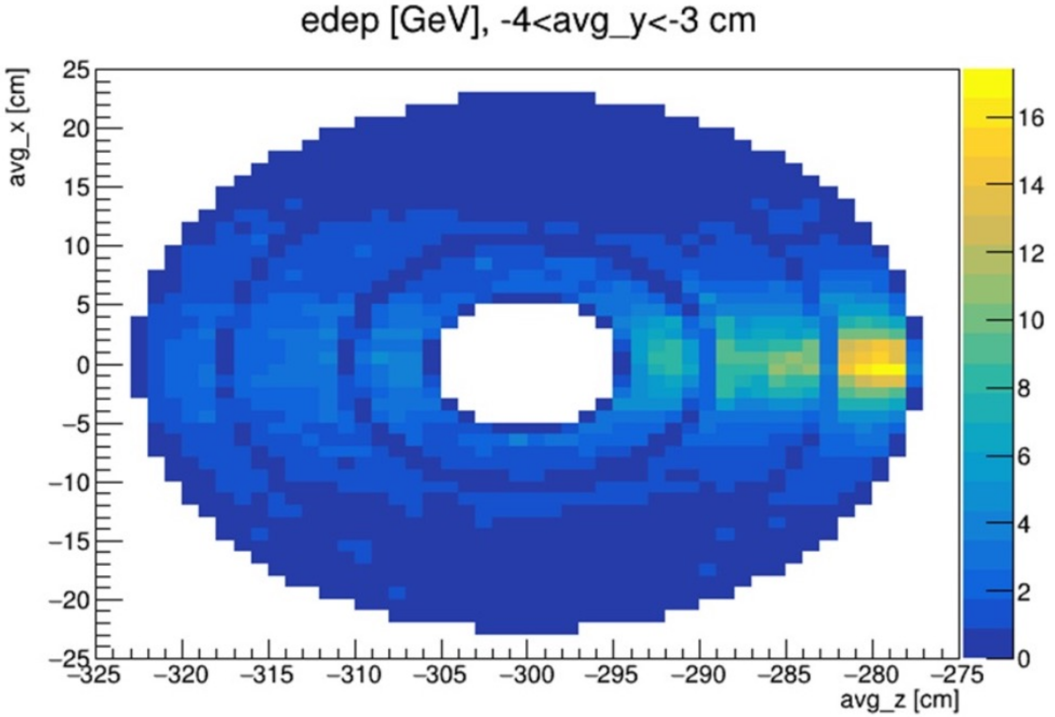



Superconducting Magnet

- The Thermal processes within the magnet is described by a general heat transfer equation:

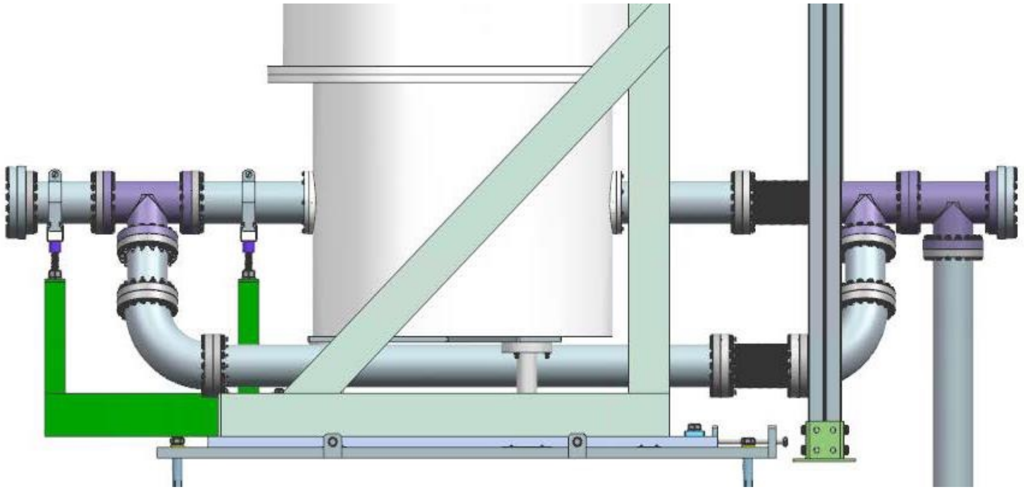
$$c\frac{\partial T}{\partial t} = \nabla(\kappa\nabla T) + P_{ext} + P_{He}$$

P_{ext} is the external-heat sources coming mainly from the beam-target interactions and P_{He} is the heat transferred to the liquid helium



The heat deposited to the magnet (P_{ext}) is simulated using Geant4

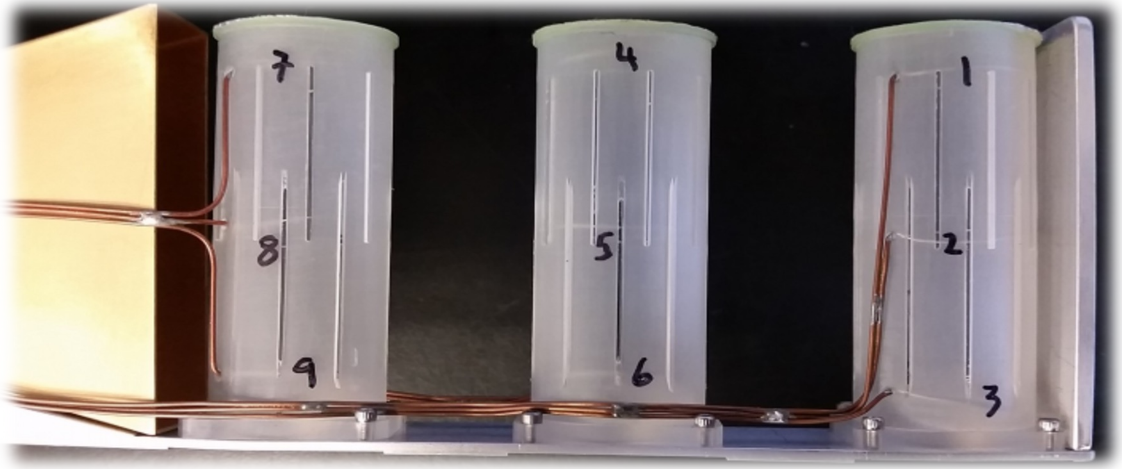
Courtesy of Zulkaida Akbar

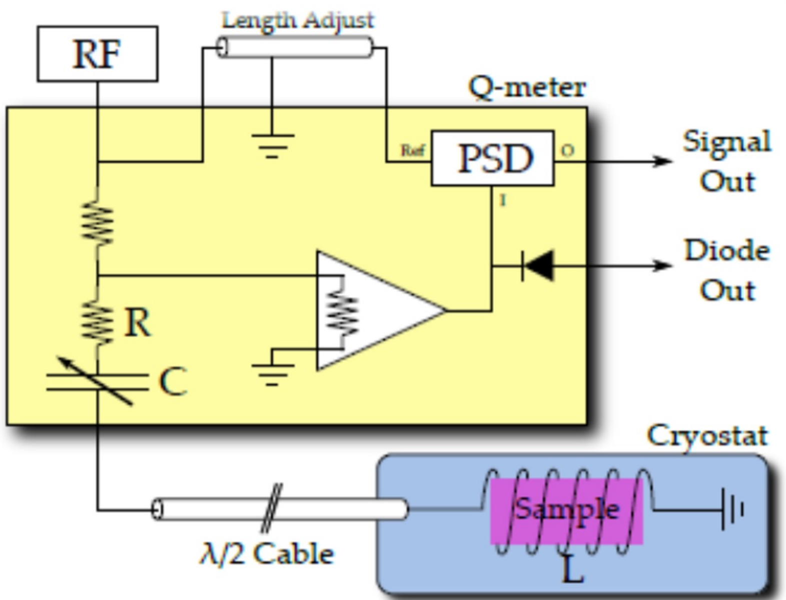


Beam Pathway

Nuclear Magnetic Resonance (NMR)

- Polarization of the proton is measured using Q-meter based NMR
- An RF field at the Larmor frequency of the proton (213 MHz at 5T) with absorption measured with constant current CW-NMR
- Series Q-meter connected to NMR coil with inductance L_c and resistance r_c that is embedded in target material
- The RF field is produced by three NMR coils inside the target cup
- An LCR Circuit is tuned to the Larmor frequency of the target material
- Due to high radiation very long cable ($\lambda/2 \geq$14 for proton) is required: 3 Different measurement techniques: UVA AI w/ Q-meter, cold NMR, and LANL Q-meter for systematic checks

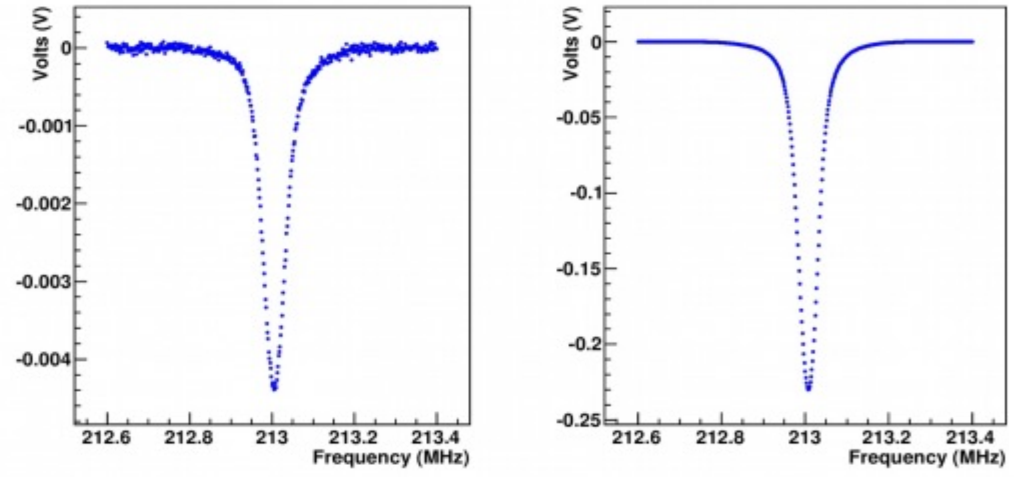




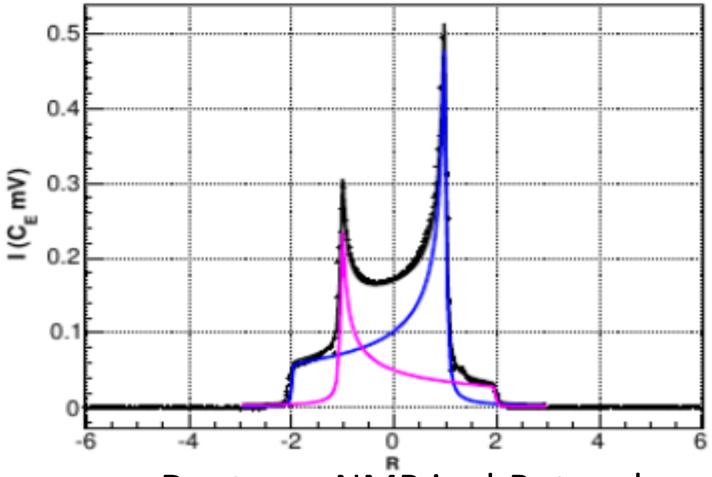
Note: PSD= phase sensitive detector

Courtesy of James Maxwell

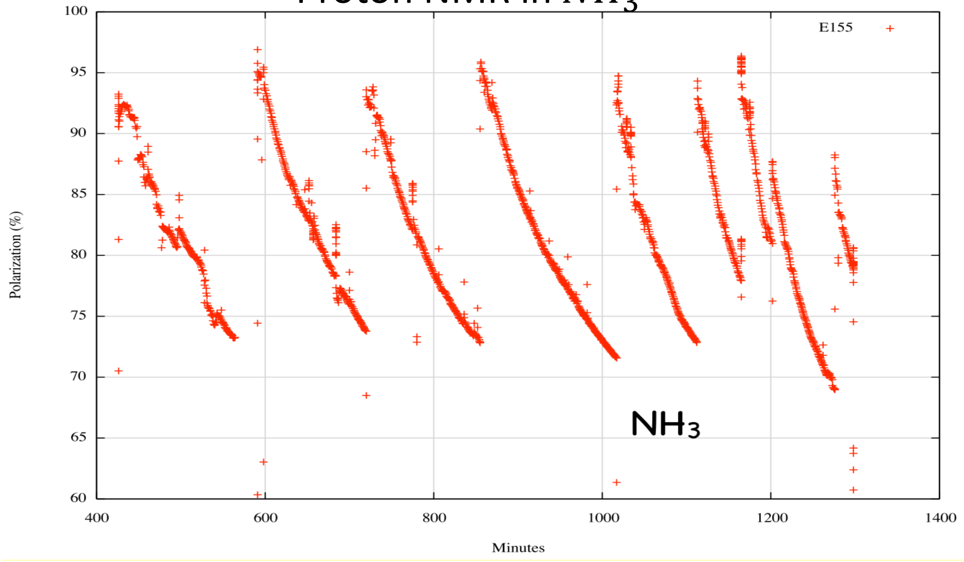
Nuclear Magnetic Resonance (NMR)



Proton NMR in NH_3

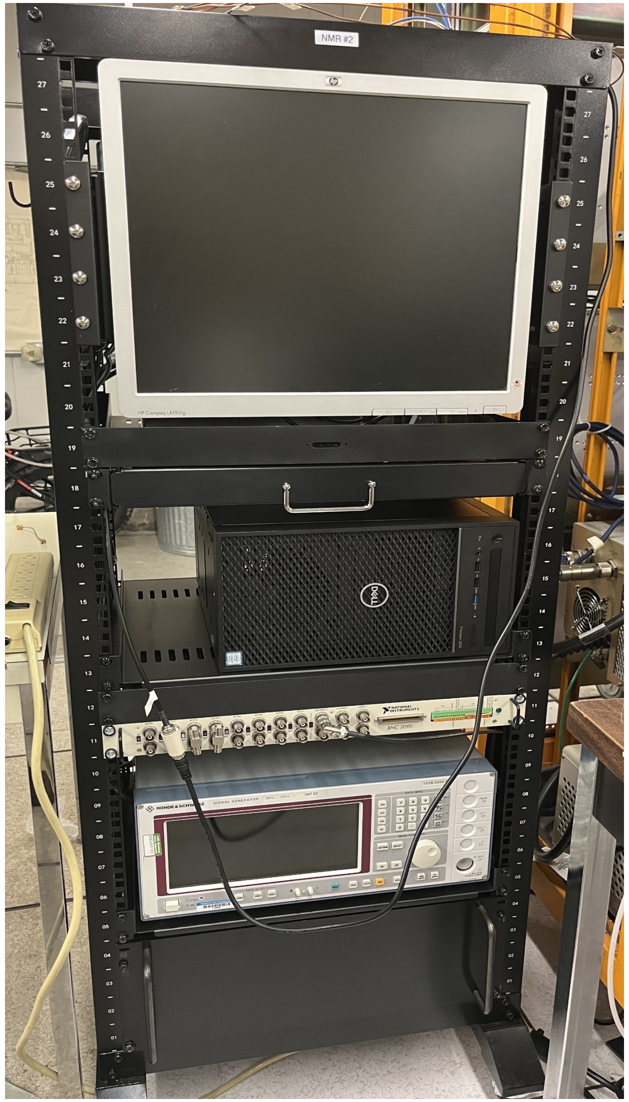


Deuteron NMR in d-Butanol



Polarization growth, radiation damage, decay of material

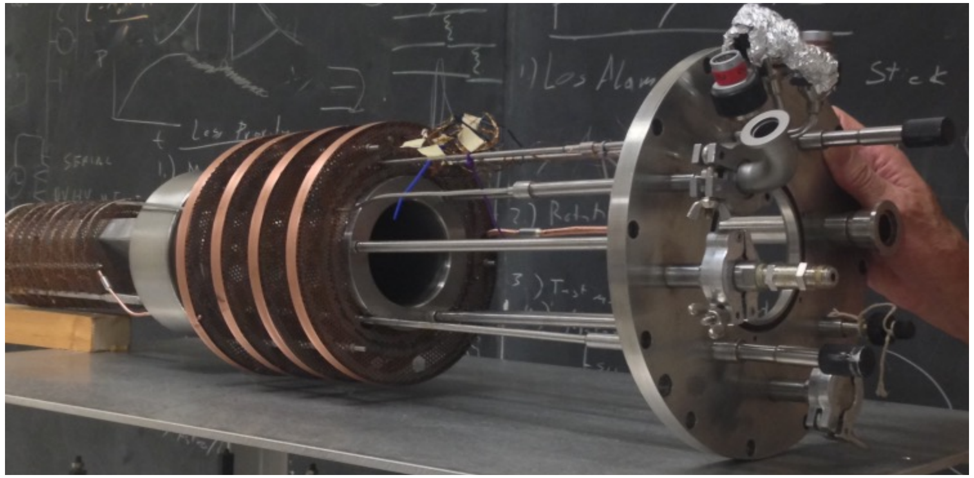
Note: This polarization growth and decay with electron-beam.



One of the UVA NMR Setups

Evaporation Refrigerator

- Evaporated He from the target nose need to be pumped out by high powered Root pump to keep the temperature at 1 K at 0.12 torr
- The Root pump having 17,000 m^3/hr
- Critical components for high-cooling power refrigerator:
  - High-power pump
  - Sufficient supply of the LHe
  - Heat exchanger that being the He temperature down from 4.2 K to 1 K
  - Thermal shielding



Note: Please see Vibodha Bandara talk on Evaporation Refrigerator. https://indico.jlab.org/event/663/contributions/13094/

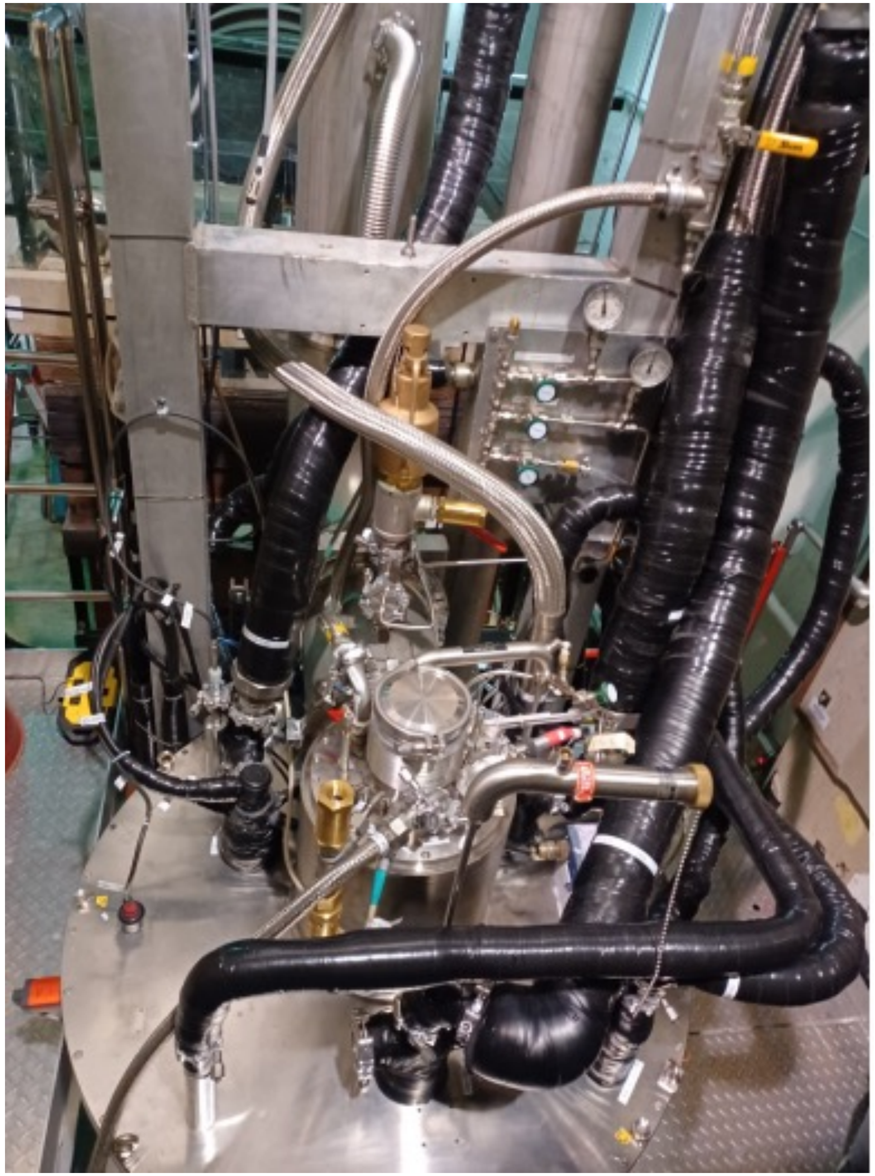
Cryo-Platform

QT Compressors

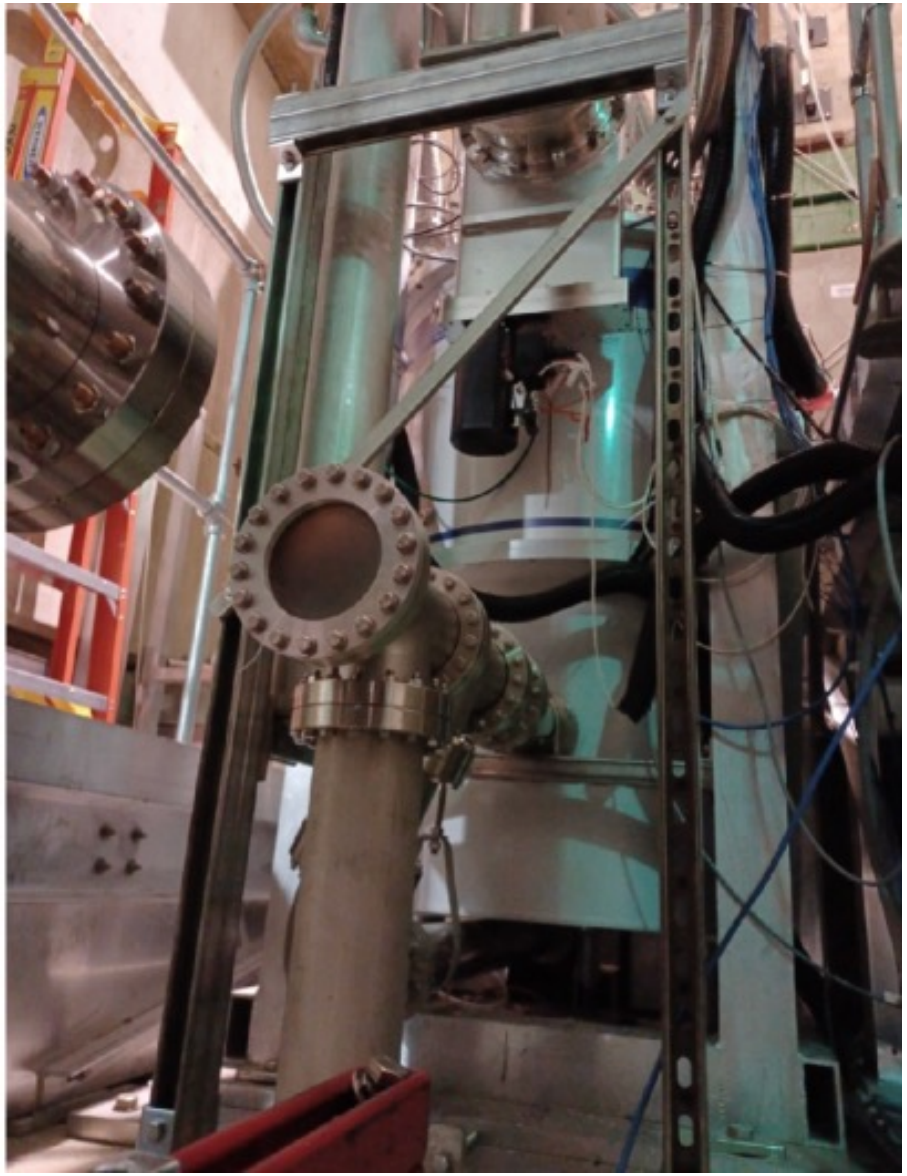
Cold heads & cold box

Root Pumps

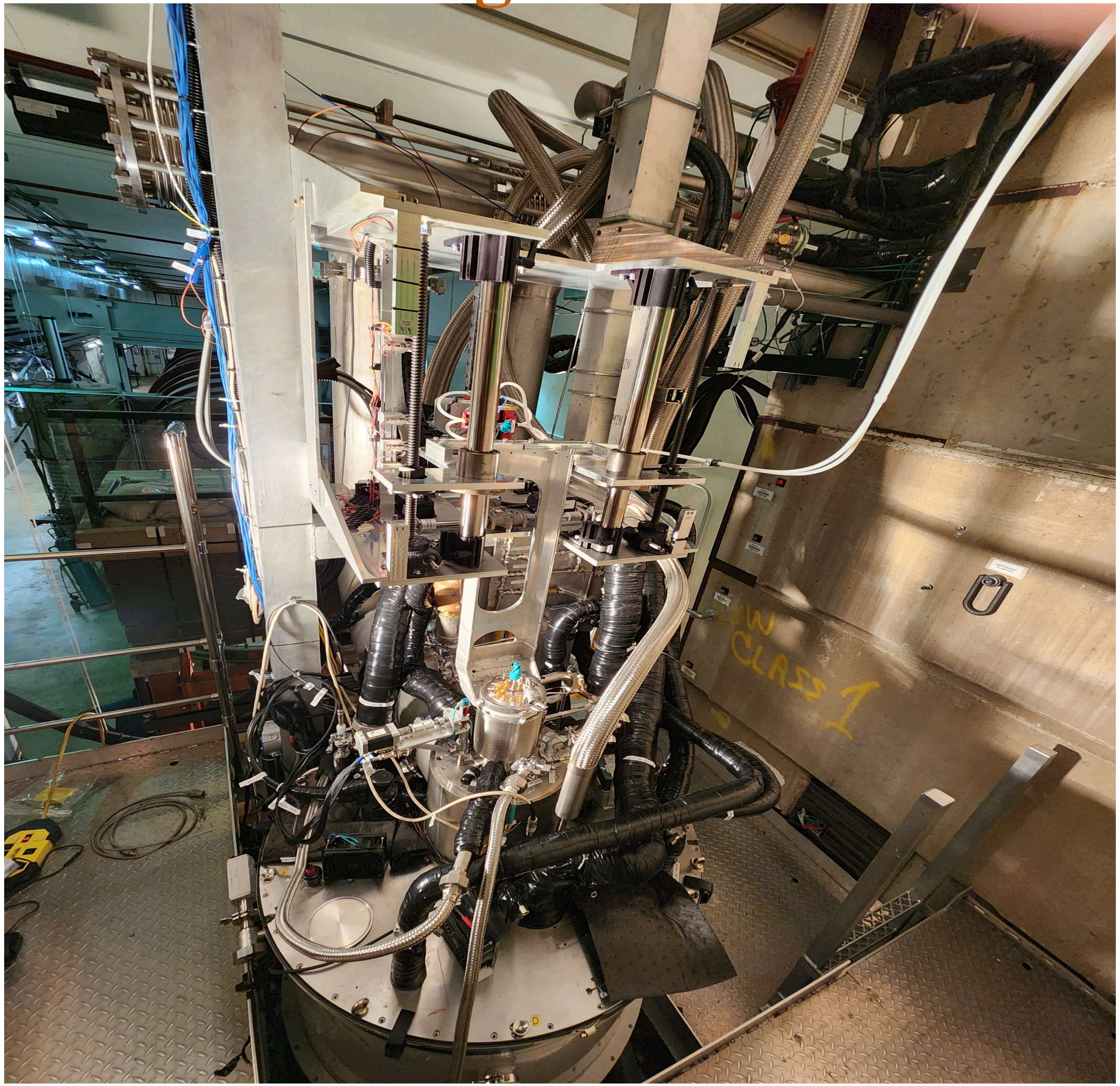
Target Cave



Beam Window



Target Cave



Target System Status

Helium Supply

- Expected Transfer Efficiency ~68%
  - Max measured so far 71%
  - Averaging 69%
- Expected magnet boil-off < 15 slm
  - Measured boil-off ~5 slm
- Expected QT production rate ~200L/day
  - Producing 195L/day
- Helium Budget at Cave =0.69*195L/day ~135L/day
  - Standby mode < 25L/day (no fridge operation)
  - Low flow production !60L/day (minimum heat load)
  - Standard production ~95L/day (expected intensity)

Target Infrastructure

- Microwave System
  - In-hall hardware Installed
  - Software controls up and running
- Superconducting magnet
  - Boil-off low with E-7 torr vacuum
  - Passed all tests (fully operational)
  - Tested at FNAL cooled down to 4K during cooldown
- 1K Refrigerator
  - Passed all tests (fully operational)
- Multichannel NMR
  - In-hall hardware Installed
  - Software controls up and running
- Integrated system test
  - Performed at UVA (95%)

- Target Insert
  - Fully constructed and ready for tests
- Target Material
  - Practicing with CH2/CD2 with cryogenics (LN2)
  - NH3/ND3 use pending ES&H approval
- Online Monitoring System
  - Fully operational
  - All alarms and subsystems working

Summary

- SpinQuest can measure the transverse single spin asymmetry (TSSA) in Drell-Yan (DY) process and charmonium production
- This can provide information to the Sivers function for the quarks and gluons
- The polarized-target system for the SpinQuest experiment consist of a 5T superconducting-split magnet, 140 GHz EIO generator, 8 cm of solid NH_3/ND_3 target, evaporation refrigerator and Q-meter based NMR system.
- During cooldowns at University of Virginia (UVa), The SpinQuest Polarized Target achieved proton polarization of 95% using Dynamic Nuclear Polarization (DNP) technique.
- System is fully constructed and awaits approval from FNAL ES&H to use the target material in the system.
- First beam expected November 2023.
- After summer shutdown, SpinQuest will do beam-target commissioning, quench testing to study maximum possible proton intensity for production running.

Welcome ⟋

Please join The Effort

- Dustin Keller (dustin@virginia.edu) [Spokeperson]
- Kun Liu (liuk@fnal.gov) [Spokeperson]

https://spinquest.fnal.gov

Experiments (virginia.edu)

Thanks

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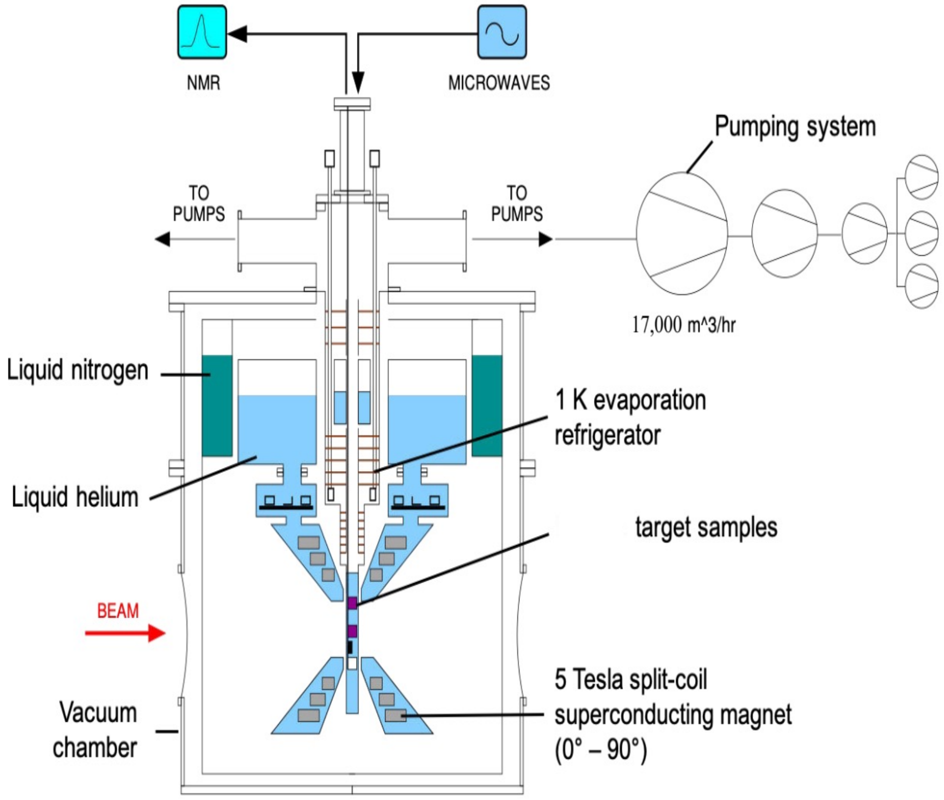
Back-up Slides

SpinQuest/E1039 Experiment Setup @ FNAL

- **LANL/UVA Polarized Target**
  - Solid NH_3, ND_3
  - 5T field, 1K fridge
  - 140 GHz microwave source (with DNP technique)
  - Helium Liquefier System (200L/day



Target Material (NH_3/ND_3)

- The ***figure of merit*** **(FOM)** is crucial for target material:

$$FOM = P_T^2 . f^2 . \rho . \kappa$$

- The dilution factor and the target polarization have the largest impact on the FOM
- The filling factor $\boldsymbol{\kappa}$ is linked to the thermal conductivity and the shape of the target material

Material	Dens. (g/cm^3)	Length (cm)	Dilution Factor	Packing Fraction	$\langle P_z \rangle$
NH_3	0.867	7.9	0.176	0.6	80%
ND_3	1.007	7.9	0.3	0.6	32%

- **Basic Dilution factor:** ratio of number of polarizable nucleons to total no. of nucleons in the target.

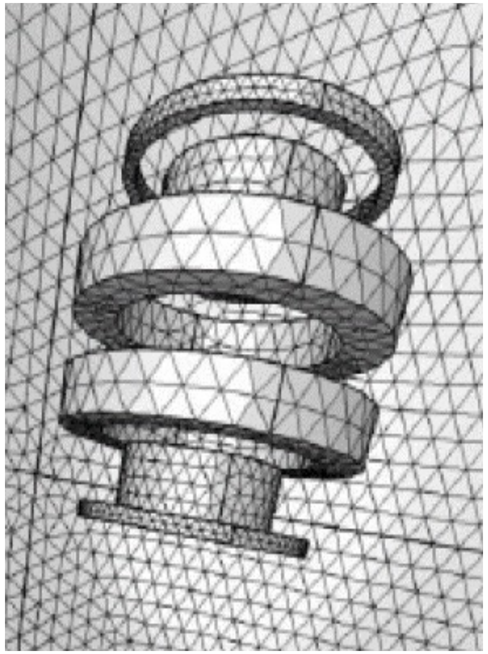
$$f_{NH_3} = \frac{N_H}{N_H + N N_{14}} = \frac{3}{3+14} = 0.176 \; ; f_{ND_3} = \frac{N_D}{N_D + N N_{14}} = \frac{6}{3+17} = 0.3$$

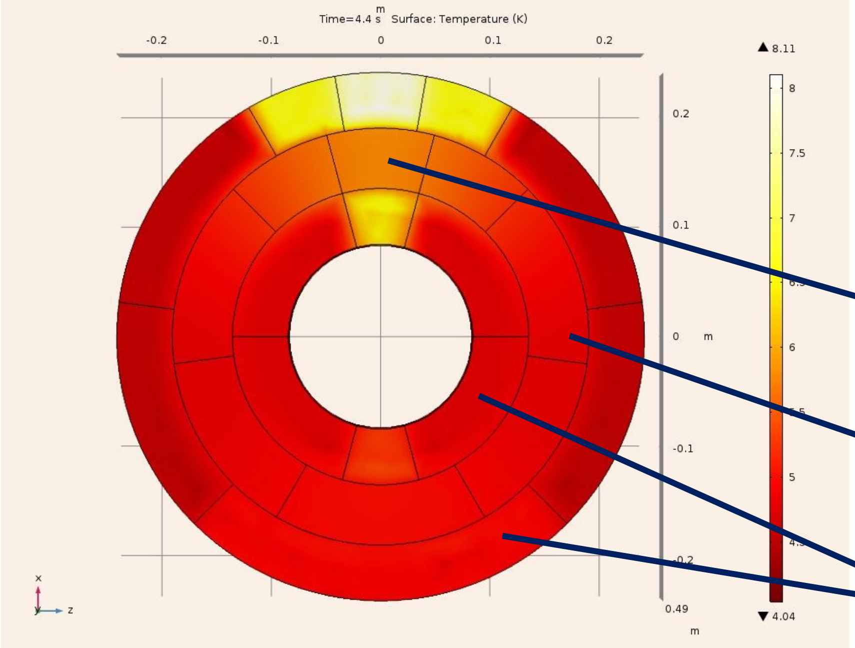
- **Kinematic Dilution factor:** ratio of cross-section of polarizable nucleons to the cross-section of all the nucleons in the target.

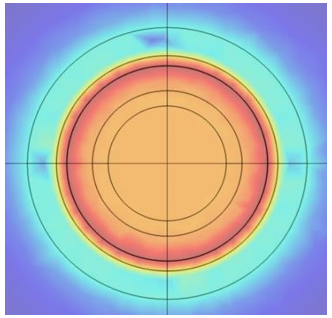
$$f(x) = \frac{N_H \sigma_{pp_\uparrow}^{DY(x)}}{N_H \sigma_{pp_\uparrow}^{DY(x)} + N N_{14} \sigma_{pp_\uparrow}^{DY(x)} + N He \sigma_{pp_\uparrow}^{DY(x)} + N Al \sigma_{pp_\uparrow}^{DY(x)} + \cdots}$$

Superconducting Magnet

- Based on this study the maximum intensity of the beam is 2.7×10^{12} proton/sec (with pumping on the He reservoir at 2.5 K with the rate of 100 SLPM)







The hot spot spread uniformly due to the thermal conductivity of the copper matrix

Magnet coil

Stainless-steel former

The simulation was done using COMSOL by applying Finite-Element Method

The simulation was done using COMSOL by applying Finite-Element Method

Courtesy of Zulkaida Akbar

Predicted Uncertainties

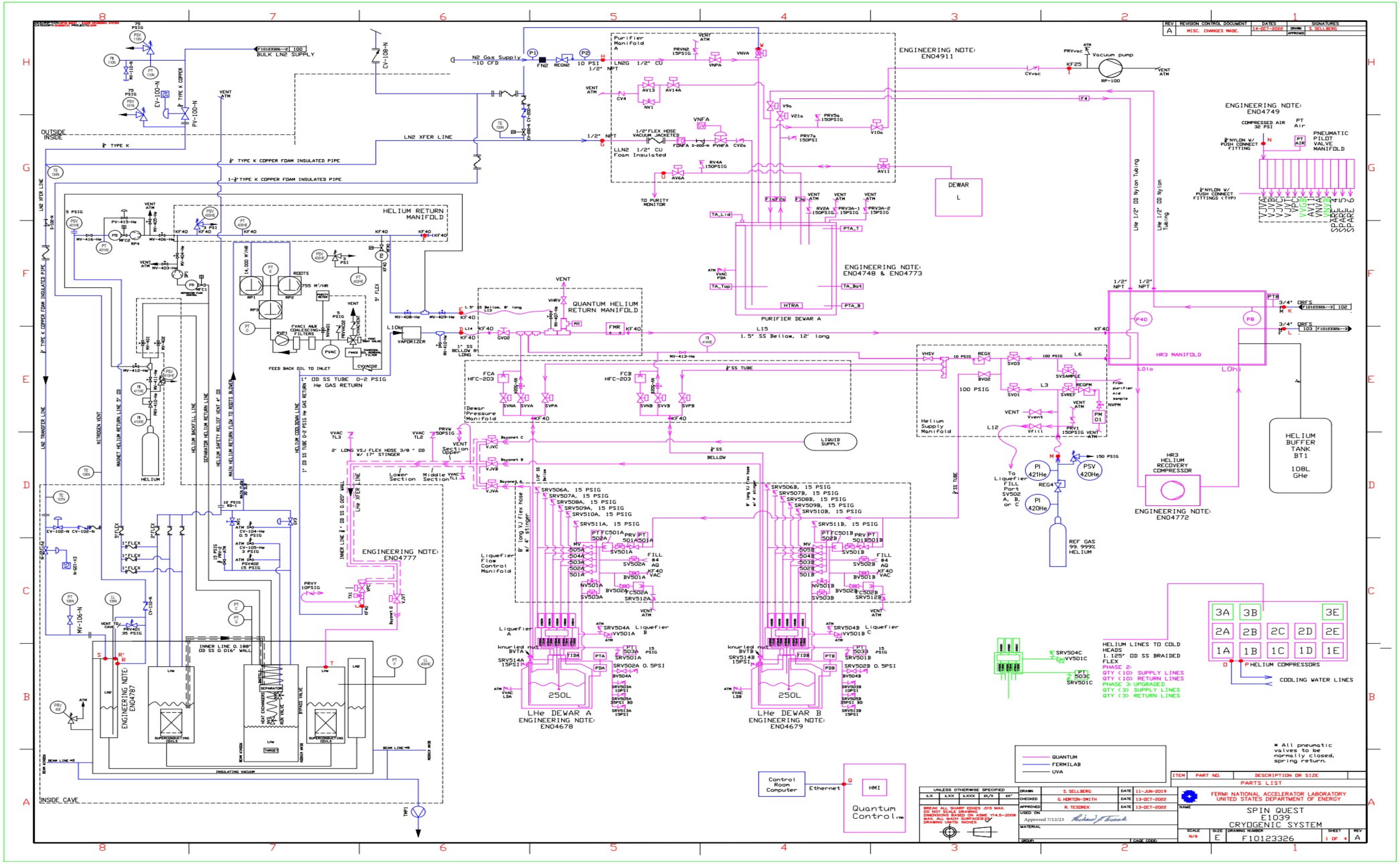
- Beam (~ 2.5%)
  - Relative luminosity (~ 1%)
  - Drifts (< 1%)
  - Scraping (~ 1%)

- Analysis sources (~ 3.5%)
  - Tracking efficiency (~ 1.5%)
  - Trigger & geometrical acceptance (< 2%)
  - Mixed background (~ 3%)
  - Shape of DY (~ 1%)

- Target (~ 6-7%)
  - TE calibration (proton ~ 2.5%; deuteron ~ 4.5%)
  - Polarization inhomogeneity (~ 2%)
  - Density of target ($NH_{3(s)}$) (~ 1%)
  - Uneven radiation damage (~ 3%)
  - Beam-Target misalignment (~ 0.5%)
  - Packing fraction (~ 2%)
  - Dilution factor (~ 3%)

Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	32%	5.7%

P&ID


BULK LN2 SUPPLY
LN2 XFER LINE
HELIUM RETURN MANIFOLD
QUANTUM HELIUM RETURN MANIFOLD
Purifier Manifold
ENGINEERING NOTE: EN04911
DEWAR L
PURIFIER DEWAR A
ENGINEERING NOTE: EN04748 & EN04773
ENGINEERING NOTE: EN04749
PNEUMATIC PILOT VALVE MANIFOLD
HR3 MANIFOLD
HELIUM BUFFER TANK BT1
108L GHe
HR3 HELIUM RECOVERY COMPRESSOR
ENGINEERING NOTE: EN04772
REF GAS 99.999% HELIUM
LIQUID SUPPLY
ENGINEERING NOTE: EN04777
ENGINEERING NOTE: EN04787
250L
LHe DEWAR A
ENGINEERING NOTE: EN04678
250L
LHe DEWAR B
ENGINEERING NOTE: EN04679
HELIUM COMPRESSORS
COOLING WATER LINES
3A 3B 3E
2A 2B 2C 2D 2E
1A 1B 1C 1D 1E
QUANTUM
FERMILAB
UVA
Control Room Computer
Ethernet
HMI
Quantum Control
INSIDE CAVE
OUTSIDE INSIDE
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
SPIN QUEST
E1039
CRYOGENIC SYSTEM
F10123326