Sustainable Cryogenic Infrastructure and Solid-State Millimeter-Wave Microwave Technology for Polarized Target System at the University of New Hampshire

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Sustainability HEP 2026 - 5th Edition

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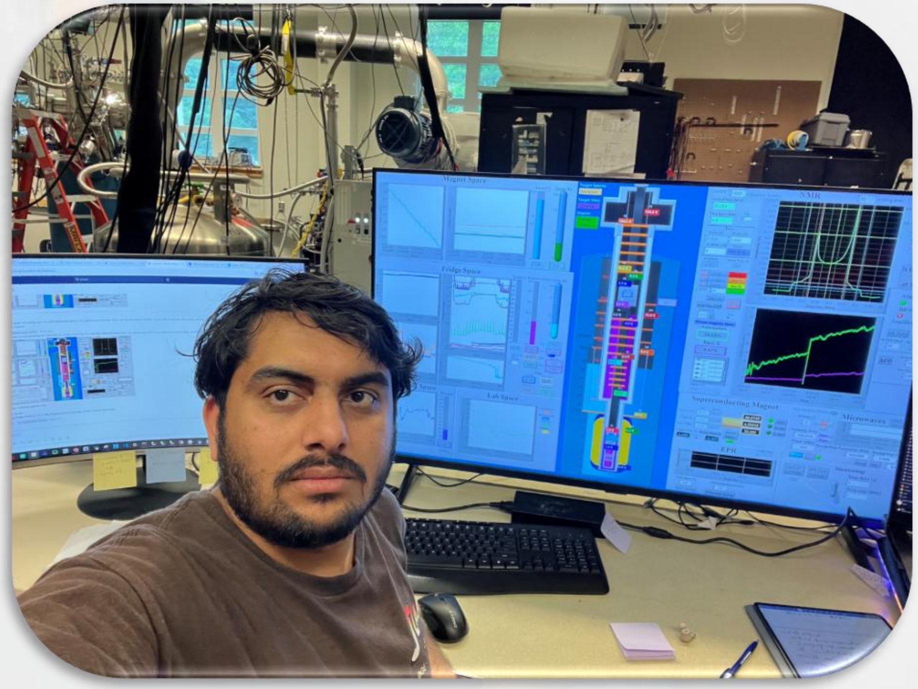
Muhammad Farooq



2nd Year PhD student in Experimental Nuclear Physics working on the Fixed Target Experiments

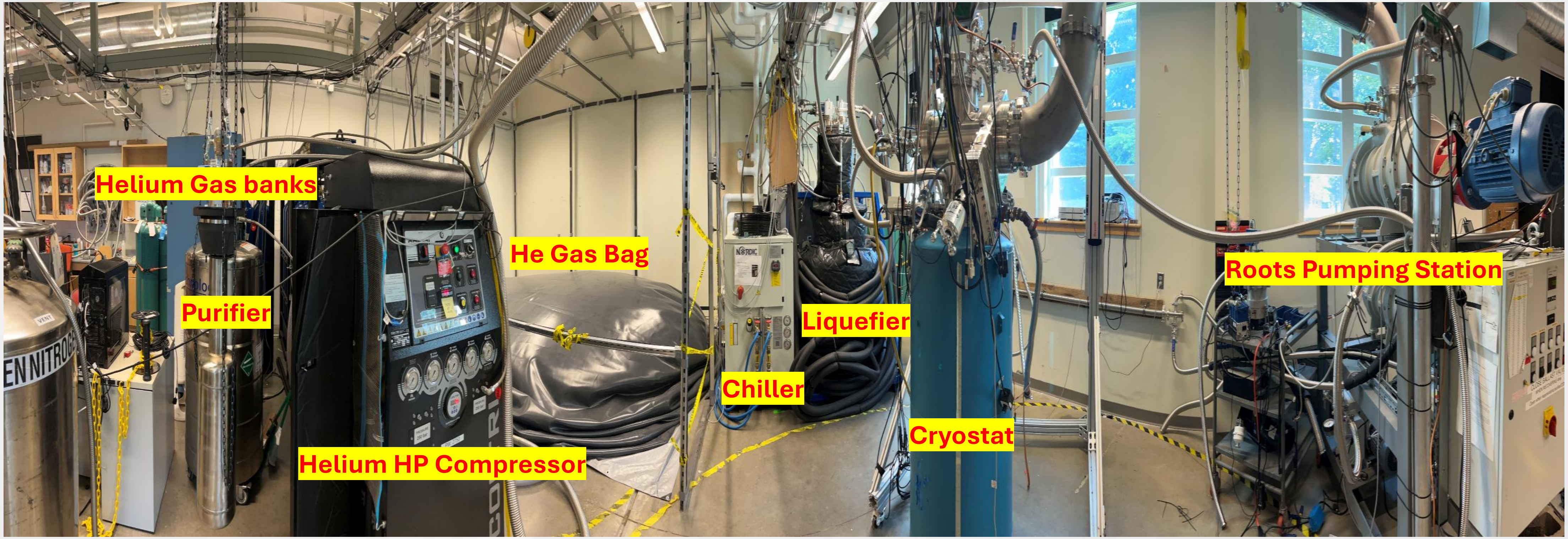
My Research: Spin Physics, Hadron Physics, Polarized Targets, R&D, Artificial Intelligence

Background: I completed my Master's in High Energy Physics and completed Master's Thesis on di-Higgs Analysis on the 2015-2018 ATALS data set.

- ➔ Spent two years at SpinQuest Experiment at Fermilab National Accelerator Laboratory as a Lab technician.
- ➔ Worked on Fixed Target Experiments and contributed to beam operations at SpinQuest Experiment.
- ➔ As a PhD student at University of New Hampshire, I am contributing to operate the 5T superconducting magnet, 1K evaporation refrigerator, solid-state microwave system, and NMR for data taking.
- ➔ Handling cryogenics and vacuum system.
- ➔ Preparing for our upcoming experiments at Jefferson Lab Virginia Newport News in the United States.
- ➔ Building automation softwares for the labs.

Contents

UNH Polarized Target System



UNH Polarized Target System

- In cryostat, we have 5T Superconducting Magnet, 1K Evaporation Refrigerator attached with roughing pumps, and 140 GHz Microwave Source.
- In liquefier system, we have 500L liquid helium dewar, gas helium bag, helium compressor, and 48 gas cylinders.
- Production rate 27/day with the recapture efficiency >85% in 2026.

- 1 week physics and 2-3 weeks of reliquification.

Consumption of Helium in Industries

Critical Dependence Across Industries

Meical and Healthcare:
- MRI machine needs ~1,700 L liquid helium
- ~40 million MRI scans/year in the US.

Semiconductor and Technology:
- Intel, TSMC, Samsung for chip fabrication cooling and leak detection.

Space and Defense:

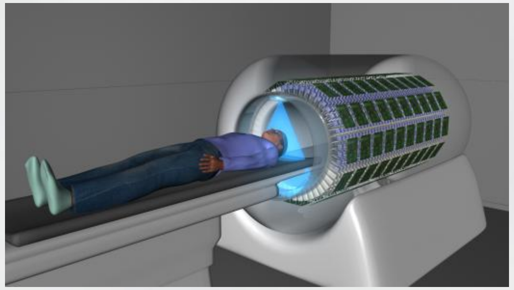
- NASA, SpaceX for pressurizing rocket fuel tanks;
- James Webb Telescope for cryogenic cooling.

Scientific Research and Quantum Computing:

- CERN, Jefferson Lab, Fermilab for accelerator magnets.
- IBM, Google for millikelvin cooling for quantum computers.

Energy – Nuclear Fusion:

- ITER tokamak for superconducting magnet cooling.

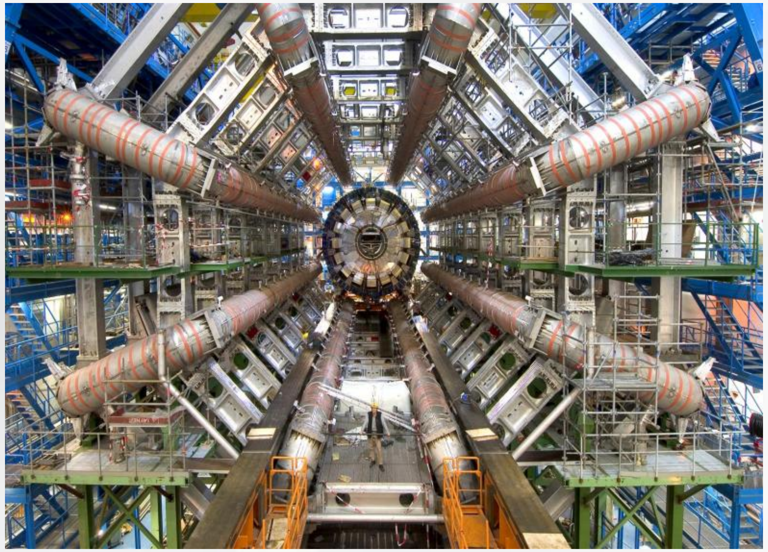


MRI Scanner

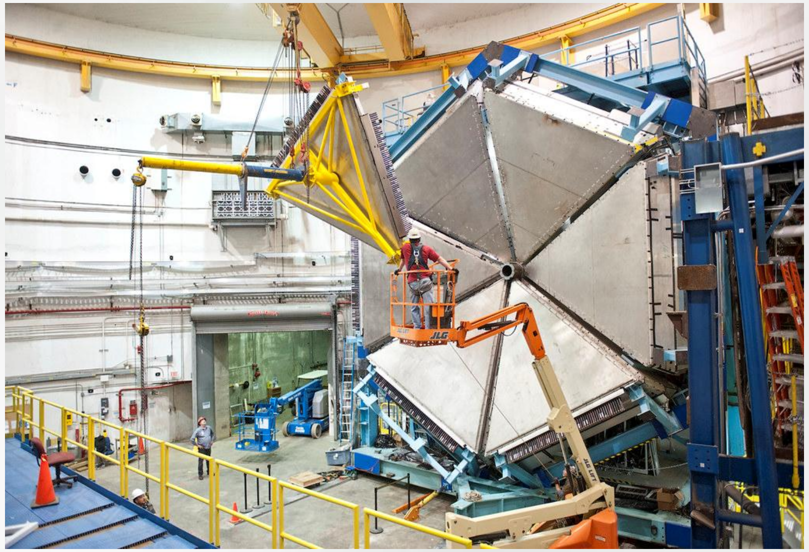
Chip Fabrication

Artemis II

Sustainability at Major Facilities

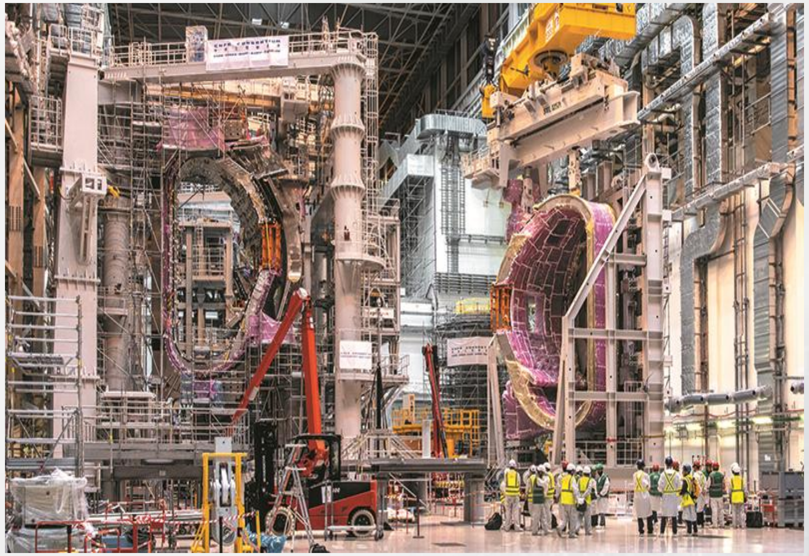


ATLAS Experiment, CERN



Hall-B Experiment, Jefferson Lab

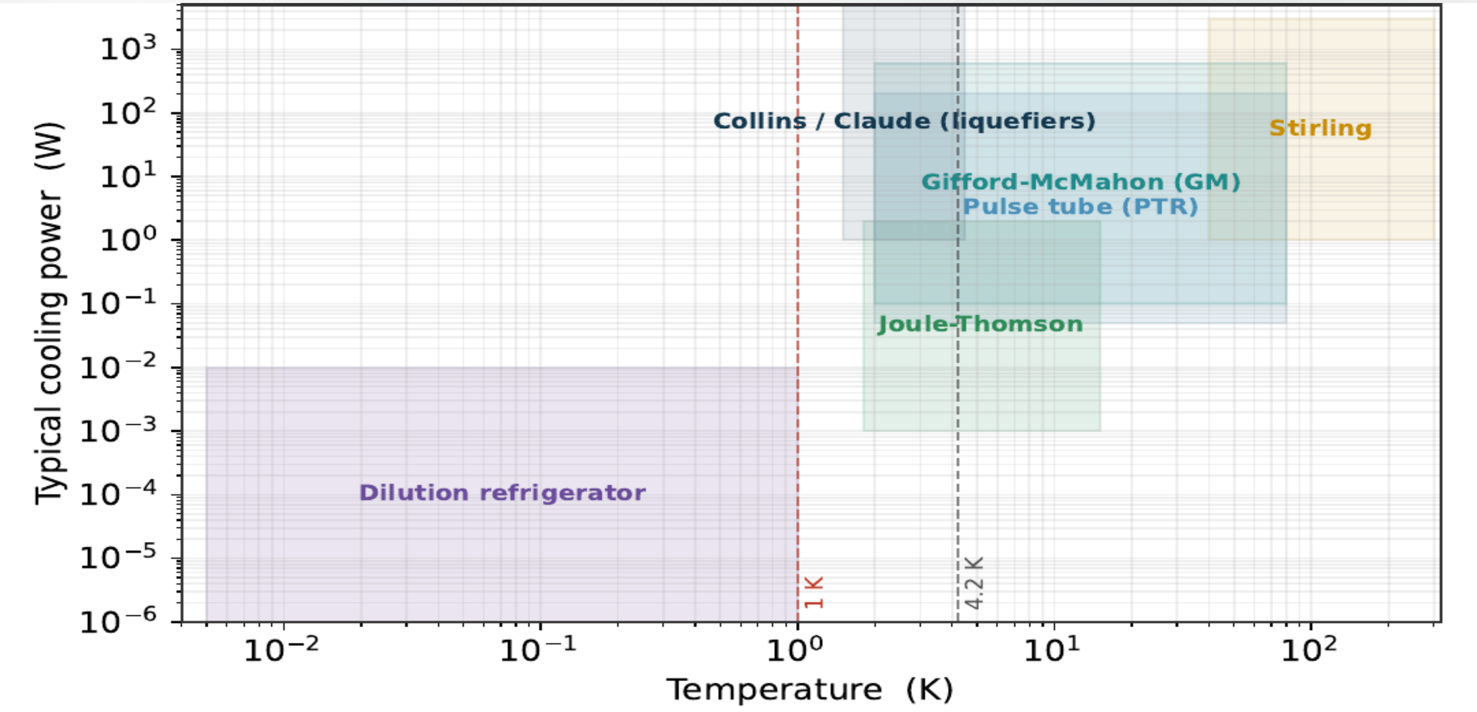
SpinQuest Experiment, Fermilab



ITER Fusion Reactor, France

Cryocooler option at University Scale (1)

- At lower temperatures, cooling power becomes harder — and more expensive — to produce.



Typical cooling power vs temperature: each family owns a region

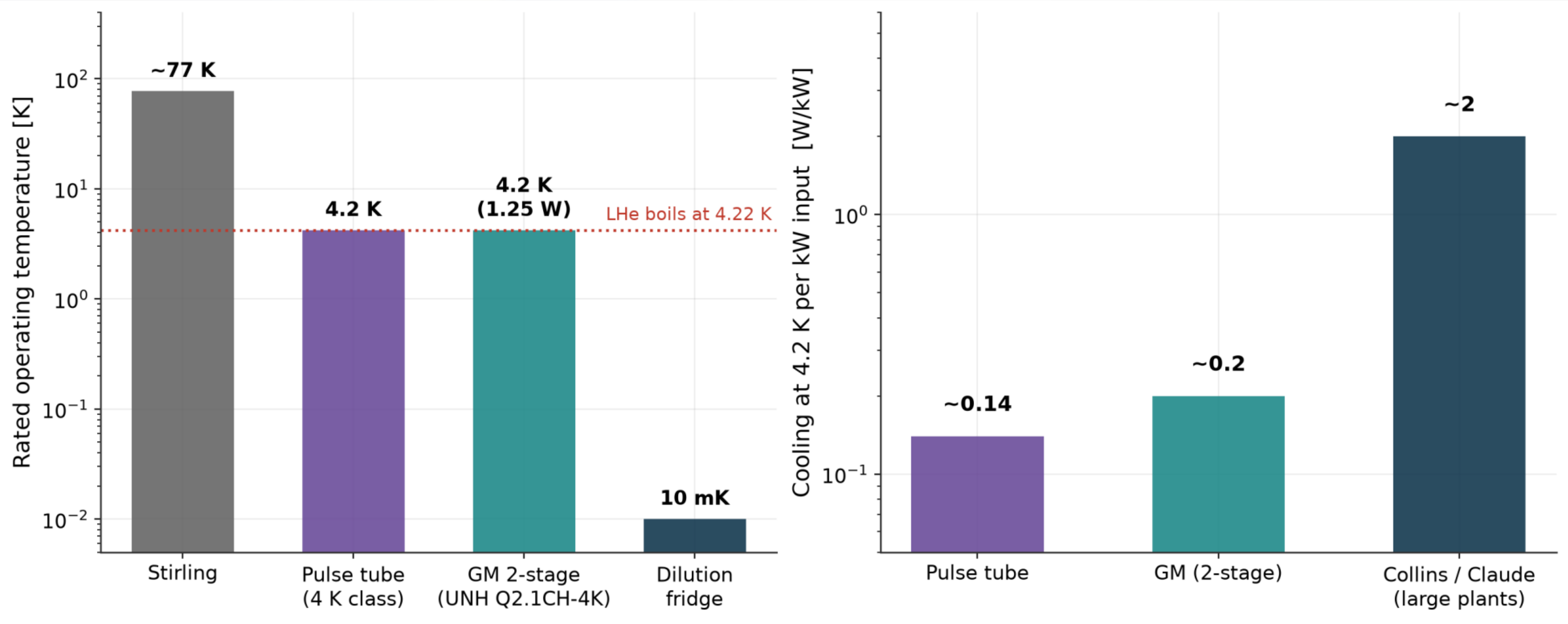
- **Each cryocooler family has its own useful range:** Stirling near 77 K, GM and pulse tube near 4 K, and dilution refrigerators below 1 K.
- **For helium recovery, the key region is around 4.2 K**, where liquid helium forms.
- GM and pulse-tube systems are the practical 4 K-class choices for a university lab.

For more information about cryocoolers:
https://uspas.fnal.gov/materials/21onlineSBU/Cryo/2021%20USPAS%20Lecture%2020.pdf

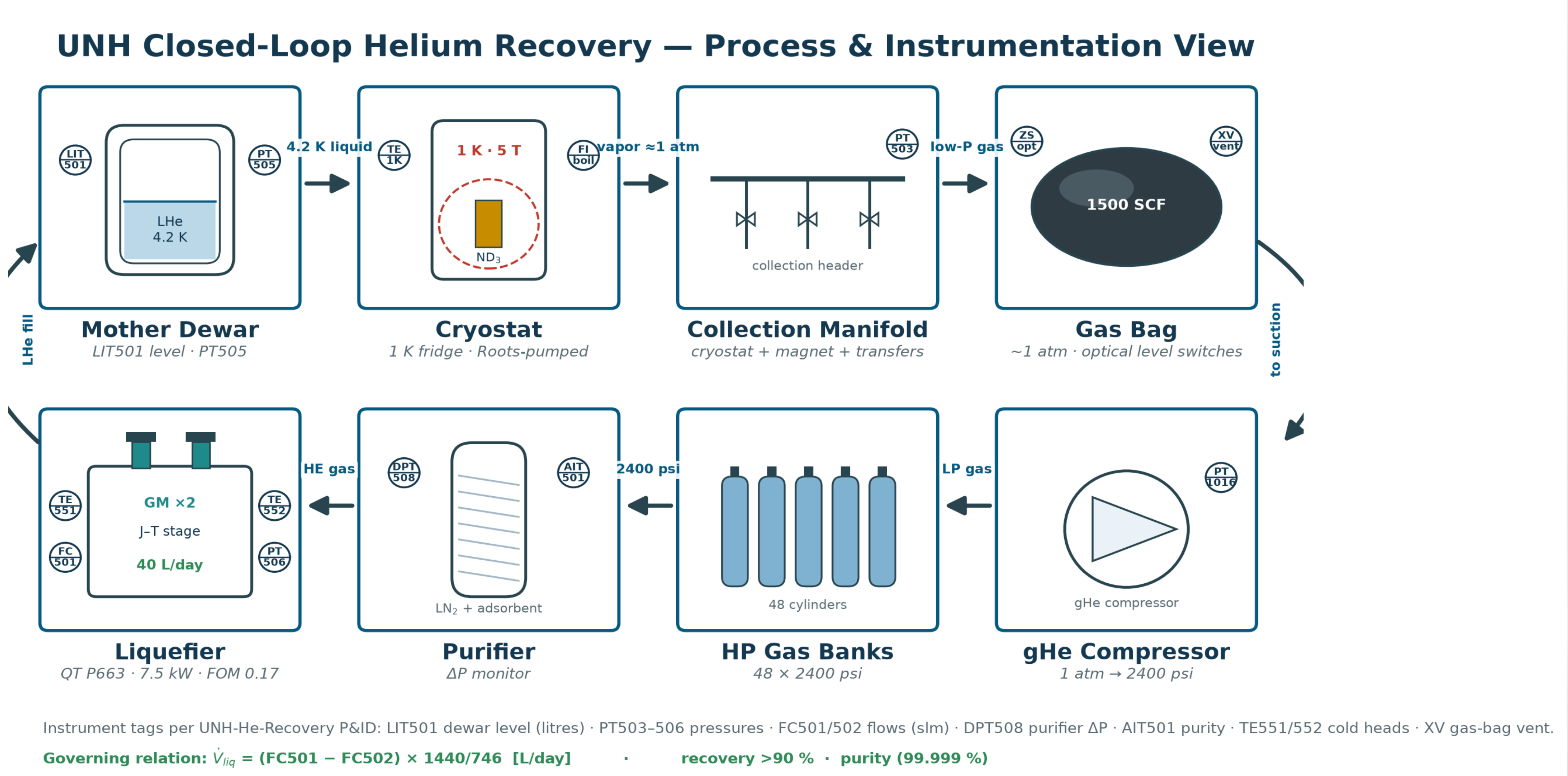
Cryocooler option at University Scale (2)

- At UNH, we use two Quantum Technology Q2.1CH-4K GM cold heads as the practical backbone of the recovery system. The first stage handles the higher-temperature heat load, giving about 40 W at 45 K for shielding and precooling. The second stage reaches the 4 K range with about 1.25 W of cooling, which prepares the helium for final liquefaction through the J–T stage. For a university lab, this was the right compromise: affordable, commercially available, and serviceable in-house.

Reference: Coldhead Manual August 2023 by Quantum Technology Corp.

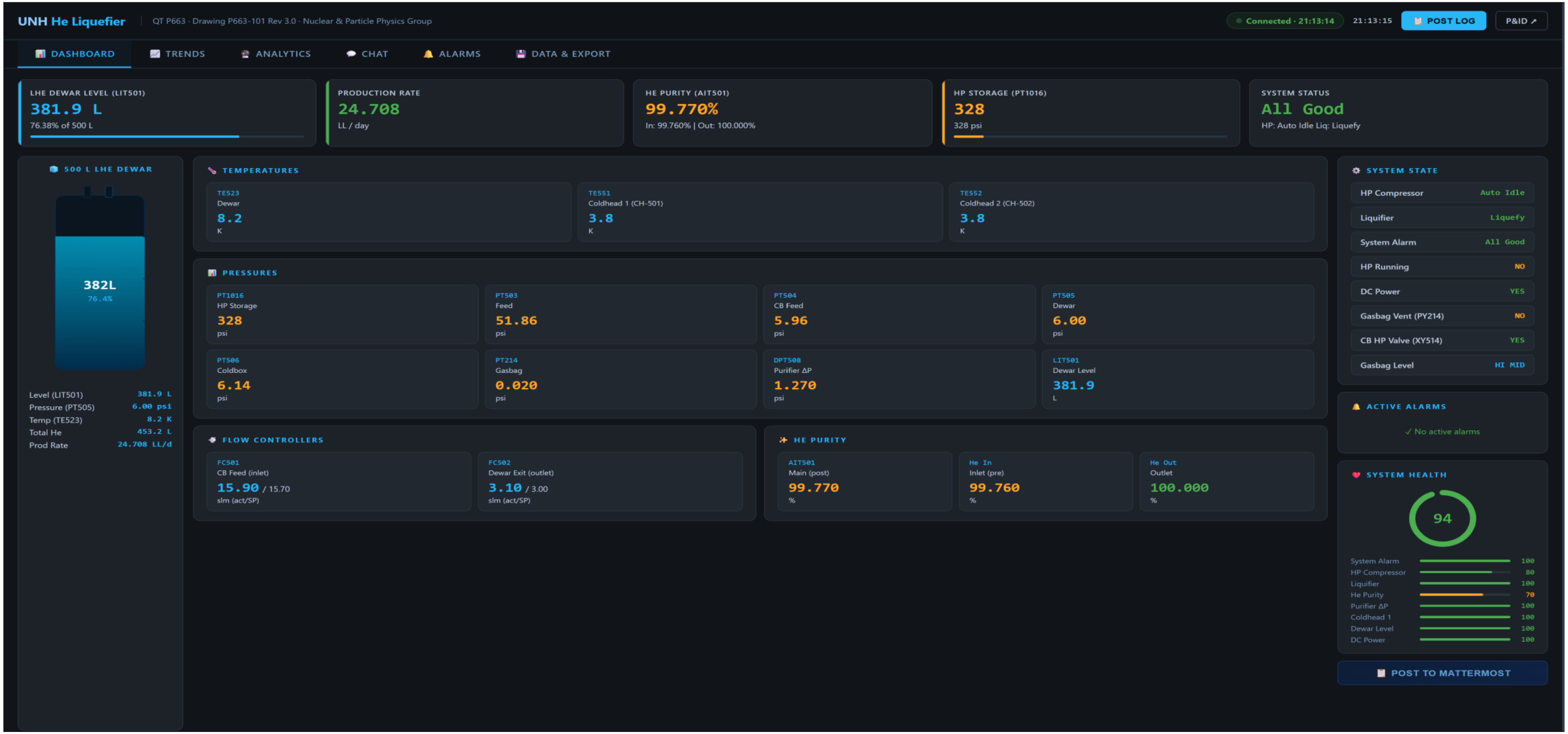


Helium Recovery System (Closed-Loop) at UNH



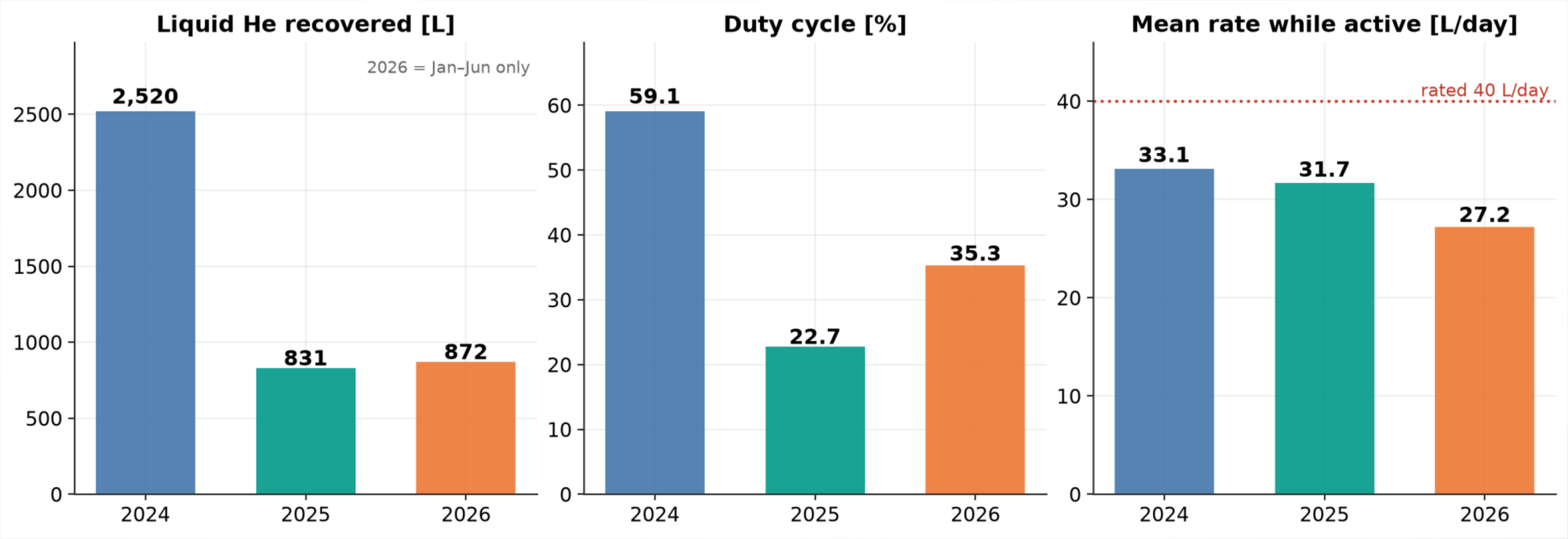
- UNH's closed-loop helium liquefier follows the same sustainability model.
- Enables extended experiments with >85% helium recapture
- Scalable solution for university-based nuclear physics programs

SCADA based Supervisory Agent for liquefier System



Yea-by-year view of the UNH helium recovery system (2024-2026)

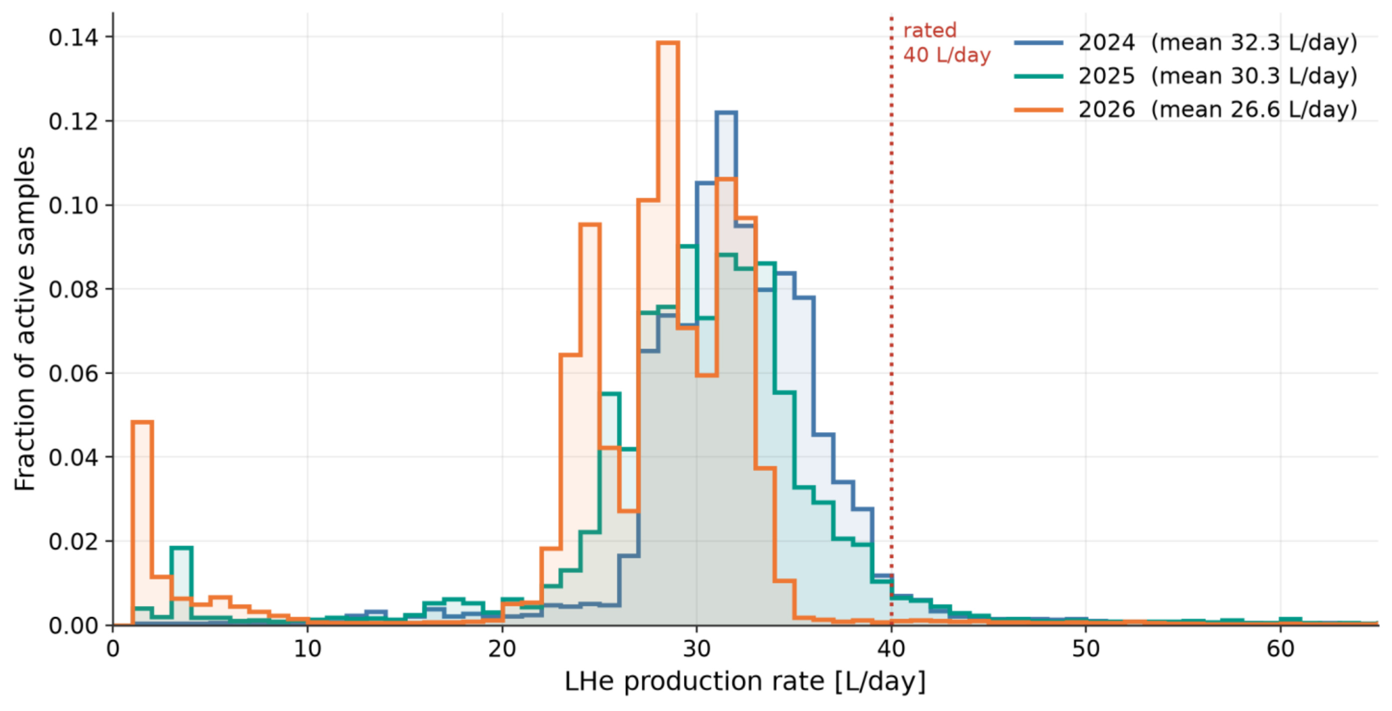
- **2024 was our strongest recovery year:** the system ran for the longest fraction of the year, with a duty cycle of about **59%**, mainly because of extended cooldown and recovery operations.
- **2025 was more stop-and-start:** the system ran in shorter operating periods, giving a lower duty cycle of about **23%** and a total recovery of **831 L**.
- **2026 is only a half-year dataset:** even with data only from January–June, the system has already recovered **872 L**, slightly more than the full 2025 total.
- **However, the active production rate is trending downward:** the mean rate while running decreased from **33.1 L/day in 2024** to **27.2 L/day in 2026**, showing reduced liquefaction performance.
- **Operational note:** during the June 2026 cooldown, about **200 psi of helium inventory** was lost from the HP compressor/storage side, which affected the overall recovery picture.



Year-by-year view of the UNH helium recovery system

Active liquefaction rate: year by year comparison

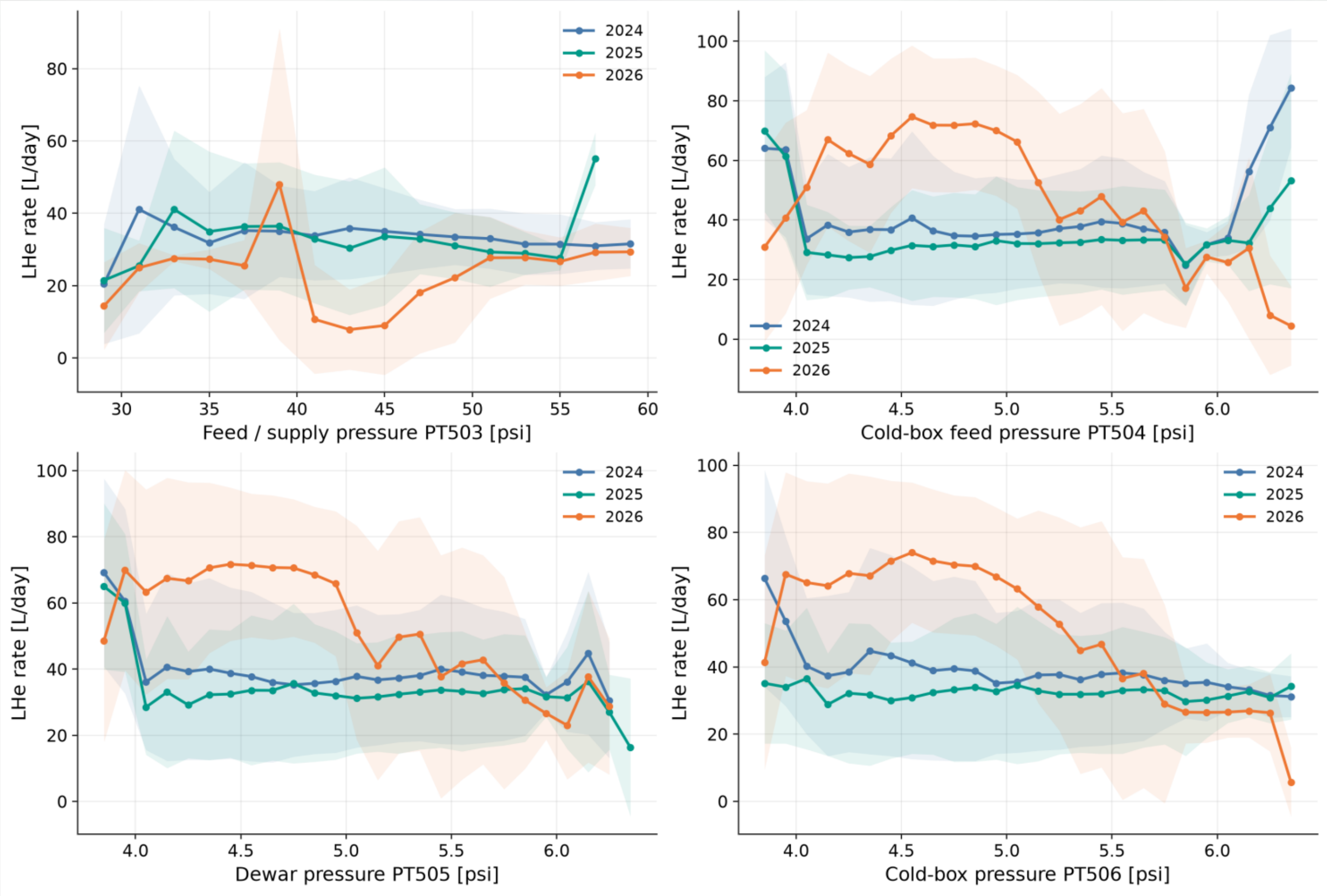
- This plot compares the helium production rate only during periods when the liquefier was actively running.



- **Rate shifts lower with time**: the mean active production rate decreases from about 32.3 L/day in 2024 to 30.3 L/day in 2025 and 26.6 L/day in 2026.
- **Clear performance degradation**: from 2024 to 2026, the active production rate drops by roughly 18%, indicating a measurable decline in liquefaction performance.
- **Still producing, but farther from rating**: the system continues to operate in the 25–35 L/day range, but the 2026 distribution sits farther below the 40 L/day rated capacity.
- **Likely degradation is because of** the decline appears connected to cold-head performance and mother-dewar conditions, and should be checked against compressor behavior, purity, vacuum, and thermal loading.

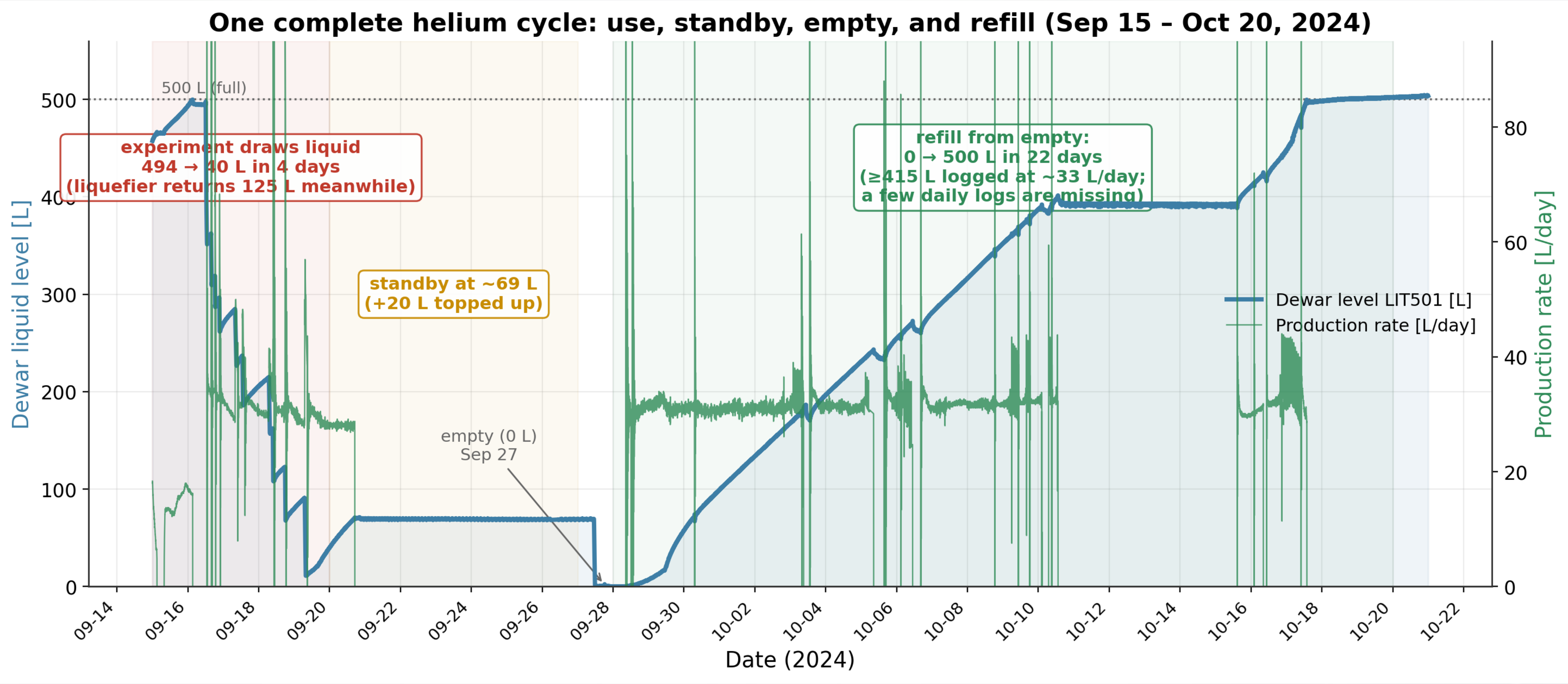
Operating pressure window for the liquefier system

- We compare liquid-helium production rate against four system pressures during active liquefaction only; shaded bands show the year-to-year spread, ±1σ).



Full 500 L dewar refill after recovery operation

- This plot shows one complete helium cycle: the experiment draws the mother dewar down, the system reaches an empty state, and the recovery system refills it back to the full 500 L capacity.



Helium recovery system: sustainability scorecard

- **4,223 L of liquid helium recovered**
  - Recovery period: **July 2024–June 2026**
  - This is helium that did not need to be purchased again.
- **$85K–$125K avoided helium purchase**
  - Estimated using **$20–$30 per liter**
  - Shows the direct financial value of the recovery system.
- **~85% closed-loop recovery efficiency**
  - Most of the helium inventory is captured and reused.
  - This reduces dependence on external helium deliveries.
- **Supply-chain resilience**
  - Protects UNH when Airgas or other vendors cannot supply LHE
  - Reduces exposure to helium shortages, inflation, and Strait of Hormuz disruptions
- **5.9 kWh/L specific energy**
  - Electrical energy required per liter of recovered liquid helium.
  - Useful metric for comparing recovery efficiency.
- **Large reduction in helium consumption**
  - Closed-loop operation greatly reduces helium use compared with open-cycle running.
  - This is the main sustainability advantage of the system.

Why DNP – and why 14-0 GHz

Transfer of spin polarization from electrons to nuclei using RF irradiation in an external magnetic field

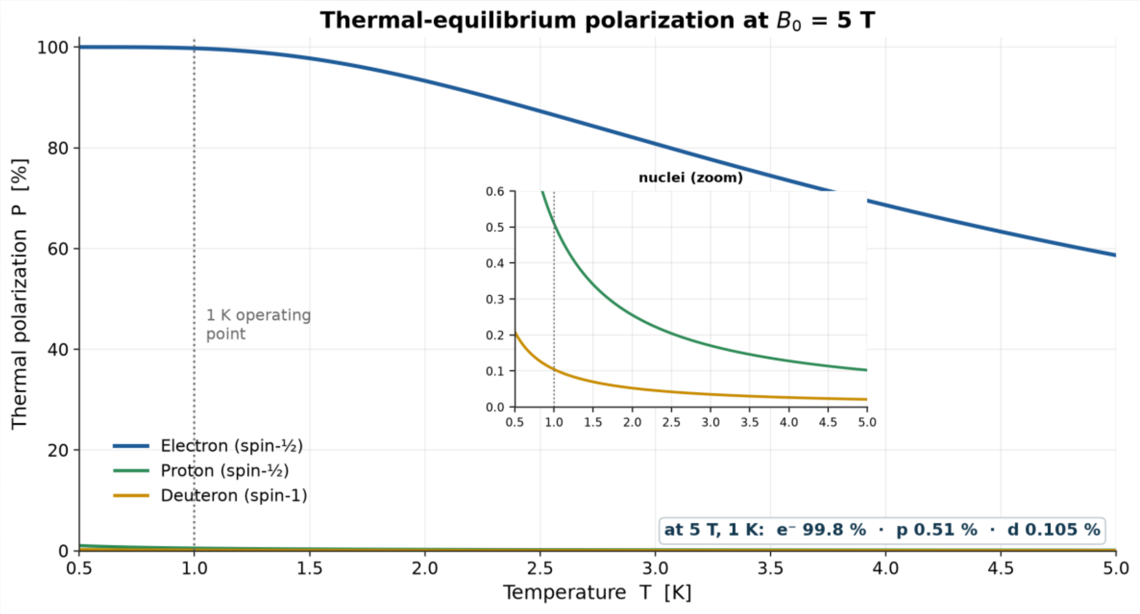
- The μ_e =660μ . Whereas the polarization at 5T and 1K of electrons is 98% and protons is 0.5%.

- 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



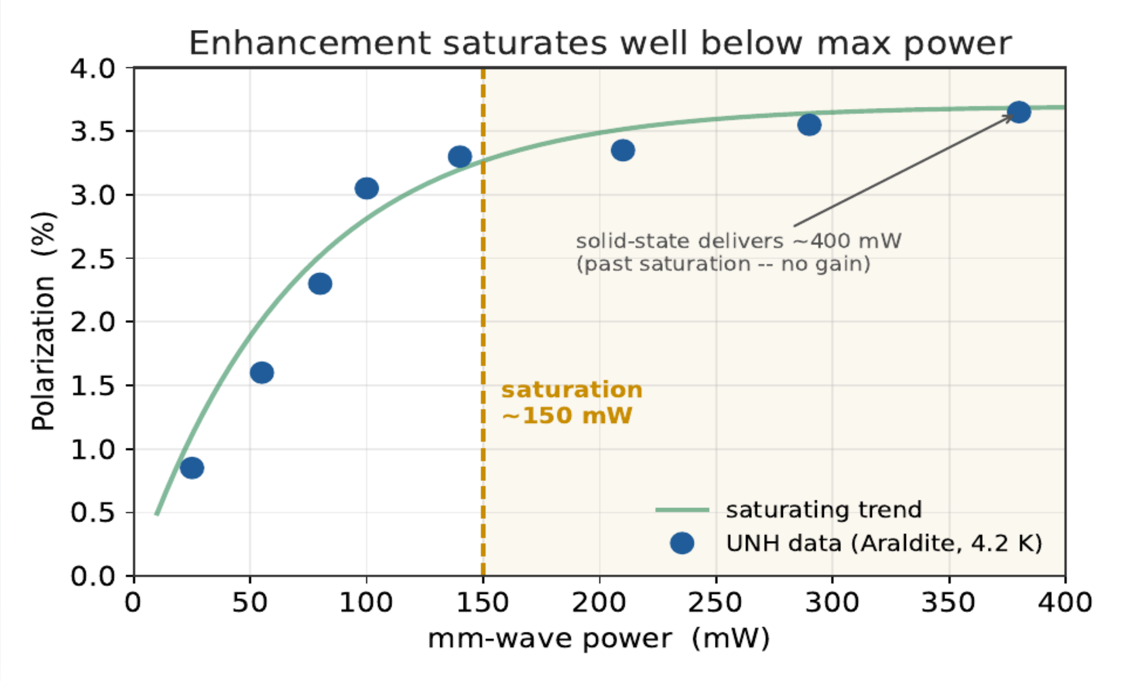
Reference: The SpinQuest (E1039) experiment's polarized target system, Muhammad Farooq

Microwave source choice: useful power vs helium cost

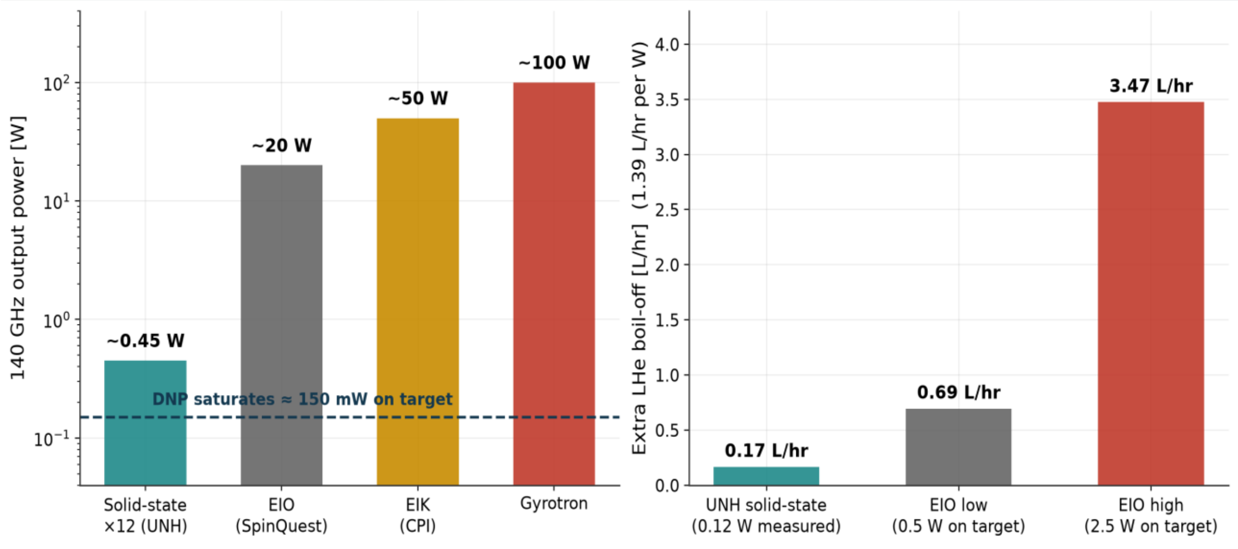
- **DNP saturates at relatively low power:** for our system, useful polarization gain is already near saturation at about **150 mW on target**.
- **High-power tube sources provide far more power than needed:** EIO, EIK, and gyrotron sources can deliver tens of watts, but most of that power does not improve the polarization once saturation is reached.
- Extra heat from the microwave source after saturating the polarization becomes the part of the heat load to 1K helium bath.
- **Heat load directly converts to helium cost:** using **1.39 L/hr per watt**, even a few watts of extra heat can produce several liters per hour of additional boil-off.
- **Main takeaway:** the solid-state chain gives enough useful microwave power for DNP while greatly reducing unnecessary helium loss.

Why 450 mW is enough?

- UNH data show that DNP enhancement saturates near 150 mW; our solid-state chain provides comfortable headroom beyond this point, without the heat load of watt-class tube sources.

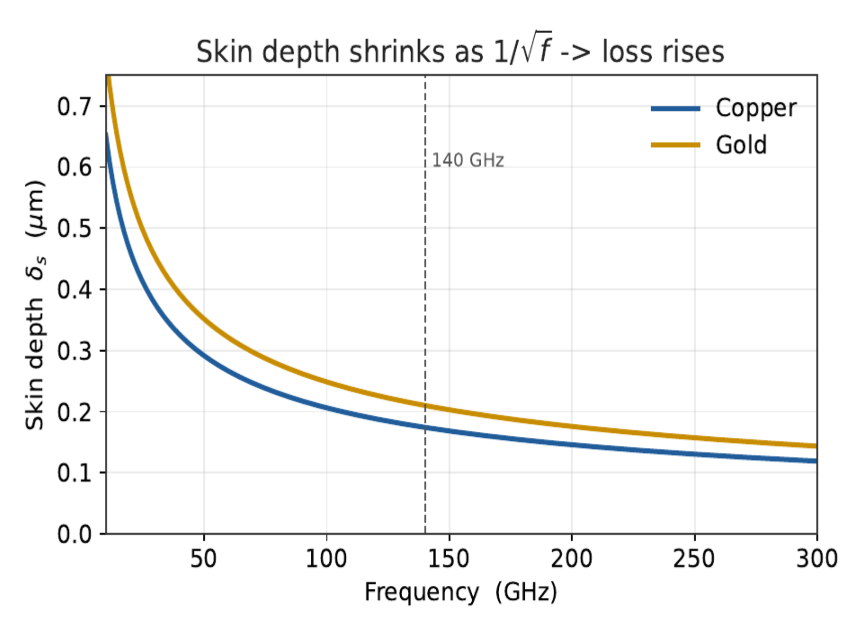


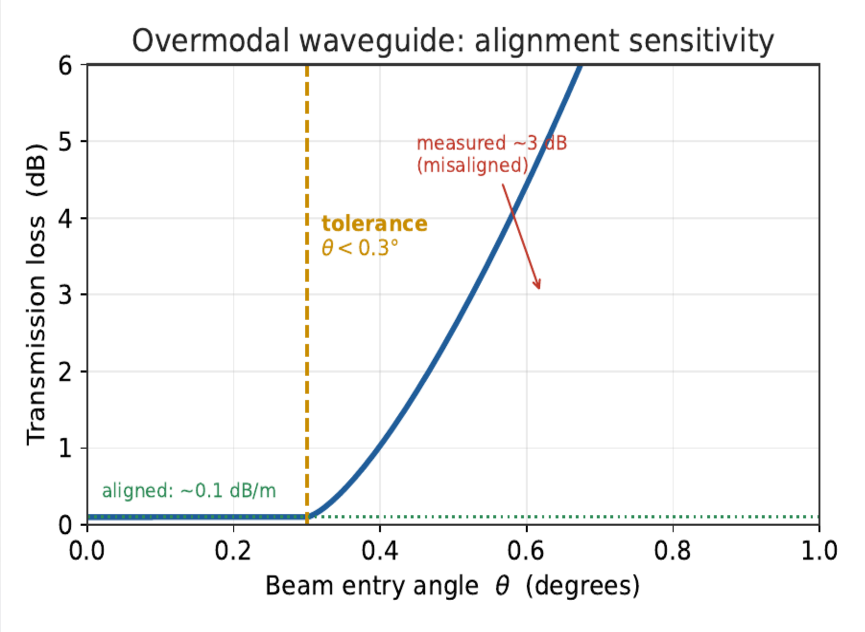
Reference: *PoS* PSTP2019 (2020) 062

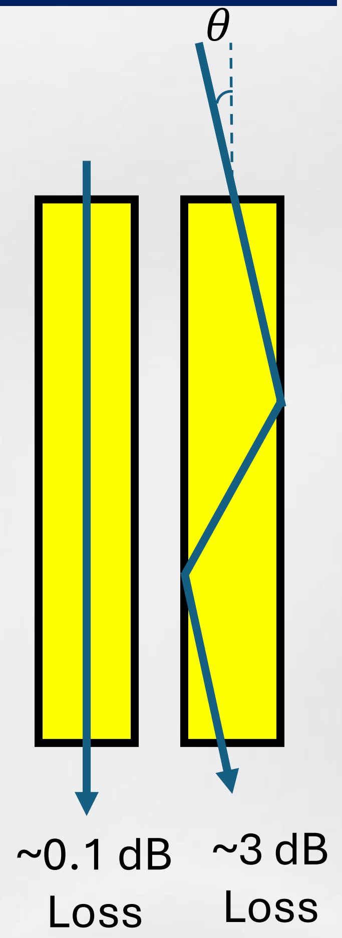


Power delivery to target

- At 140 GHz, conductor losses increase because the microwave field penetrates only a very thin surface layer. To keep the power delivery efficient, the UNH system uses a short Cu/Au-plated overmoded waveguide with very low loss when properly aligned.
- **At 140 GHz, skin depth is very small**, so conductor loss becomes an important part of microwave power delivery.
- **Cu/Au-plated waveguides help reduce loss**, but the guide must still be kept short and clean.
- **Alignment is the main tradeoff:** small entry-angle errors can cause mode conversion and raise the transmission loss quickly.
- **Main takeaway:** we can deliver the solid-state source power efficiently, but careful waveguide alignment is essential.





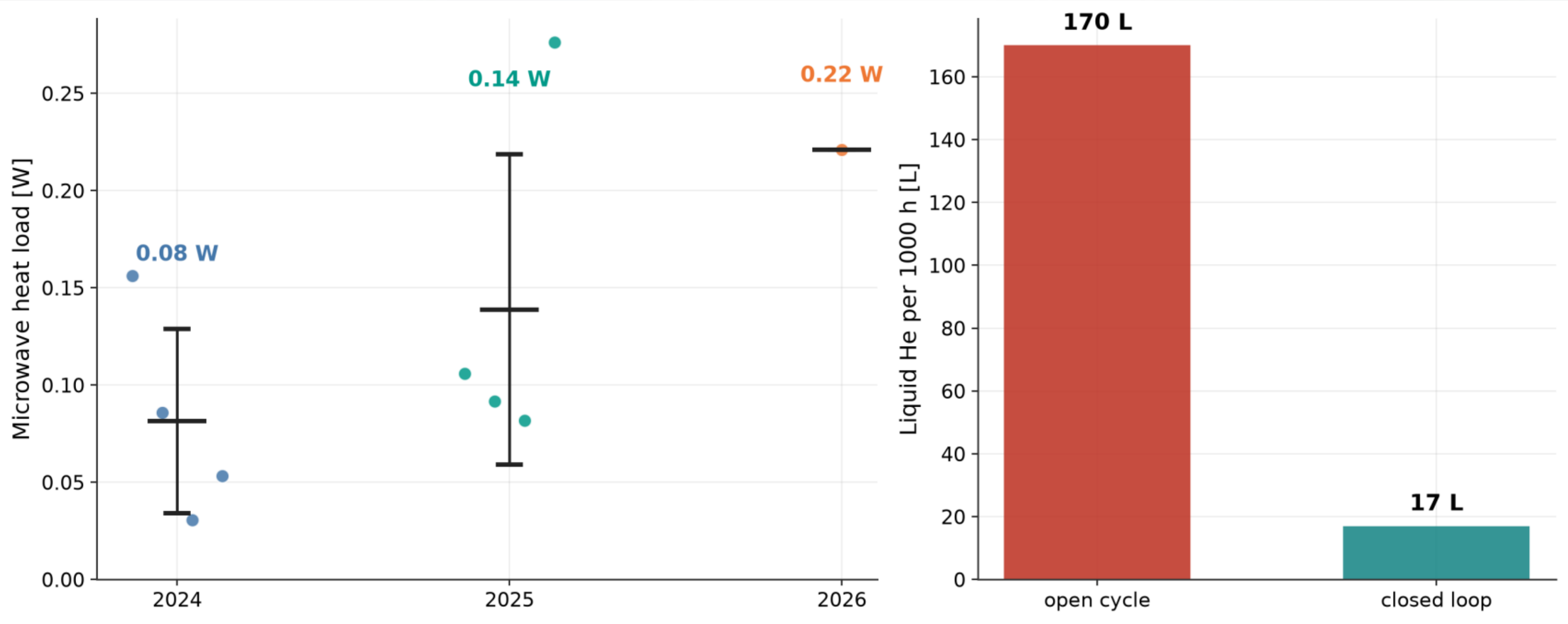


Reference: 2021-12-13 Long, PolTar meeting

The microwave heat budget

- **Microwave heat load is small:** measured values are only about **0.08–0.22 W** across clean run days.
- **Open-cycle helium cost is measurable:** a **0.12 W** microwave heat load would boil off about **170 L per 1000 hours**.
- **Closed-loop recovery changes the picture:** with more than **90% recovery**, the net helium loss drops to about **17 L per 1000 hours**.

- **Main Takeaway:** the solid-state microwave chain adds a small, manageable heat load, especially when operated with helium recovery.



Microwave source comparison: power, heat, and operating cost

- DNP only needs about 150 mW on target. The UNH solid-state chain provides enough useful power with much lower heat load, simpler operation, and much lower electrical/helium cost than other microwave sources.

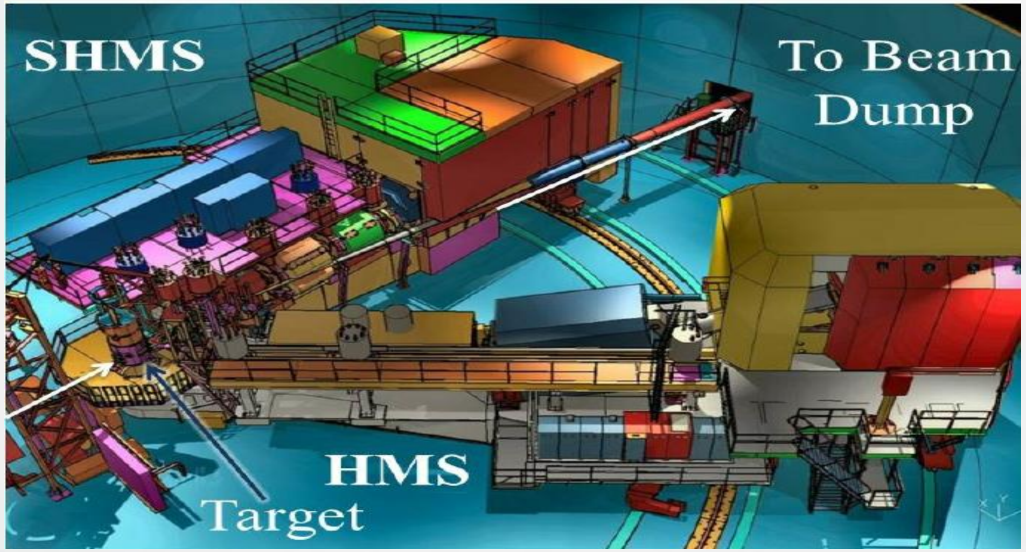
Parameter	UNH solid-state	SpinQuest EIO	CPI EIK (140 GHz)	Gyrotron
Source output power	~450–500 mW	~20 W	50 W avg	10–100+ W
Estimated power at target	~120 mW	0.5–2.5 W	—	≫ saturation
Heat load to 1 K bath	0.08–0.22 W (measured)	~0.5–2.5 W	—	(needs attenuation)
Helium boil-off penalty	~0.17 L/hr	~0.7–3.5 L/hr	—	—
Power supply requirement	8–12 V DC	4–21 kV	multi-kV	HV + SC magnet
Electrical input power	air	forced liquid/air	liquid	water
Electrical input power	~10 W	~1.5 kW	~2 kW	~30 kW
Electrical energy per 1000 h	~0.1 MWh	~1.5 MWh	~2 MWh	~30 MWh
Tuning method	electronic	mechanical cavity	mechanical	magnet/gun
Main lifetime/consumable issue	3-4 diode lifetime	cathode life	cathode life	tube + magnet

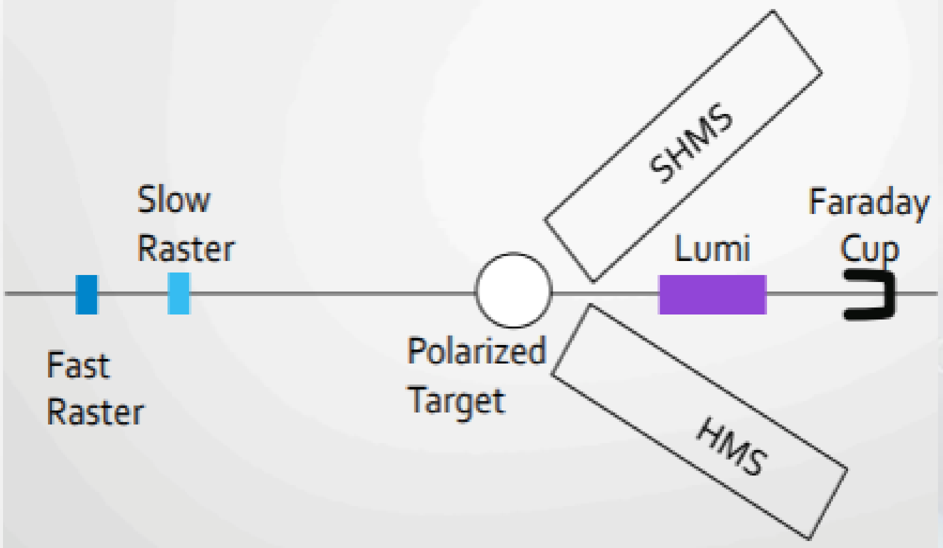
Solid-state 140 GHz DNP: sustainability scorecard

- **~10 W electrical input**
  - Delivers about **450 mW at 140 GHz**
  - Operates with simple **8–12 V DC power**
- **~15× lower energy use**
  - Compared with the previous EIO tube system
  - Over **1000 hours of operation**
- **Small measured heat load**
  - Only **0.08–0.22 W** into the **1 K bath**
  - Much lower than other microwave tube heating
- **Low helium penalty**
  - About **170 L / 1000 h** in open-cycle operation
  - Reduced to about **17 L / 1000 h** with closed-loop recovery
- **Strong DNP performance**
  - Achieved ~**51% sustained deuteron polarization** in June 2026.
  - Shows that solid-state power is sufficient for the target
- **Simpler infrastructure**
  - No high-voltage racks
  - No water cooling
  - Compact, air-cooled operation
- **Main takeaway**
  - **Solid-state 140 GHz DNP provides enough microwave power while reducing energy use, heat load, helium loss, and system complexity.**

b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiments in the Hall C (Jefferson Lab)

- **E12-13-011: The Deuteron Tensor Structure Function b_1.**
  - Approved by JLab with an A^- Physics Rating. Link
- **E12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries.**
  - Approved by JLab with an A^- Physics Rating. Link
- I am performing analysis on RGC data to prepare for the b_1 and A_{zz} experiments.





Summary

- **Closed-loop helium recovery (QT P663):** 4,223 L of LHe recovered 2024–2026 at >85 % recovery, ~$85k–125k of purchases avoided.
  - Stable performance: 27–33 L/day active rate every year; FOM 0.17 (L/h)/kW (~5.9 kWh/L).
  - Single loss incident (74.6 L, May 2026, chiller failure) quantifies exactly what the loop is worth.

- **Solid-state 140 GHz DNP source:** ~450 mW circularly polarized from ~10 W wall power (×12 chain, 8–12 V DC, air-cooled).
  - Measured heat load into the 1 K bath: 0.08–0.22 W — ~20× less helium boil-off than a watt-class EIO; 15× less energy.
- **Polarization performance:** best sustained deuteron |P| = 28 % → 55 % → 52 % (2024–2026).
  - Colder bath → higher polarization: best |P| lives in the reliquefier-fed 0.9–1.2 K band.

- **b_1 and Azz at Jefferson Lab (Hall C):** the twin systems deliver the weeks-long 1 K running and polarization the tensor program (P_{zz} > 30 %) requires.

Future Plans:

- Repair or swap the coldhead.
- Repair the HP compressor.

Please join the effort

Please join the effort:

- Karl Slifer (karl.slifer@unh.edu) [Spokesperson of b_1(E12-13-011) Experiment]
  - **E12-13-011: The Deuteron Tensor Structure Function b_1.** Link
- Elena Long (elena.long@unh.edu) [Spokesperson of A_{zz} (E12-15-005) Experiment]
  - **E12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries.** Link

Thanks

University of New Hampshire

UNH NPG

U.S. DEPARTMENT OF ENERGY | Office of Science

This work is supported by DOE contract *DE-FG02-88ER40410*

b_1 (E12-13-011) and A_{zz} (E12-15-005) Collaboration

RunGroup Spokespersons

Chen, Day, Higinbothan, Kalantarians, Keller,
Long, Rondon, Santiesteban, Slifer

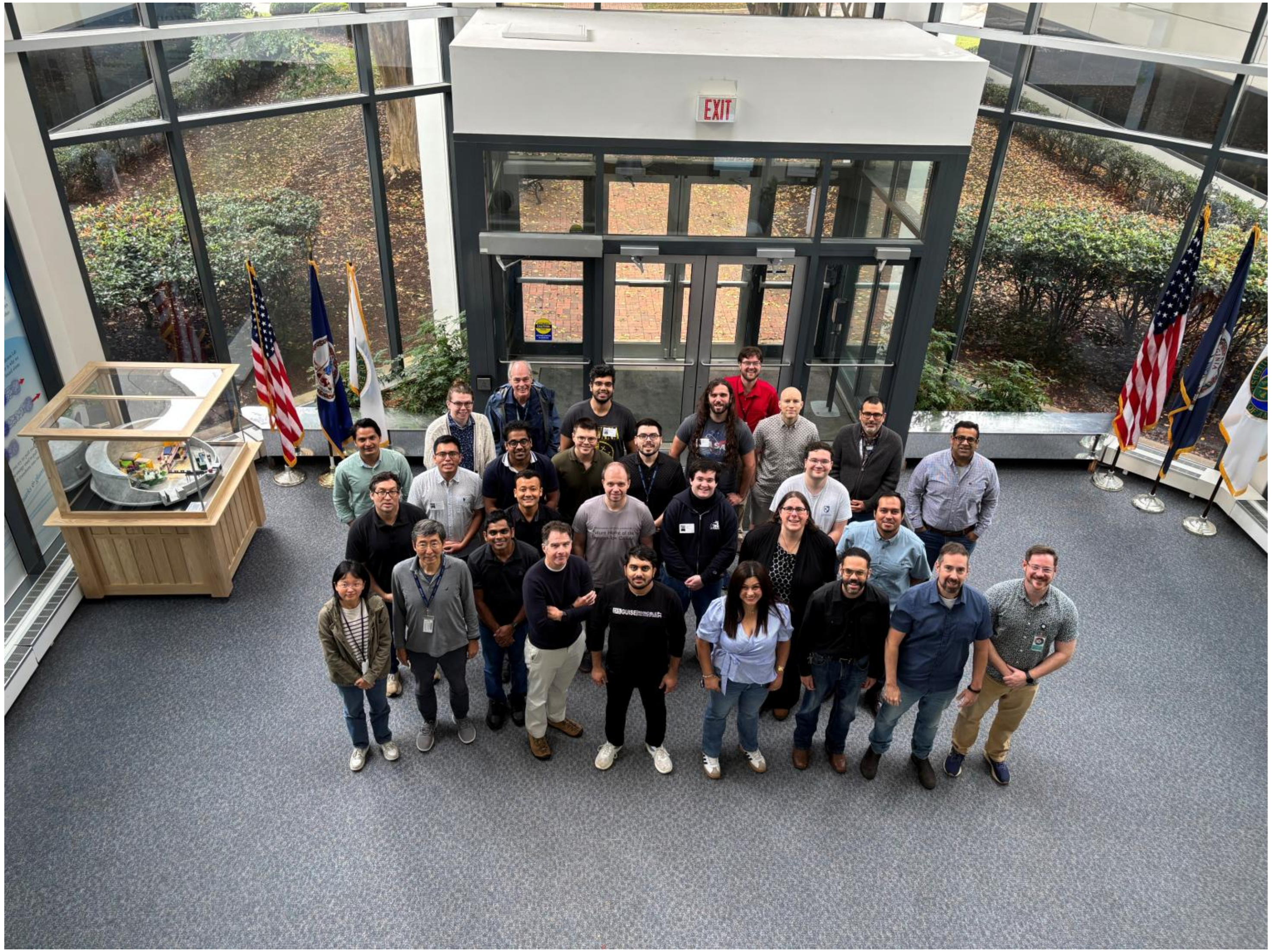
- 14 different active institutions
- 12 identified PhD students (from 3 universities)
- 3 active post-docs + 1 more expected
- Weekly meetings

Join by going to link https://mailman.jlab.org/mailman/listinfo/Tensor

OR

just send an email to karl.slifer@unh.edu to be added

b1/Azz Tensor Collaboration at Jefferson Lab



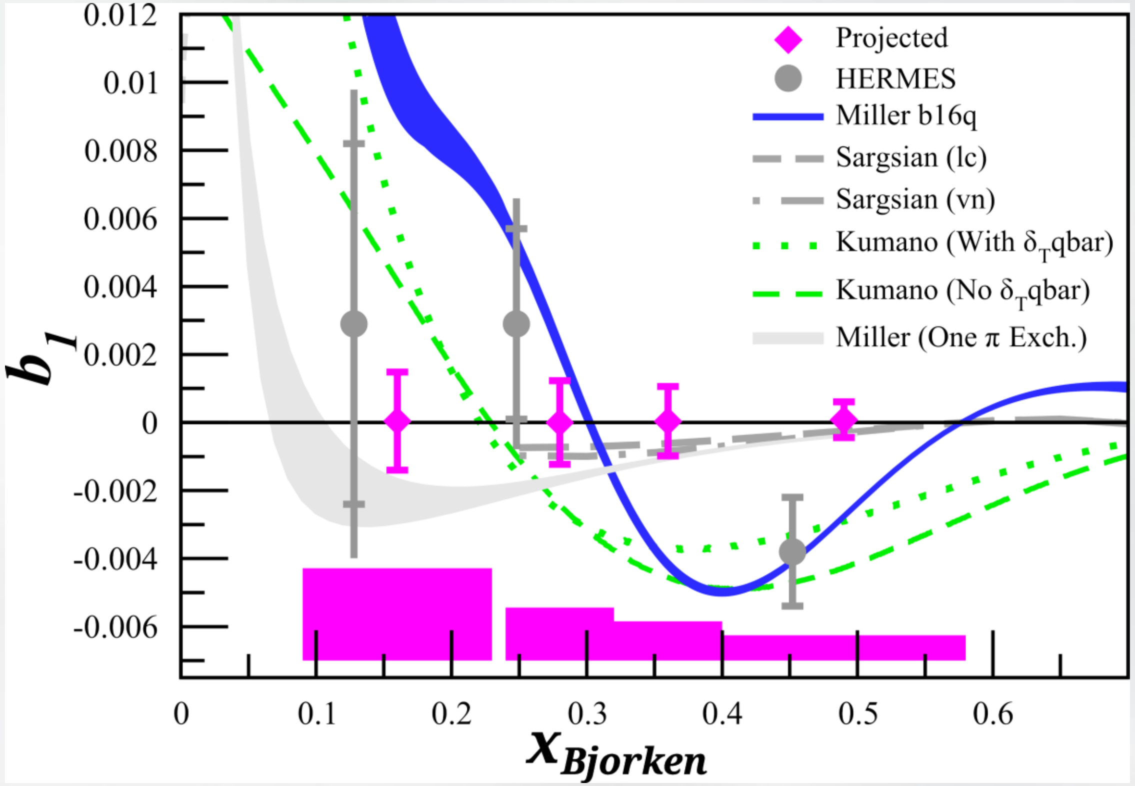
Backup Slides

b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiments in the Hall C (Jefferson Lab)

b_1 (E12-13-011) Experiment in the Hall C (Jefferson Lab)

- Intended to improve upon HERMES 2005 data.
- Tensor Physics at quark level
- Tensor-polarized quark sea (violating sum rules).
- Enhanced D-wave nucleon motion.

E12-13-011: The Deuteron Tensor Structure Function b_1

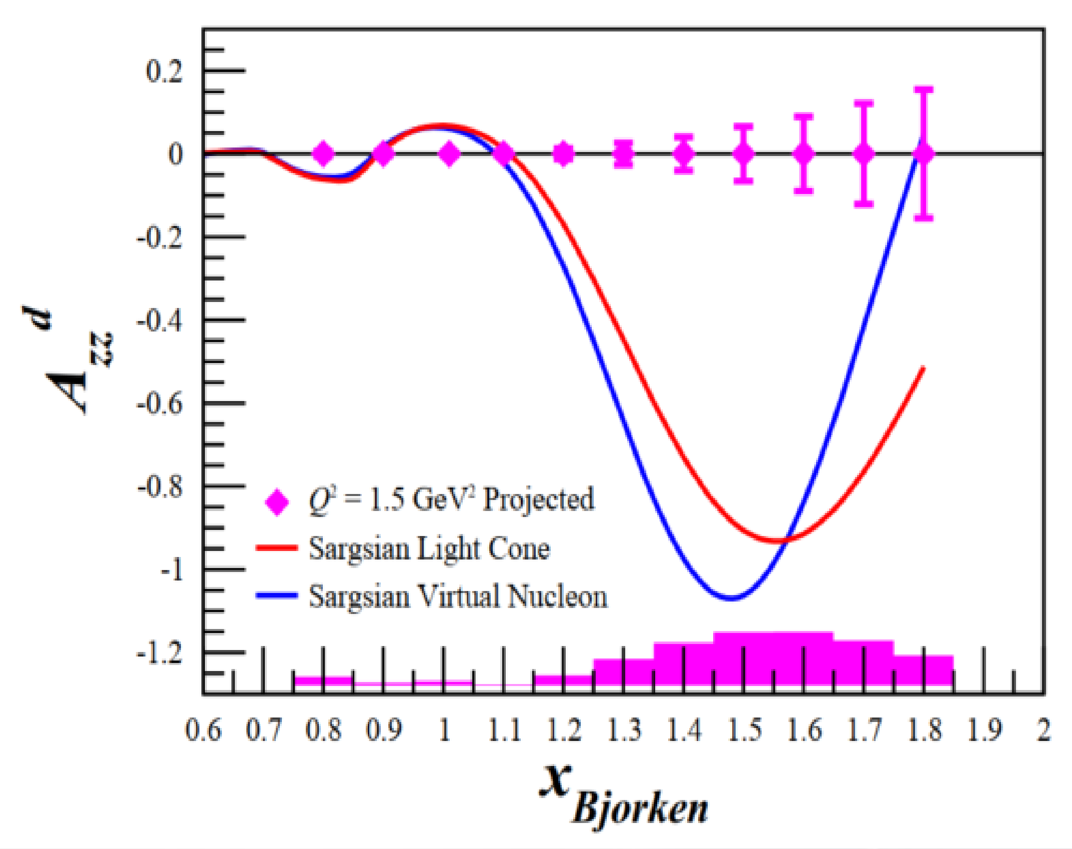


K. Slifer et al, Jlab E12-13-011.

A_{zz} (E12-15-005) Experiment in the Hall C (Jefferson Lab)

- **First-ever quasi-elastic A_{zz} measurement:** – a new window into deuteron structure,
- **Relevance to short-range correlation (SRC):** physics – probes a short-range correlations and deuteron wavefunctions dynamics,
- **Broad kinematic reach:** widest x-range covered by a single A_{zz} experiment,
- **Additional observable:** simultaneous extraction of T_{2o}.
- **Note:** Both experiments will conduct at the beam energy of 11.0 GeV with 115 nA beam current.
- Implement tensor enhancement techniques: selective semi-saturated (ssRF).
- **Both approved by JLab with A^{-} Physics Rating.**

E12-15-005: Measurement of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries.



E. Long et al, Jlab E12-15-005.

b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiments in the Hall C (Jefferson Lab)

b_1 Systematic Estimates

Source	Systematic
Polarimetry	8.0%
Dilution Factor/Packing Fraction	4.0%
Others	2.1%
Total	9.2%

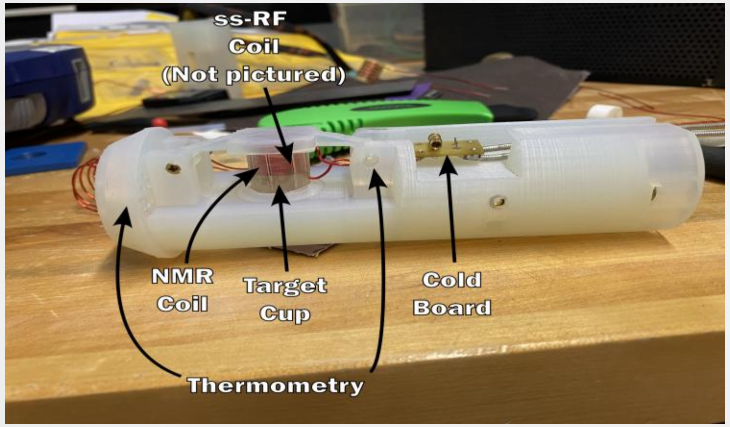
A_{zz} Systematic Estimates

Source	A_{zz} Systematic	T_{20} Systematic
Polarimetry	6.0%	6.0%
Dilution Factor	6.0%	2.5%
Packing Fraction	3.0%	3.0%
Others	2.5%	2.5%
Total	9.2%	7.4%

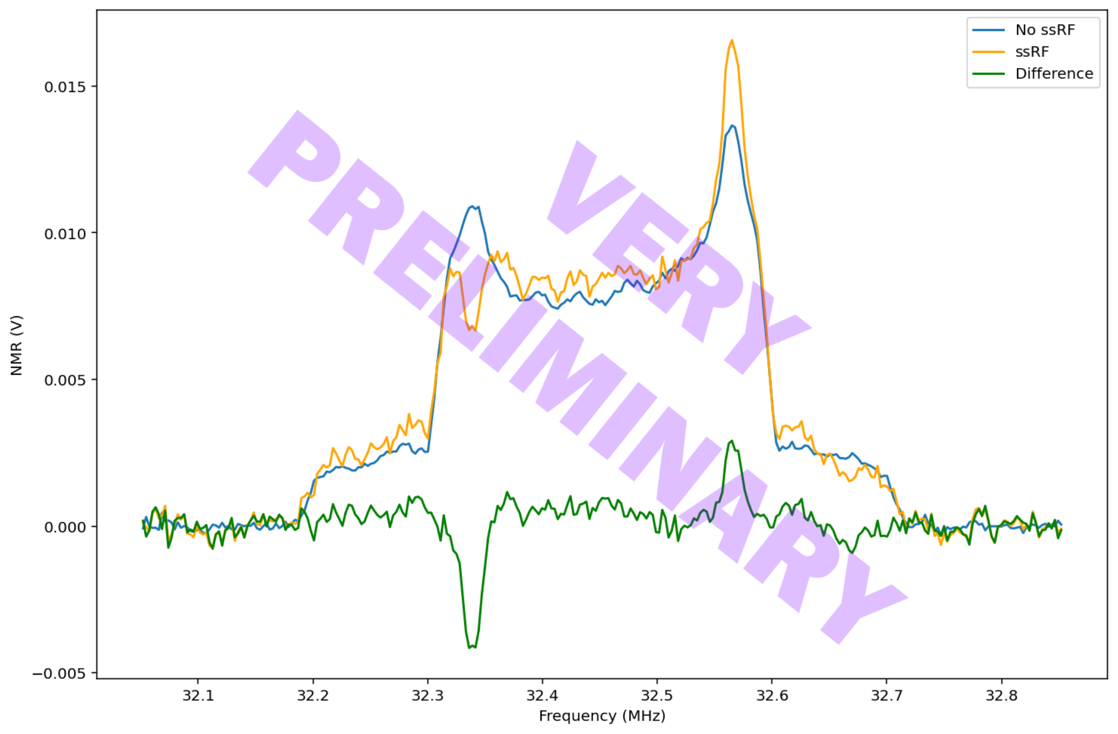
- Both experiments require a highly ($\geq 30\%$) tensor-polarized deuterium target with precise measurement of tensor polarization.

Selective Semi-Saturated (ssRF) (Hole Burning)

- selective semi-saturated RF (ssRF) spin-manipulation is implemented at selected frequencies to enhance the tensor polarization.
- ssRF implemented through dedicated ssRF coil which is coaxial to NMR coil.
- Hole burning is lasted by ten minutes (by eye) before lineshape recovered.
  - Analysis being refined to estimated vector and tensor polarization on ssRF signal.



Credit: Allison Zac



Above: Comparison between the lineshape before (blue) and after (Orange) implementing ssRF and difference (green) shows between No ssRF and ssRF at each frequency bin.

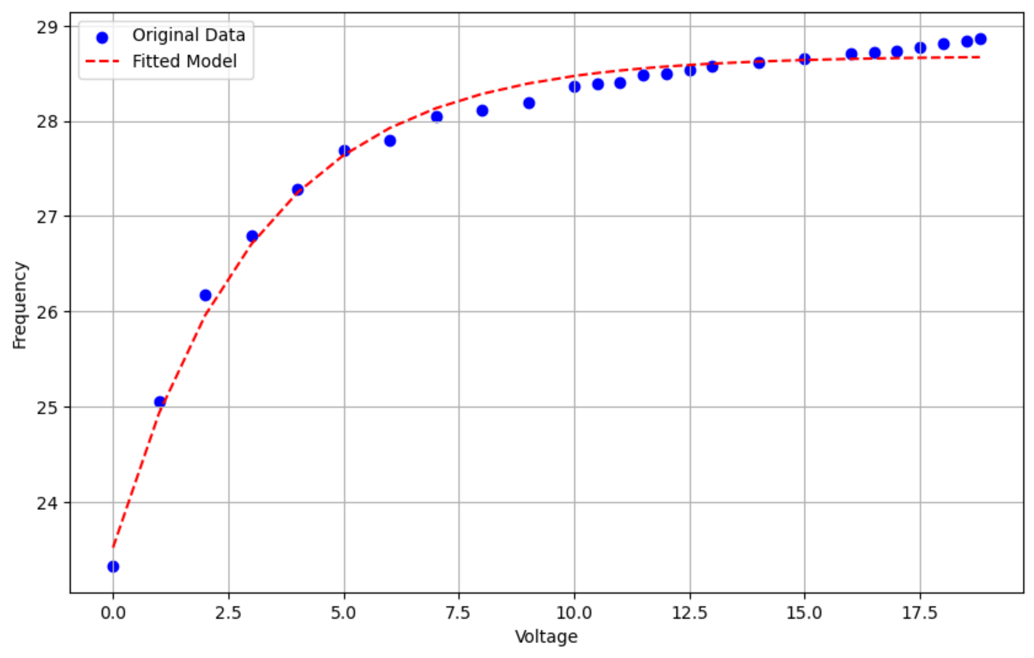
Acknowledge: Acknowledgement to Prof. E. Long.

NMR System at UNH

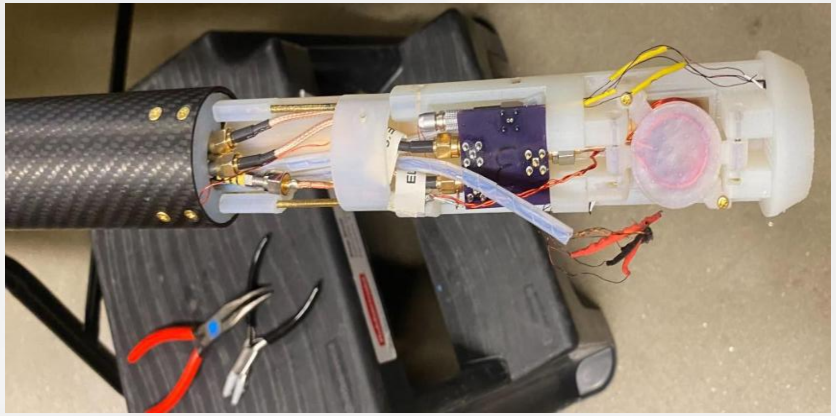
- NMR system at deuteron spin transition central frequency ($\approx 30\ MHz$)
- It is LANL Q-Meter design

- RF "cold board" produces NMR signal from VME output.

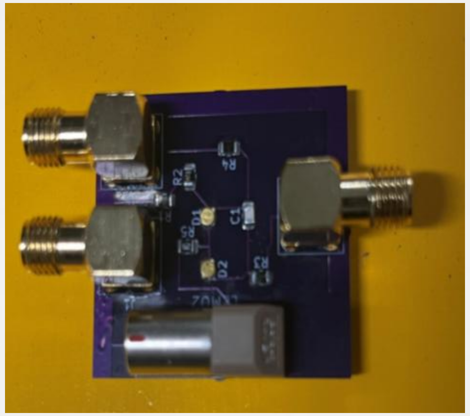
- By increasing the voltage up-to 18.9 volts helps to enhance the frequency up-to 5 MHz.
- We can tune it inside the cryo-stat.



Changing cold-board frequency by changing the cold-board voltage



Target cup with cold-board and ssRF and NMR coils



Coldboard

G.R. Court, et al, Volume 527, Issue 3, 21 July 2004, Pages 253-263

Target Materials

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

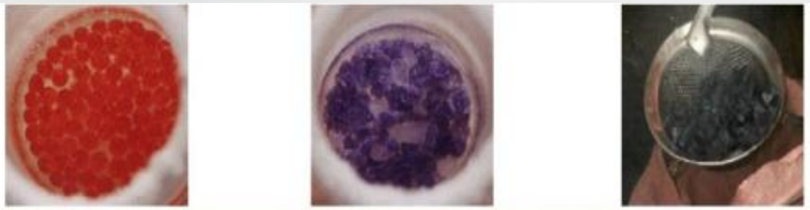
$$FOM = P_T^2 . f^2 . \rho . \kappa$$

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

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

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

$$f(x) = \frac{N_H \sigma_{pp_\uparrow}^{DY(x)}}{N_H \sigma_{pp_\uparrow}^{DY(x)} + NN_{14} \sigma_{pp_\uparrow}^{DY(x)} + NHe \sigma_{pp_\uparrow}^{DY(x)} + NAl \sigma_{pp_\uparrow}^{DY(x)} + \cdots}$$



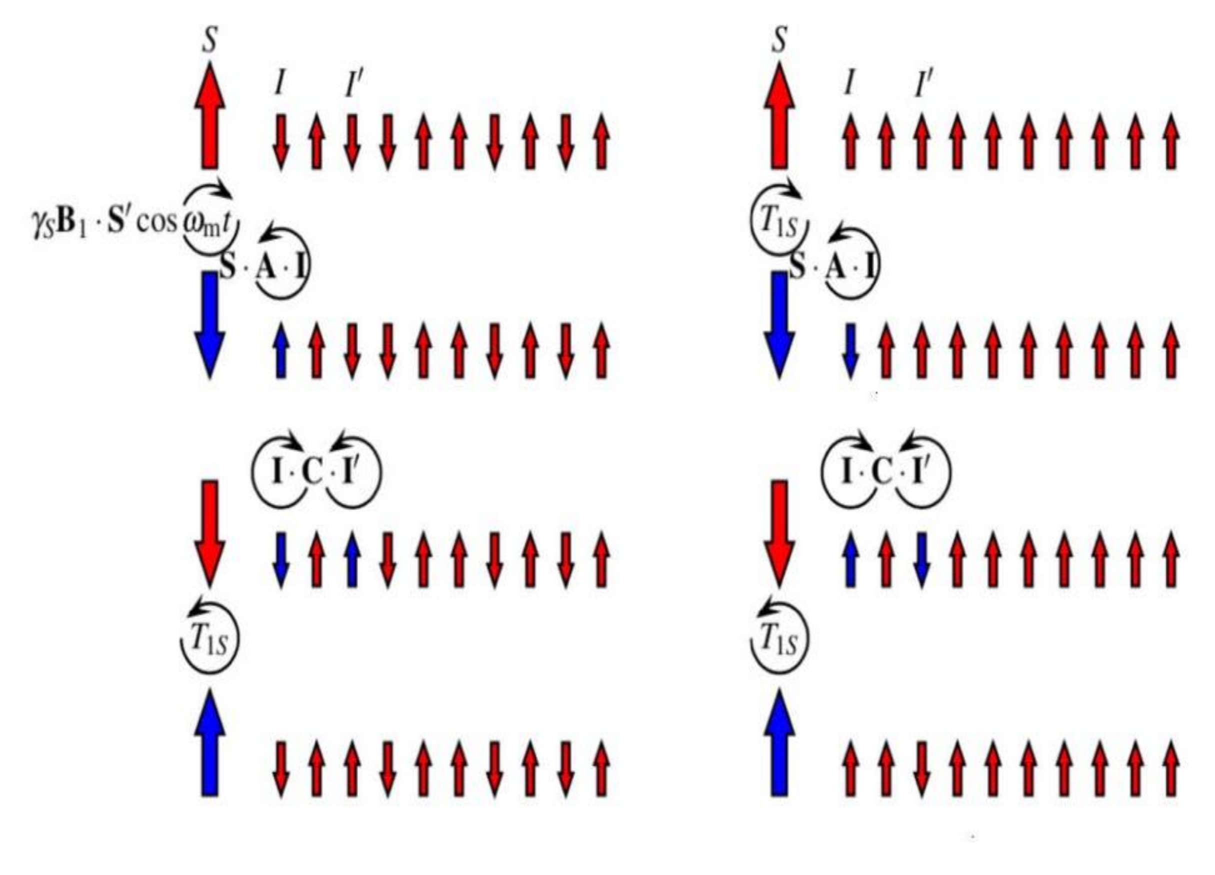
Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high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

Target Material Figure of Merit

- More detail in SPIN2023 by M. Farooq: https://inspirehep.net/literature/2814906

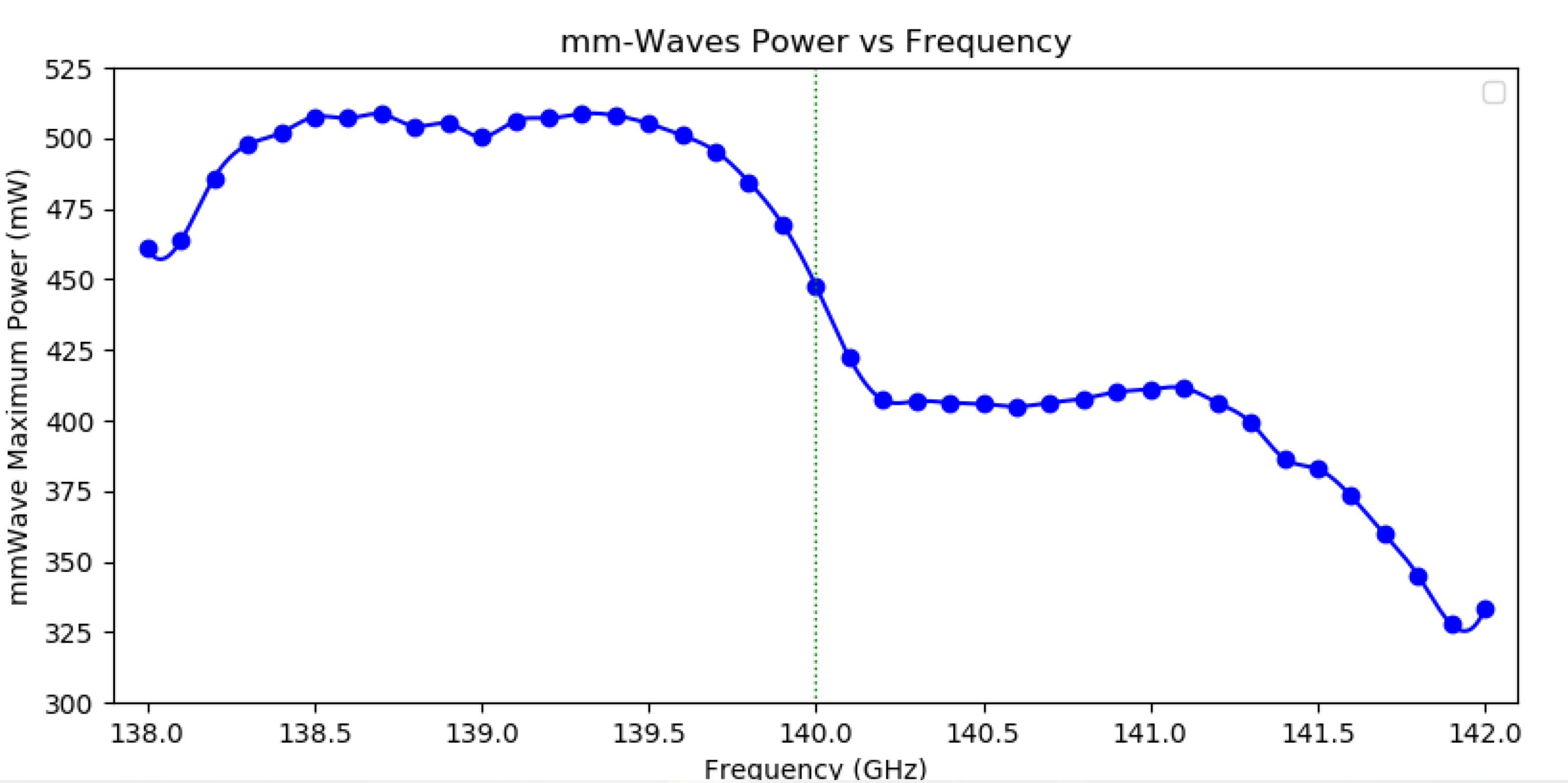
Dynamic Nuclear Polarization (DNP)

- 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.



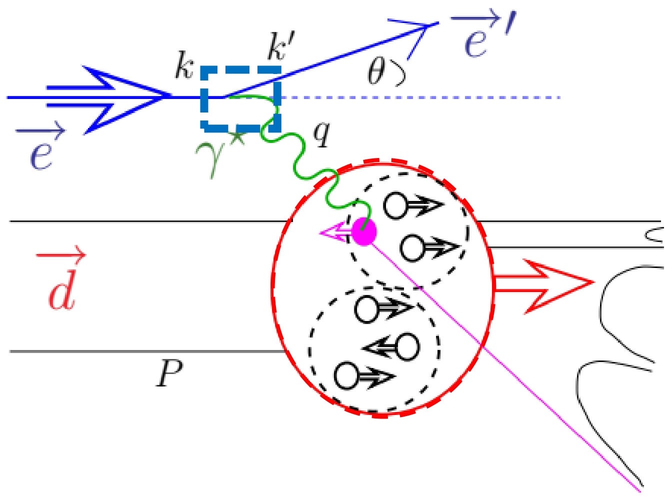
Solid State Effect (SSE)

UNH Solid-State Microwave



- Solid-state microwaves producing > 100 mW power between 136 and 144 GHz.
- This source is moveable by remote motor control.
- This source is designed by Bridge12 inc.
- Cheaper than Extended-Interaction Oscillator (EIO) and it do not need cooling through chiller.
- **Note:** We are also working on EIO for our polarization studies.

b_1 (E12-13-011) and A_{zz} (E12-15-005) Experiment in the Hall C (Jefferson Lab)



Polarized Deep-Inelastic lepton-deuteron reaction. Ref: Link

- The DIS cross-section:

$$\left.\frac{d^2\sigma}{dE'd\Omega}\right| = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

- $L_{\mu\nu}$ is a Leptonic tensor
- $W^{\mu\nu}$ is a hadronic tensor

$W_{\mu\nu}$ = Unpolarized Structure Functions + Spin-dependent Structure Functions + Tensor Polarization Structure Functions

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2\frac{P_\mu P_\nu}{\nu} + i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma}q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma}q^\lambda(p.qs^\sigma - s.qp^\sigma) - b_1 r_{\mu\nu} + \frac{1}{6}b_2(s_{\mu\nu}+t_{\mu\nu}+u_{\mu\nu}) + \frac{1}{2}b_3(s_{\mu\nu}-u_{\mu\nu}) + \frac{1}{2}b_4(s_{\mu\nu}-t_{\mu\nu})$$

$$A_{zz} = \frac{2}{fP_{zz}}\frac{\sigma_T - \sigma_0}{\sigma_0}$$

σ_T: Tensor Polarized Cross-section
σ_0: Unpolarized Cross-section
P_{zz}: Tensor Polarization
f : Dilution Factor

$$b_1 = -\frac{3}{2}F_1^d A_{zz}$$

Physics Motivation:

- Probe the Quark Structure of Spin-1 Nuclei
- Probe exotic nuclear components beyond nucleons
- Understand nuclear medium effects on spin structure