



SFU



Commissioning Progress of PENELOPE at TRIUMF

Dennis Salazar

June 23, 2026

In Collaboration with:



&

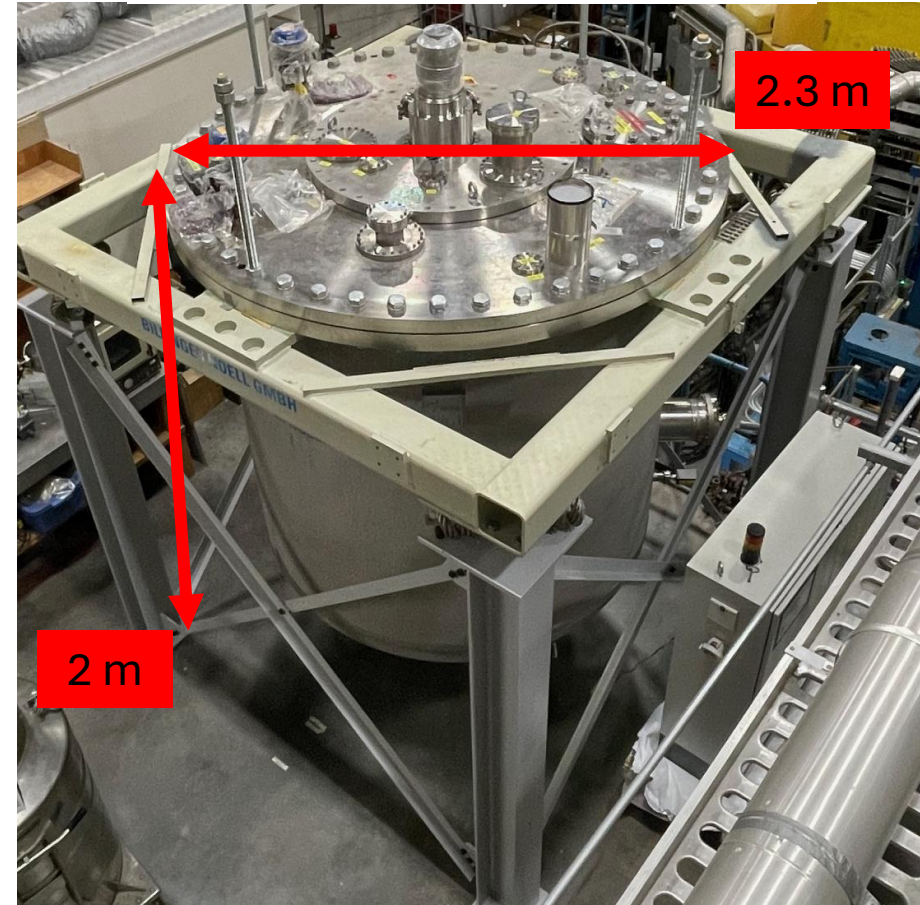
Technical
University
of Munich



PENeLOPE: (Precision Experiment on the Neutron Lifetime Operating with Proton Extraction)

- Precision goal of neutron lifetime measurement: $\Delta\tau = \pm 0.1$ s
- Magneto-gravitational trap (or bottle)
 - Stores ultracold neutrons (UCNs)
- Fabricated and shipped to Technical University of Munich (TUM) in 2020
- Moved to TRIUMF in 2023
- Designed to detect both neutrons and decay protons
 - No other bottle experiments have done this!

PENeLOPE in TRIUMF's Meson Hall



Why Measure a Precise Neutron lifetime?

- Free neutron β^- Decay:

- $n \rightarrow p + e^- + \bar{\nu}_e + 0.783\text{MeV}$

- Weak interaction process \rightarrow determines CKM element V_{ud}

Motivations:

- Standard Model Test

- Verification of CKM Matrix unitarity

- Cosmology:

- Improved predictions of primordial light-element abundances from Big Bang Nucleosynthesis

- Helium-4, Deuterium, Helium-3

- Resolving the Neutron Lifetime Puzzle

- Beam vs bottle discrepancy on measured neutron lifetime values

- Beam: $\tau_n = 887.7 \pm 2.2$ s (Yue 2015)

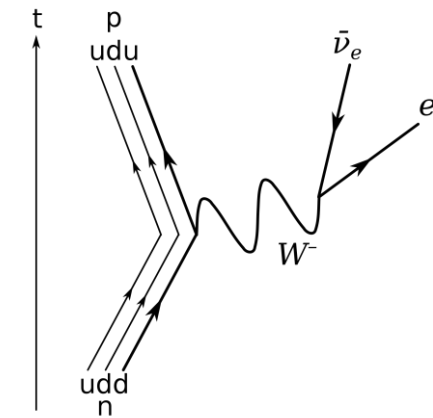
- Bottle: $\tau_n = 878.3 \pm 0.4$ s (PDG average 2026)

- 4 - 5σ discrepancy (~ 9 s) separation between these values

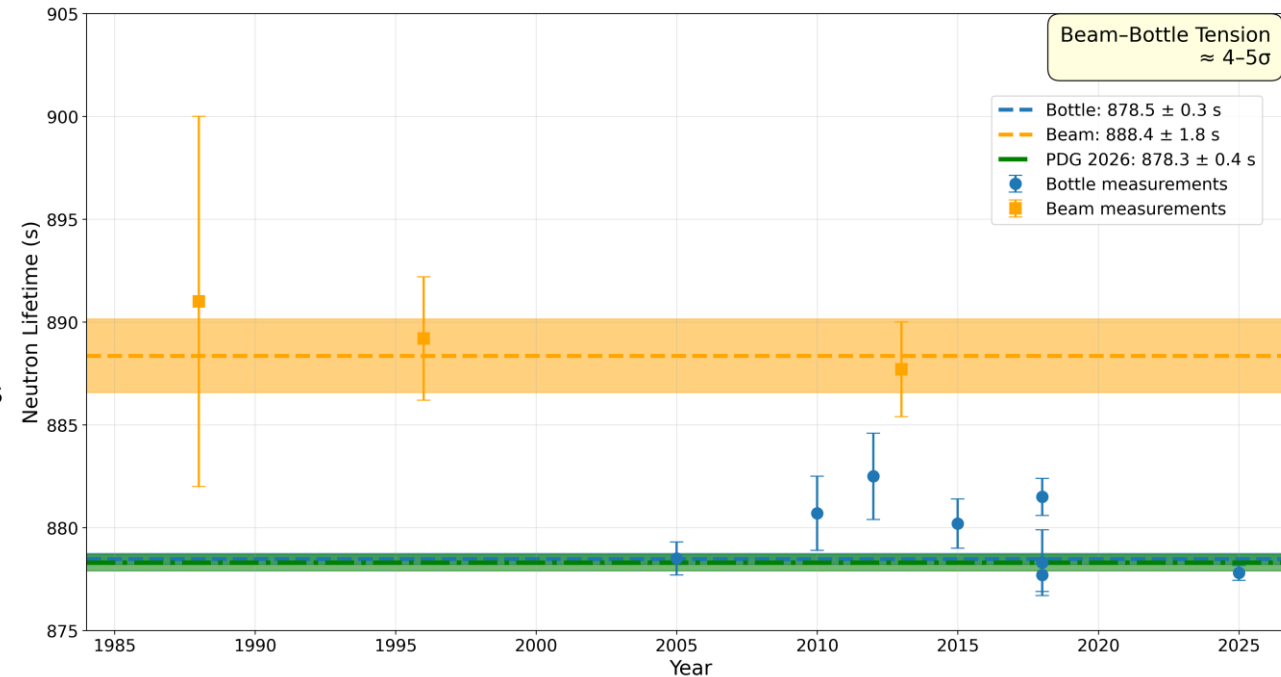
CKM Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

β^- Decay Feynman Diagram

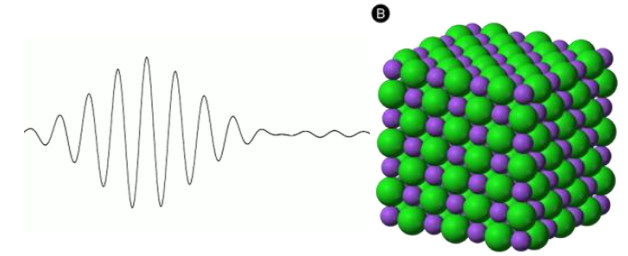


Neutron Lifetime Measurements vs Year



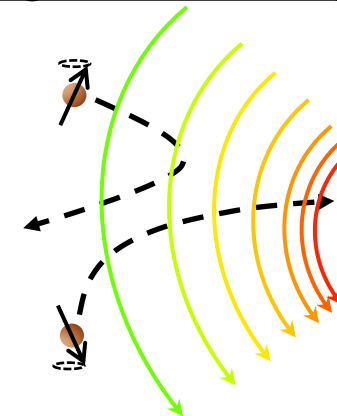
Trapping Ultracold Neutrons (UCNs): Strong Force, Gravity and Magnetism

- Ultracold: $E_{kin} < 300 \text{ neV} \equiv T < 3 \text{ mK}$
- Pseudo Fermi Potential: $V_F = \frac{2\pi\hbar^2}{m_n} N a_B$
 - Reflected at ALL angles of incidence: $E_{kin} < V_F$
- Gravitational potential: $V_g = m_n g h \approx \frac{102 \text{ neV}}{\text{m}} \cdot h$
- Magnetic potential: $V_m = \pm |\mu| |\mathbf{B}|$, $|\mu| \approx \frac{60.3 \text{ neV}}{1 \text{ T}}$
- 2 species of UCN:
 - Low Field Seekers (**LFS**) = Attraction to **lower B field** regions
 - High Field Seekers (**HFS**) = Attraction to **higher B field** regions



Material	V_F (neV)	v (m/s)
Stainless Steel	183	5.92
NiV	227	6.6
Al	54	3.2

Magnetic Field Trapping



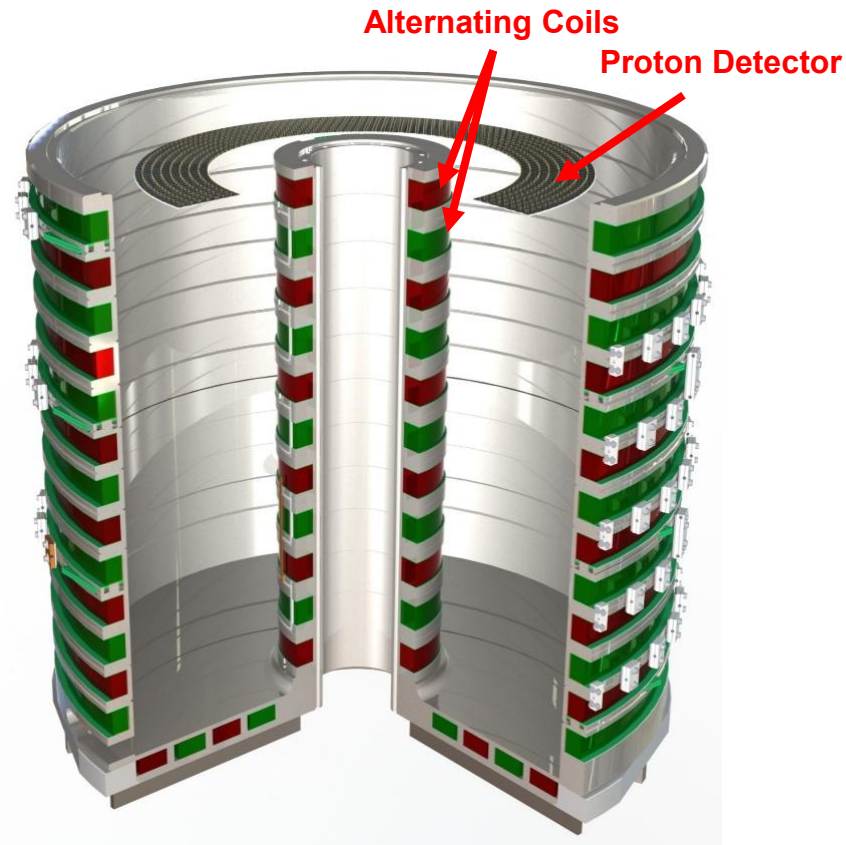
- LFS (+) attracted to **low B field**
- HFS (-) are pulled to **high B field**

a_B – scattering length
 N – number density of atoms
 μ – neutron magnetic moment

PENeLOPE: Magneto-gravitational Trapping

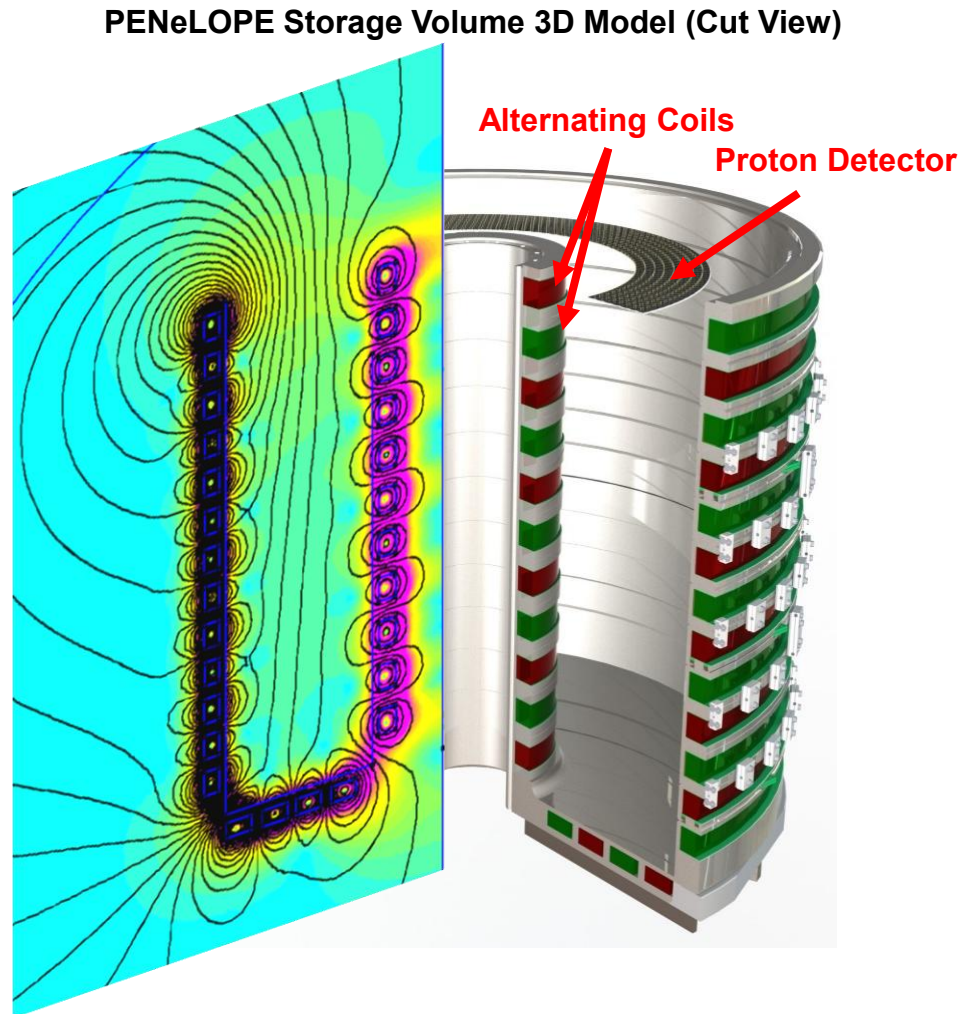
- Magneto-gravitational UCN trap
 - 1.8 Tesla Magnetic Field
 - ~ 110 neV UCN trapping potential
- Superconducting winding coils create the magnetic field
- Using gravity as a lid:
 - Put proton detector at top
- **Low Field Seekers (LFS)** under trapping potential are stored

PENeLOPE Storage Volume 3D Model (Cut View)



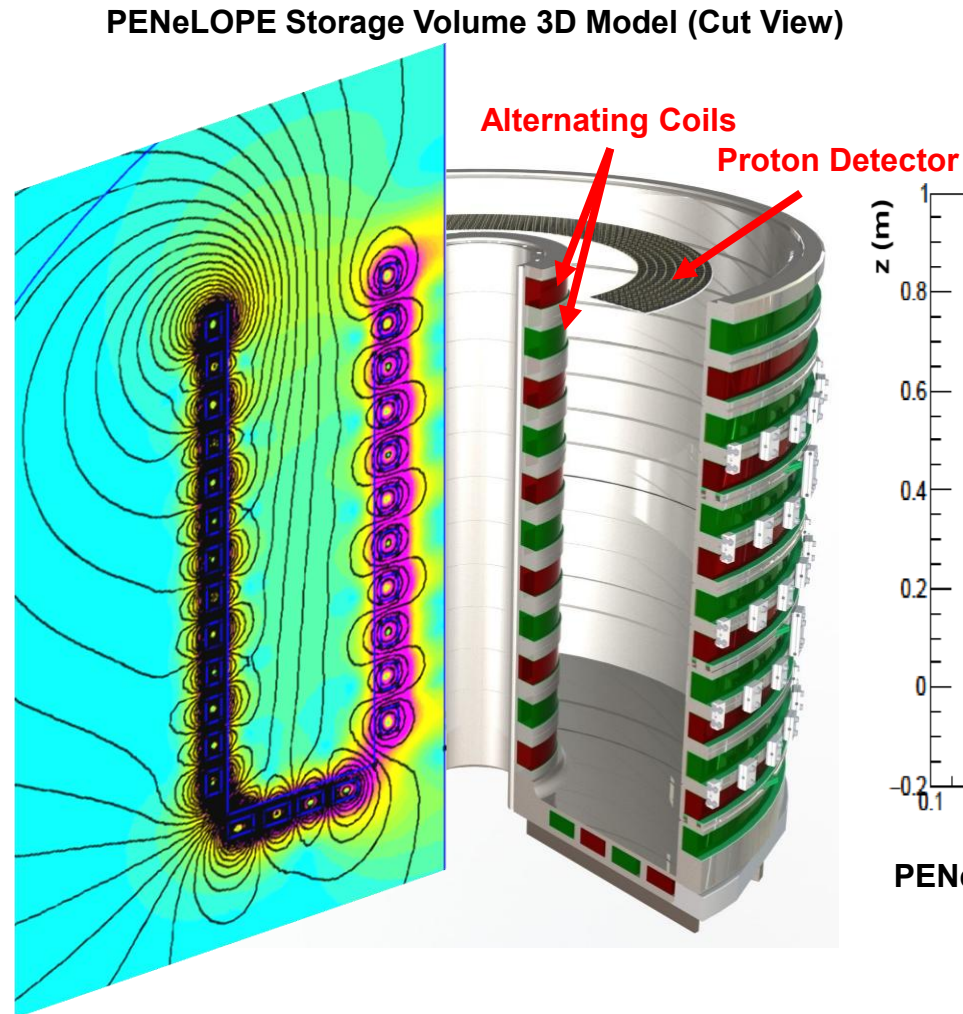
PENeLOPE: Magneto-gravitational Trapping

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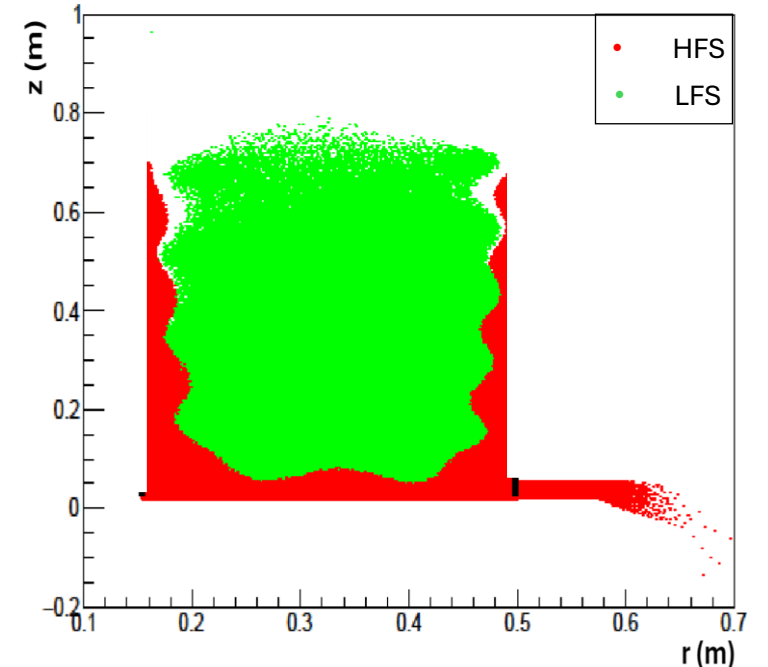


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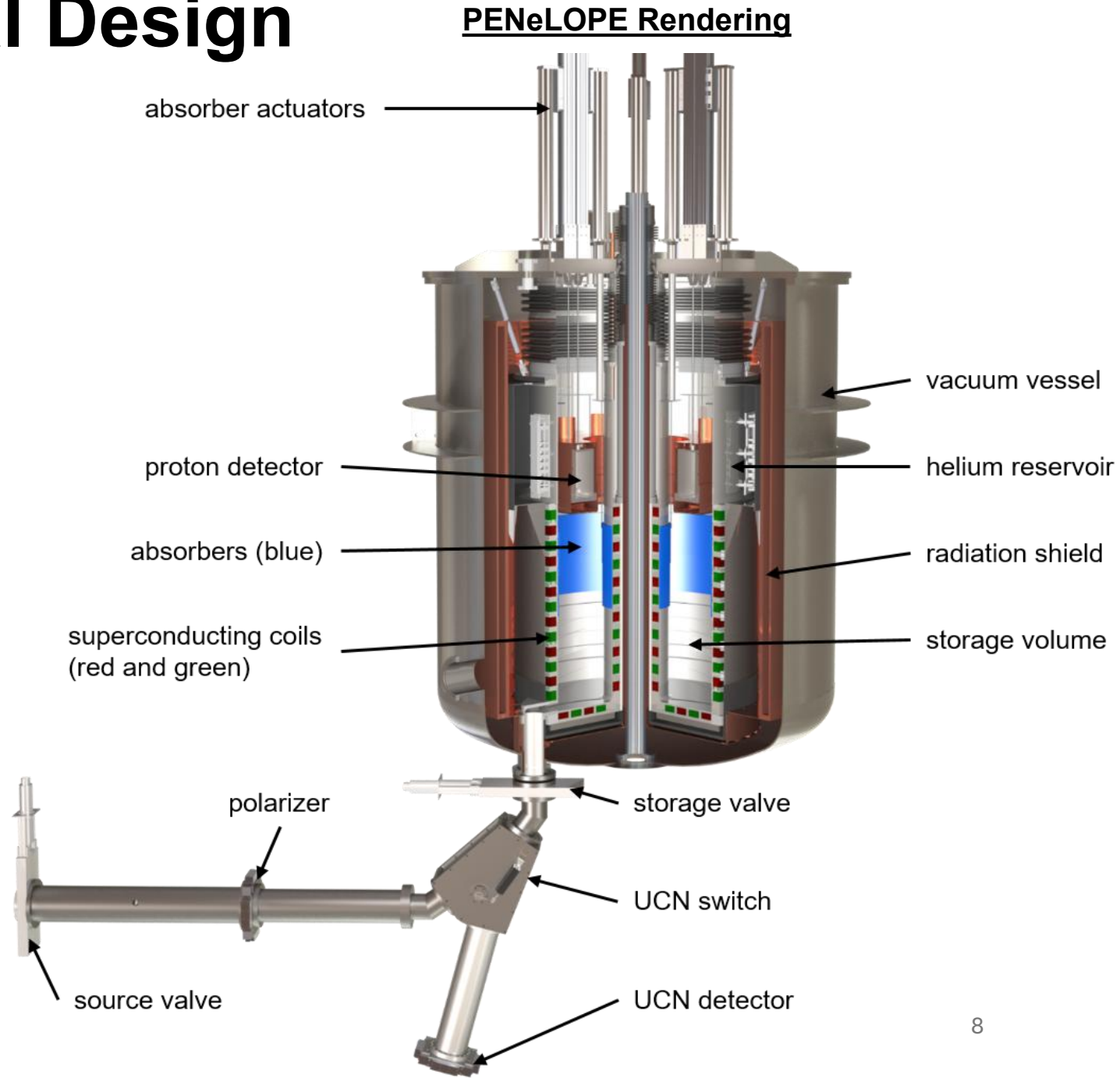
LFS – Low field seeker UCNs
(+) polarization
HFS – High field seeker UCNs
(-) polarization



PENeLOPE - Side Projection (Height vs Radius)

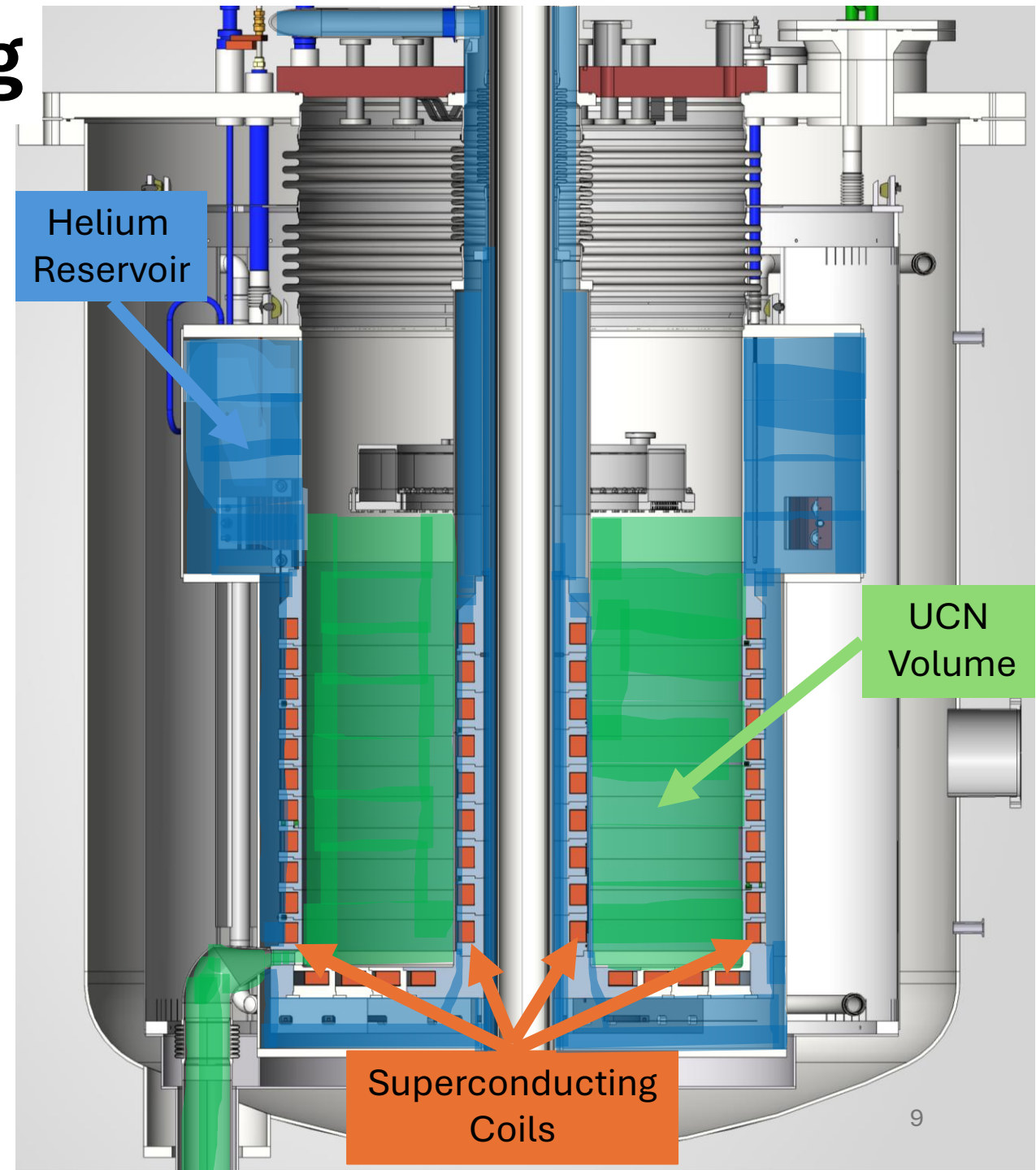
PENeLOPE: Conceptual Design

- **Fill:**
 - Fill UCN storage volume from a source
 - Maximize stored LFS population
- **Store:**
 - Turn on magnetic field
 - Keep **LFSs** + Take out **HFSs**
 - Count decay protons
- **Count:**
 - Turn off magnetic field
 - Empty storage volume using gravity
 - Count with UCN detector



PENeLOPE Commissioning

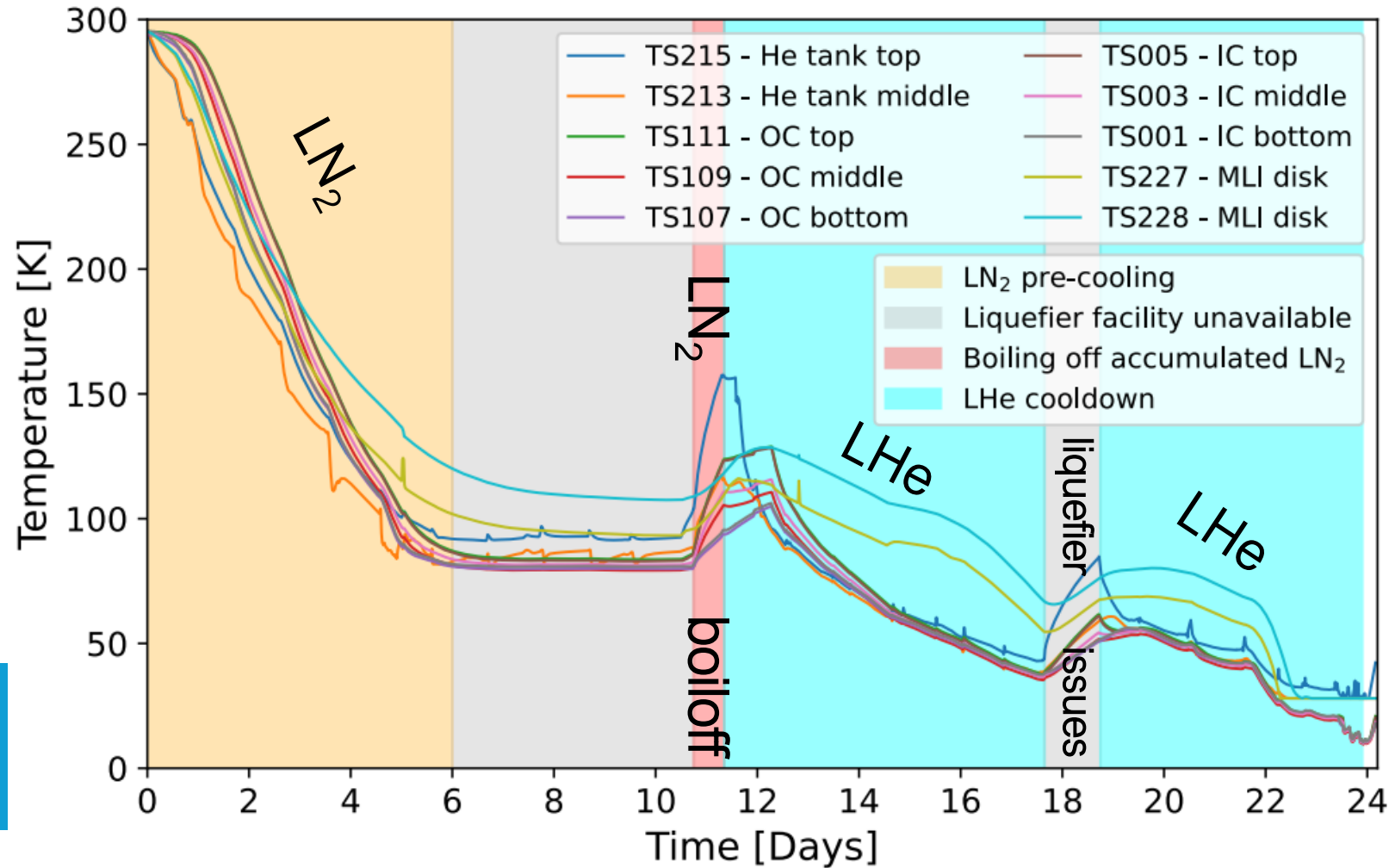
- Before measuring the neutron lifetime w/ PENeLOPE, we need to:
 1. Verify cryostat works
 - Cooldown the superconducting coils to 4.7 K
 2. Produce magnetic field
 - Find coil operating current
 3. Verify UCN yield
 - Fill, Store, Count UCN
- We are still on step 1...



PENeLOPE: 1st Cooldown at TRIUMF

- Cooled to ~ 9.7 K
 - Stopped cooldown due to excess heat load entering the system
- Problem: Vacuum deterioration in UCN volume
 - Suspected cause:
Icing on lid from Helium exhaust walls

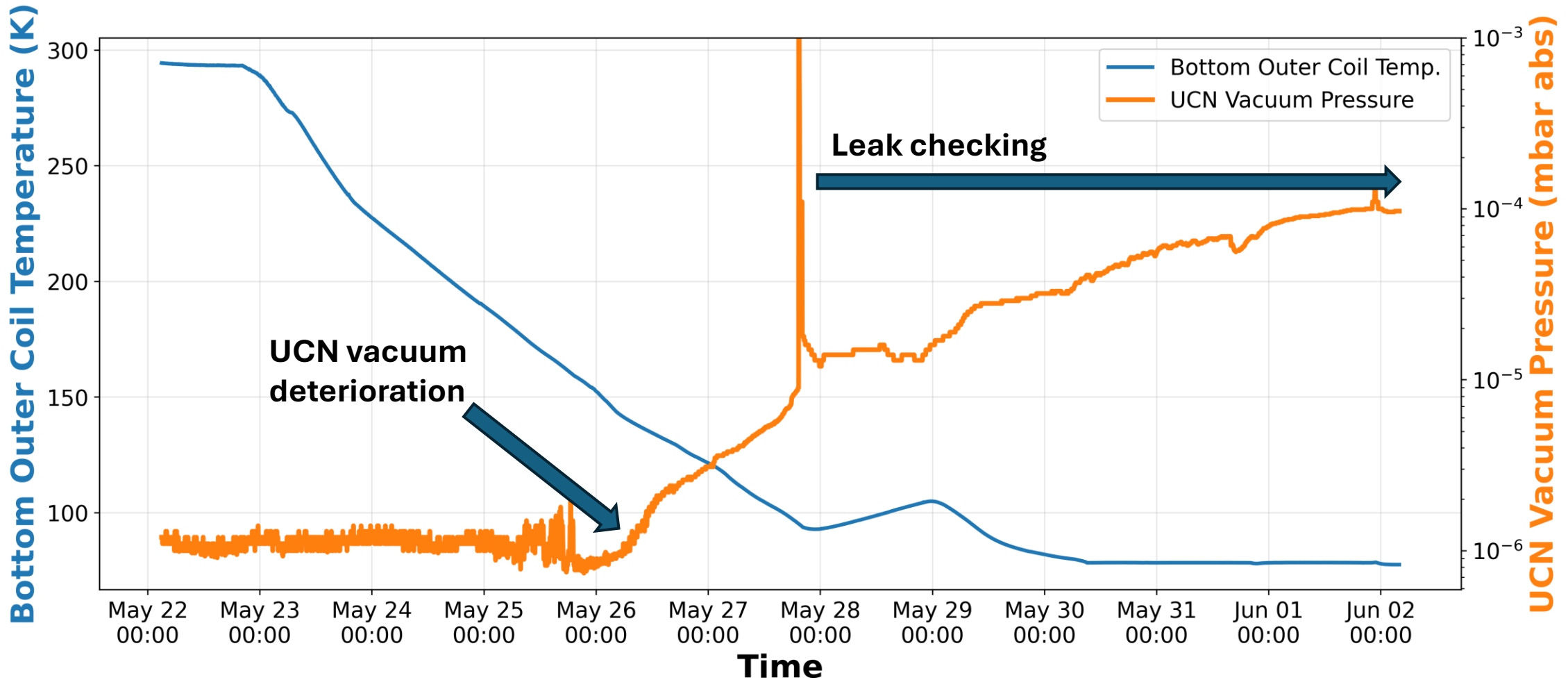
PENeLOPE Lid



PENeLOPE: 2nd Cooldown (w/Nitrogen)

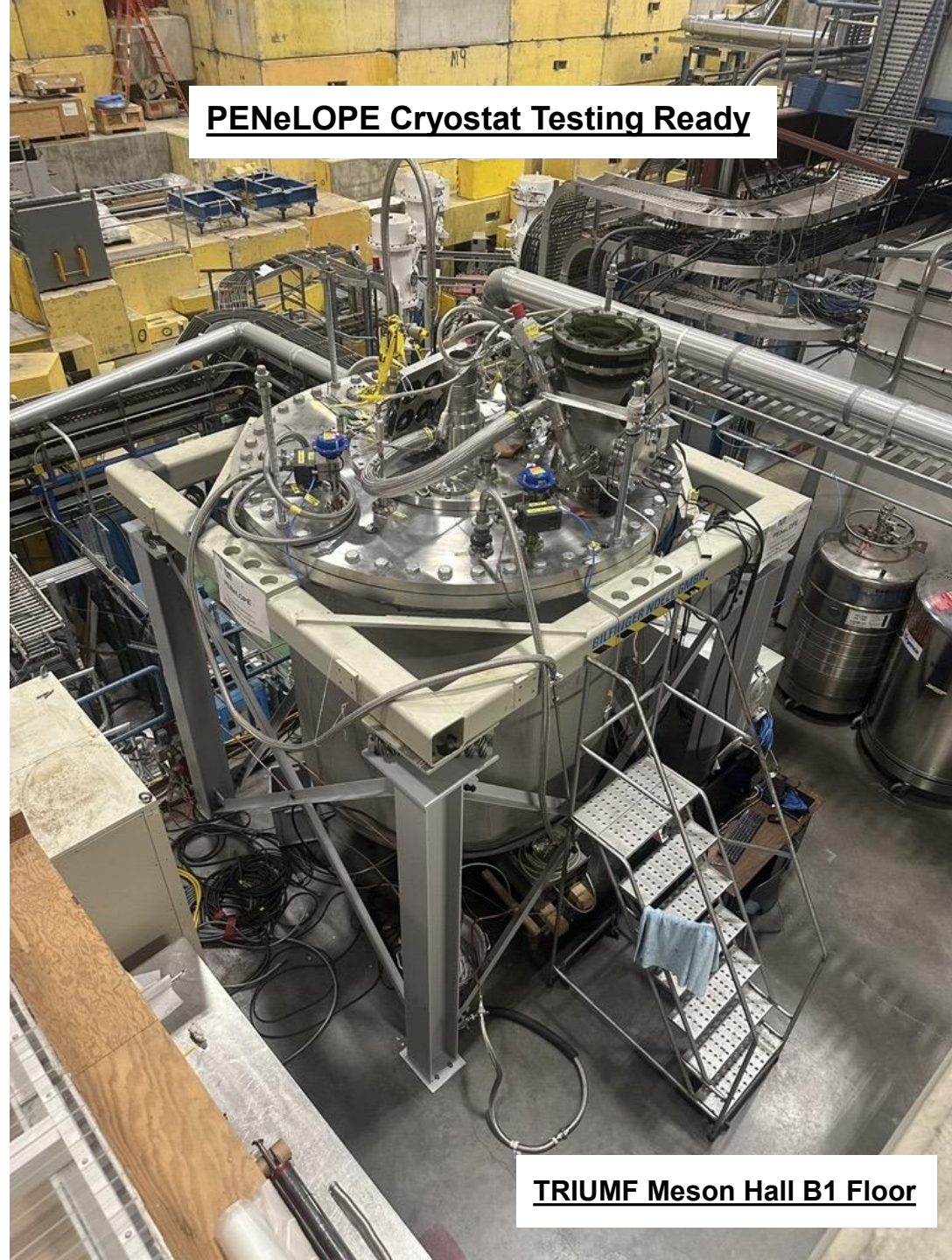
- Helium reservoir temp. at 140 K, UCN volume started deteriorating
- Cooldown failed at Nitrogen temperature
- Suspecting a leak between UCN volume and Helium Reservoir

2nd Cooldown: Bottom Outer Coil Temperature and UCN Vacuum Pressure



Conclusion

- PENeLOPE is a magneto-gravitational UCN trap experiment
- Measure neutron lifetime to a precision of ± 0.1 s
- Commissioning starts with cryostat testing:
 1. Find problem with cryostat
 2. Repair cryostat
 3. Produce magnetic field
 4. Trap ultracold neutrons
 5. Measure neutron lifetime



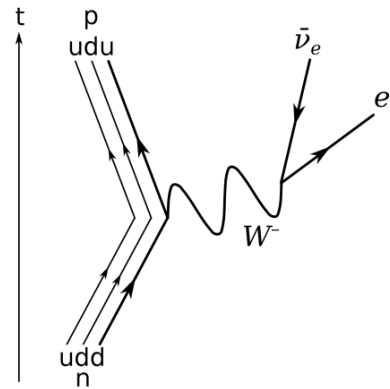
- Extras

Why a Precise Neutron lifetime?

- Free neutron β – Decay:

$$n \rightarrow p + e^- + \bar{\nu}_e + 0.783\text{MeV}$$

- Mediated by the weak force
- down quark transition to an up quark (flavor change)



- Cabbibo-Kobayashi-Maskawa (CKM) Matrix:
 - Mixing between 3 flavors of quarks

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- From Fermi's Golden Rule:

$$|V_{ud}|^2 = \frac{10^3}{0.1897(1 + 3(\frac{g_A}{g_V})^2)(1 + 0.0739(8))} \cdot \frac{1}{\tau_n} \text{ s}$$

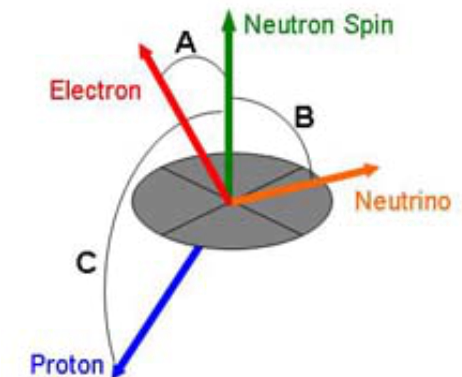
- Unitarity in CKM (1st row):

- Check to see if **only** 3 generations of mixing occurs
- 3σ deviation from unitarity

Quark Generations

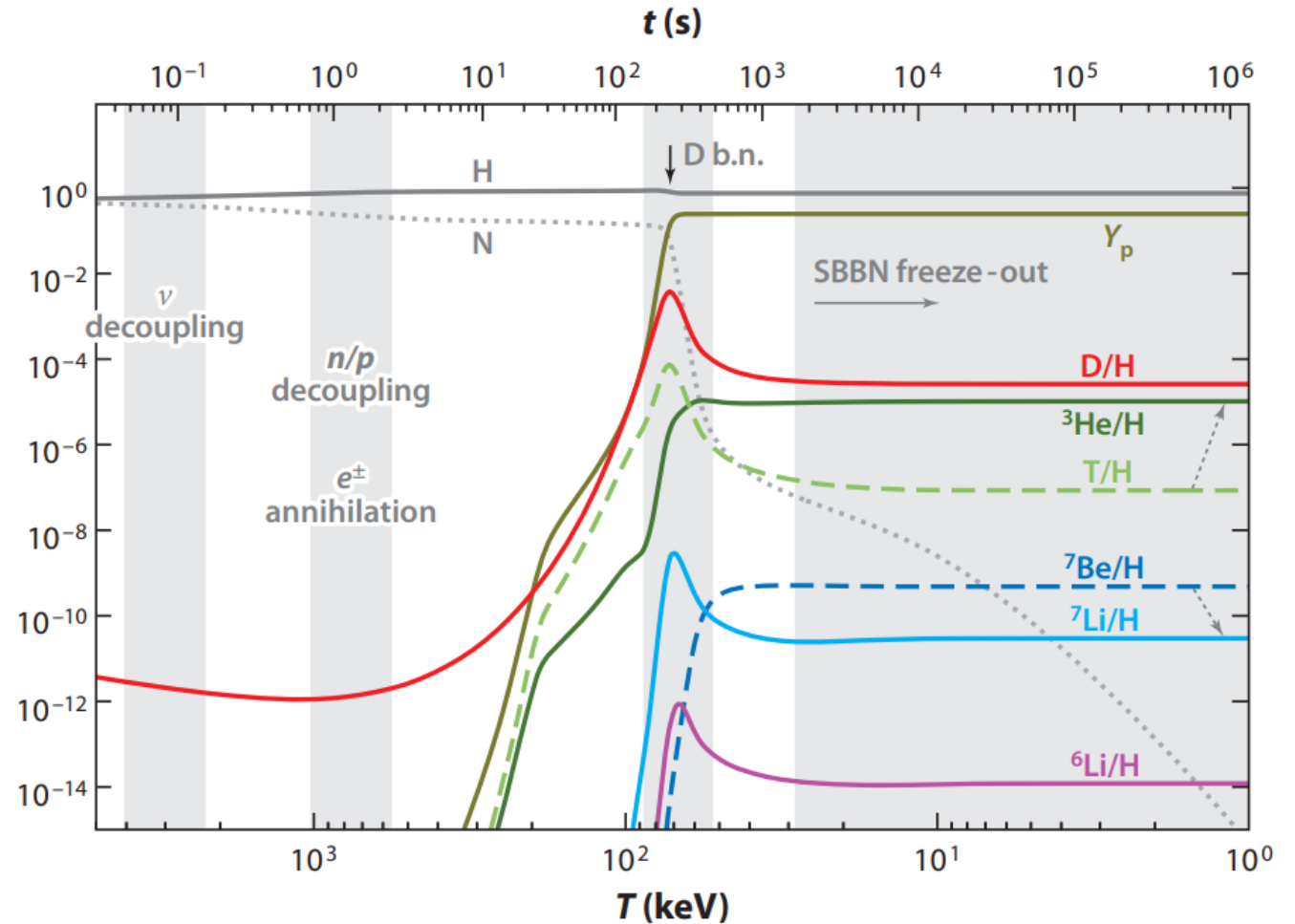
	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	U up	C charm	t top
	d down	s strange	b bottom
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$

β – asymmetry studied for coupling constants



Why a Precise Neutron lifetime?

- Big Bang Nucleosynthesis
 - After ~ 1 second, neutrons and protons decouple
- Neutron abundance decreases as neutrons undergo β - Decay
 - Light elements produced at ~ 500 s depend on neutron abundance

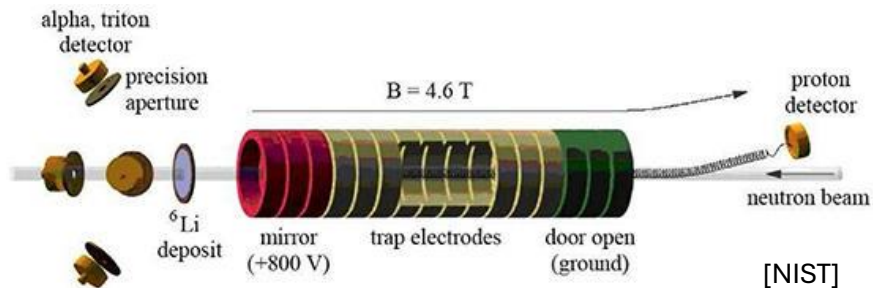


Standard Big-Bang nucleosynthesis of the most abundant primordial nuclei

Finding Neutron Lifetime: Beam vs Trap Experiments

Neutron Beam Measurements

- Direct a beam of cold neutrons down a long volume
- Capture decay protons using magnetic fields and count them

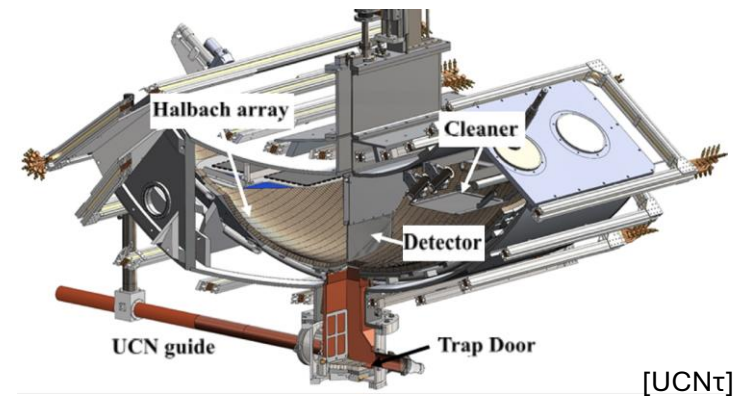


Best measurement: Yue 2013

$$\tau_n = 887.7 \pm 2.2 \text{ s}$$

Neutron Trap Measurements

- Store neutrons in a container
- Counts surviving neutrons after waiting for some time



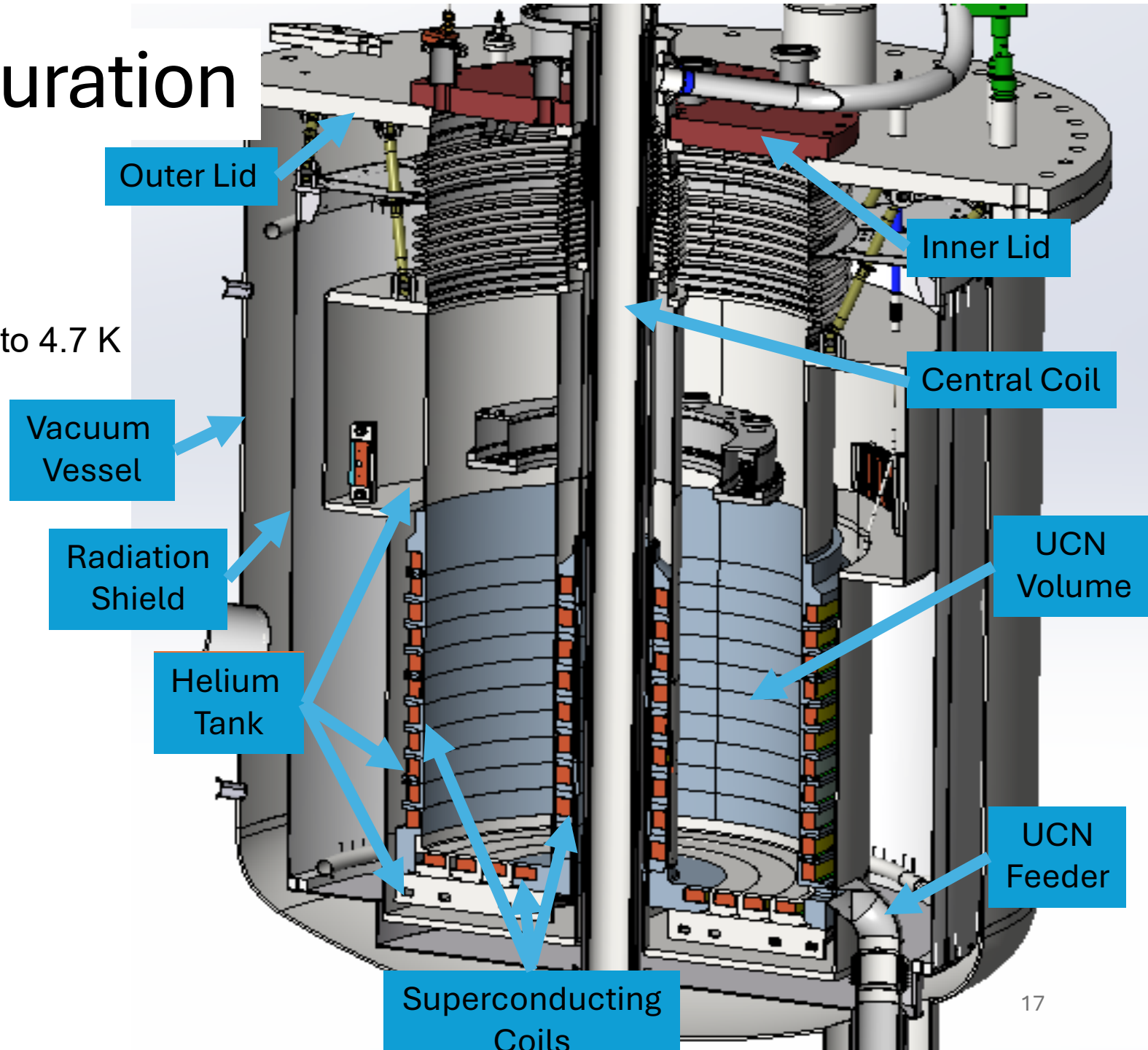
- PDG (2026) has updated its average to include only trap measurements!
- $\tau_n = 878.3 \pm 0.4 \text{ s}$

τ_n – neutron lifetime

PENeLOPE Configuration

- For starting a neutron lifetime measurement we need to:

1. Cool the superconducting coils to 4.7 K
2. Produce magnetic field
3. Fill and Store UCN



PENeLOPE UCN Storage Volume

Stainless Steel Surfaces

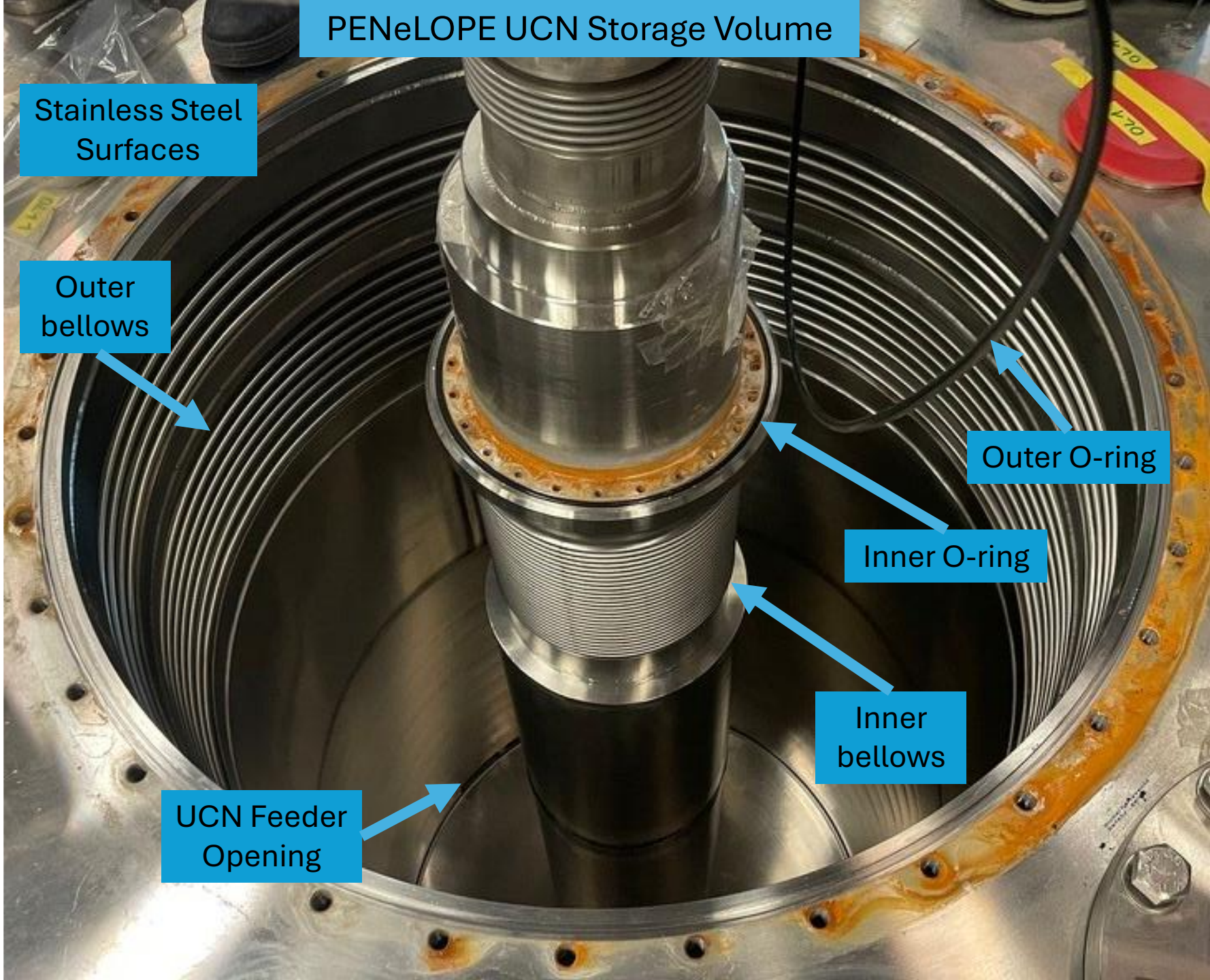
Outer bellows

Outer O-ring

Inner O-ring

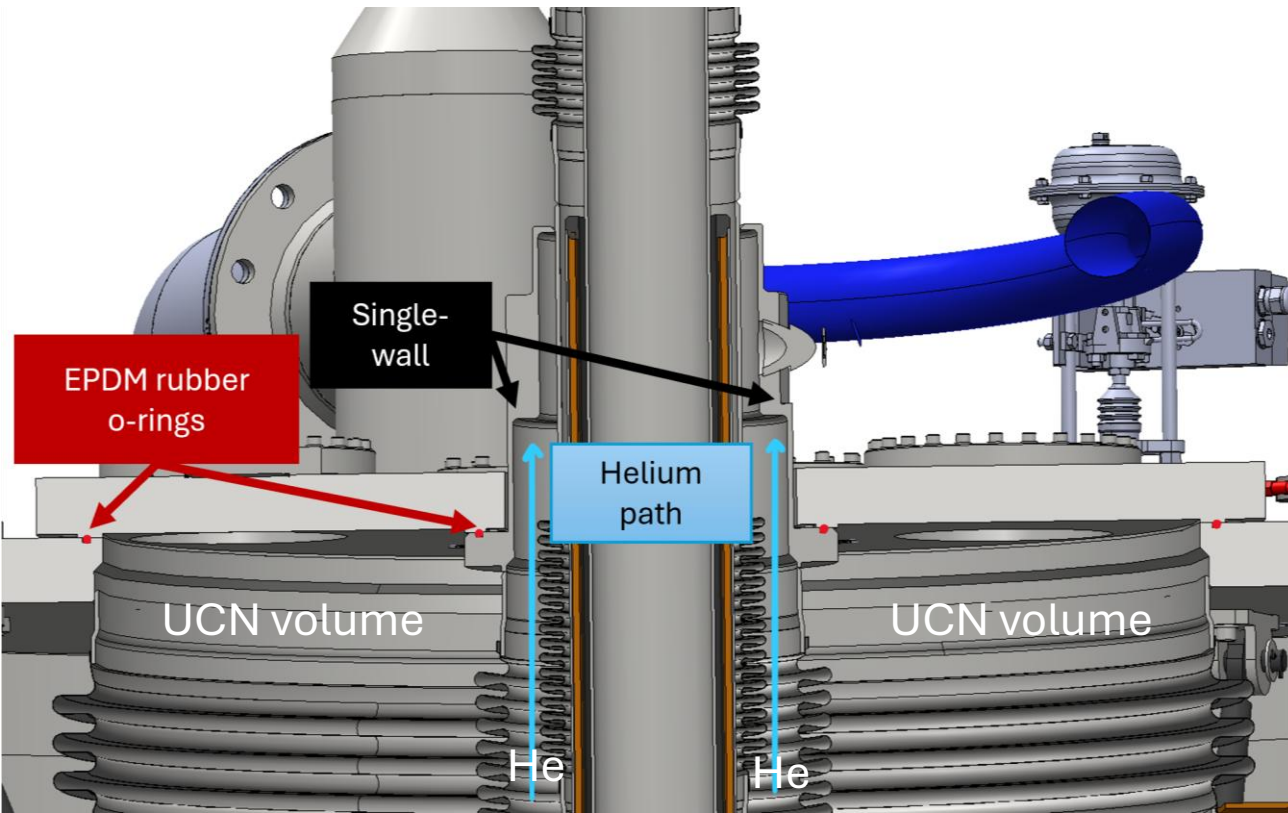
Inner bellows

UCN Feeder Opening

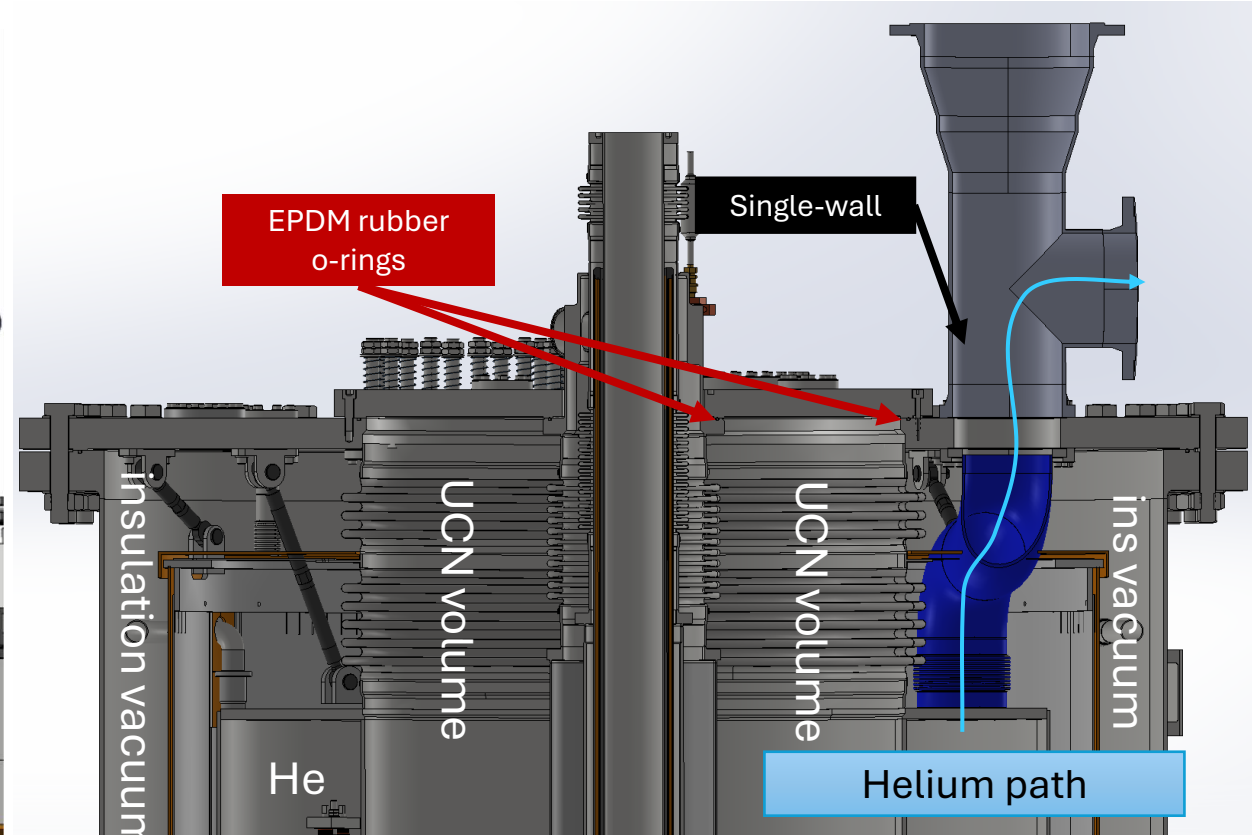


PENeLOPE: Cryostat Design Issues

- Single wall He vents -> Icing -> nearby o-rings compromised -> vacuum deteriorates



Central Channel

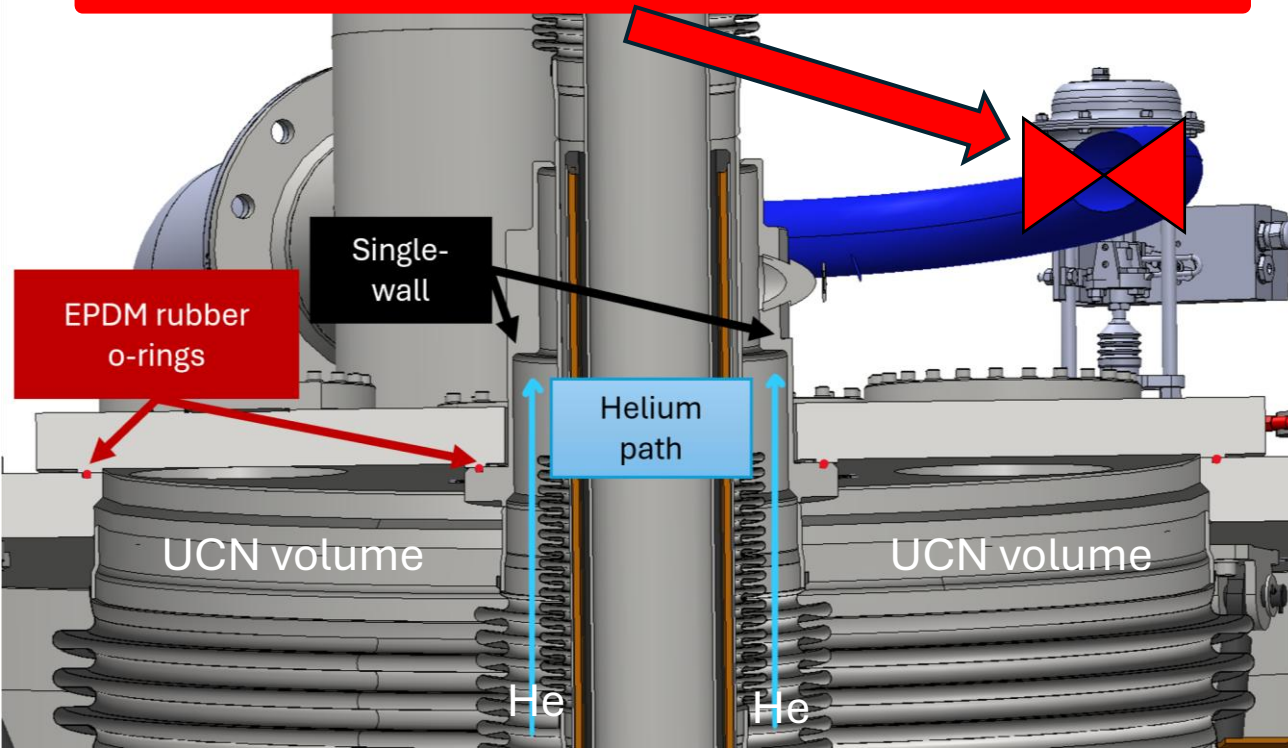


Outer Turret

PENeLOPE: Cryostat Fixes after 1st Cooldown

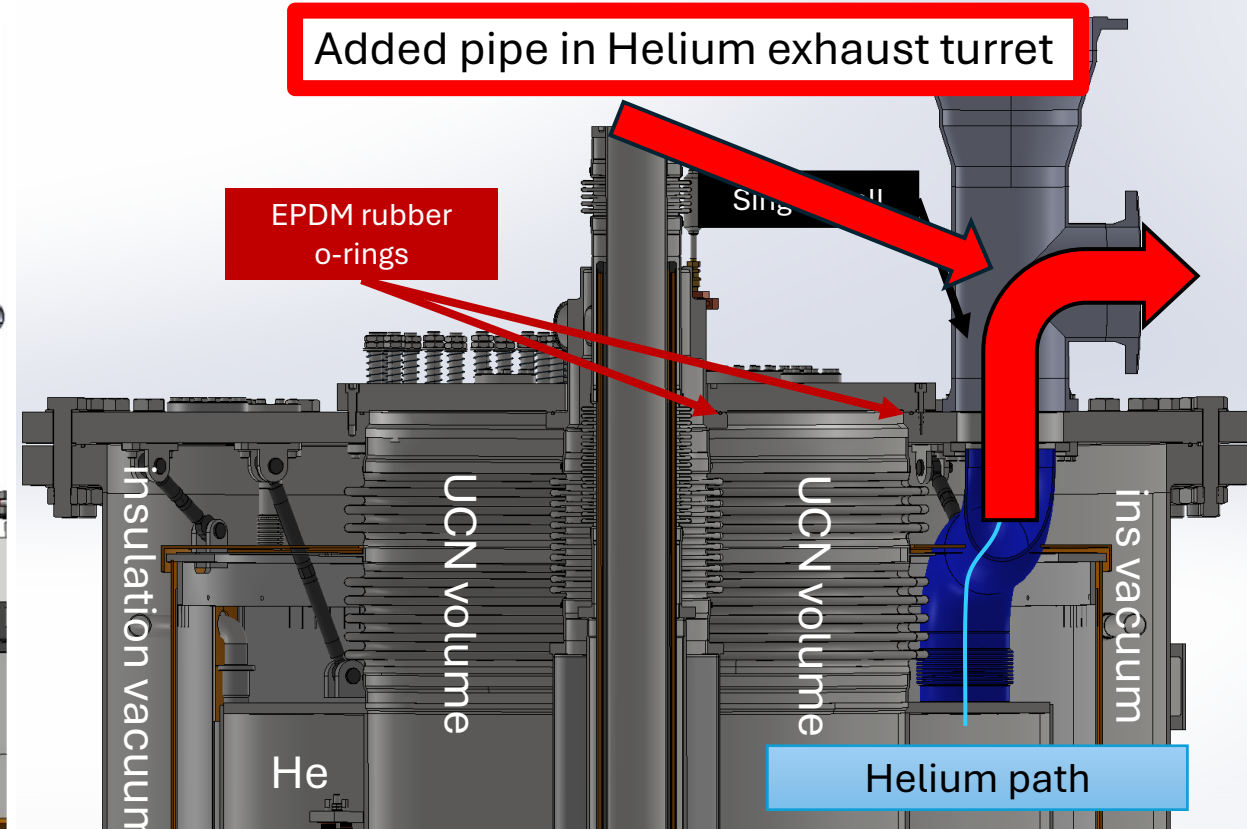
- Central Channel path blocked: Vapor lock
- Outer Turret: Add Second Inner Pipe to have a “double wall exhaust” path

Installed manual valve to central channel Helium path



Central Channel

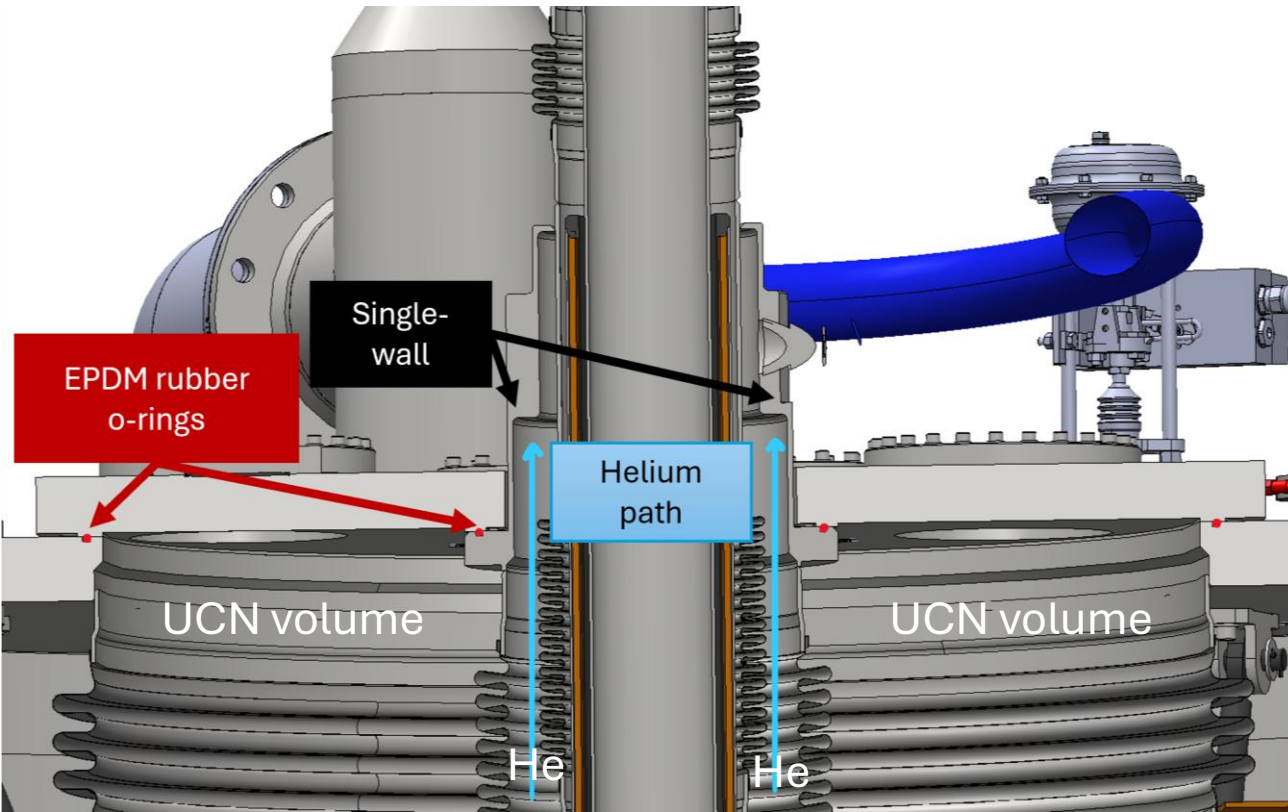
Added pipe in Helium exhaust turret



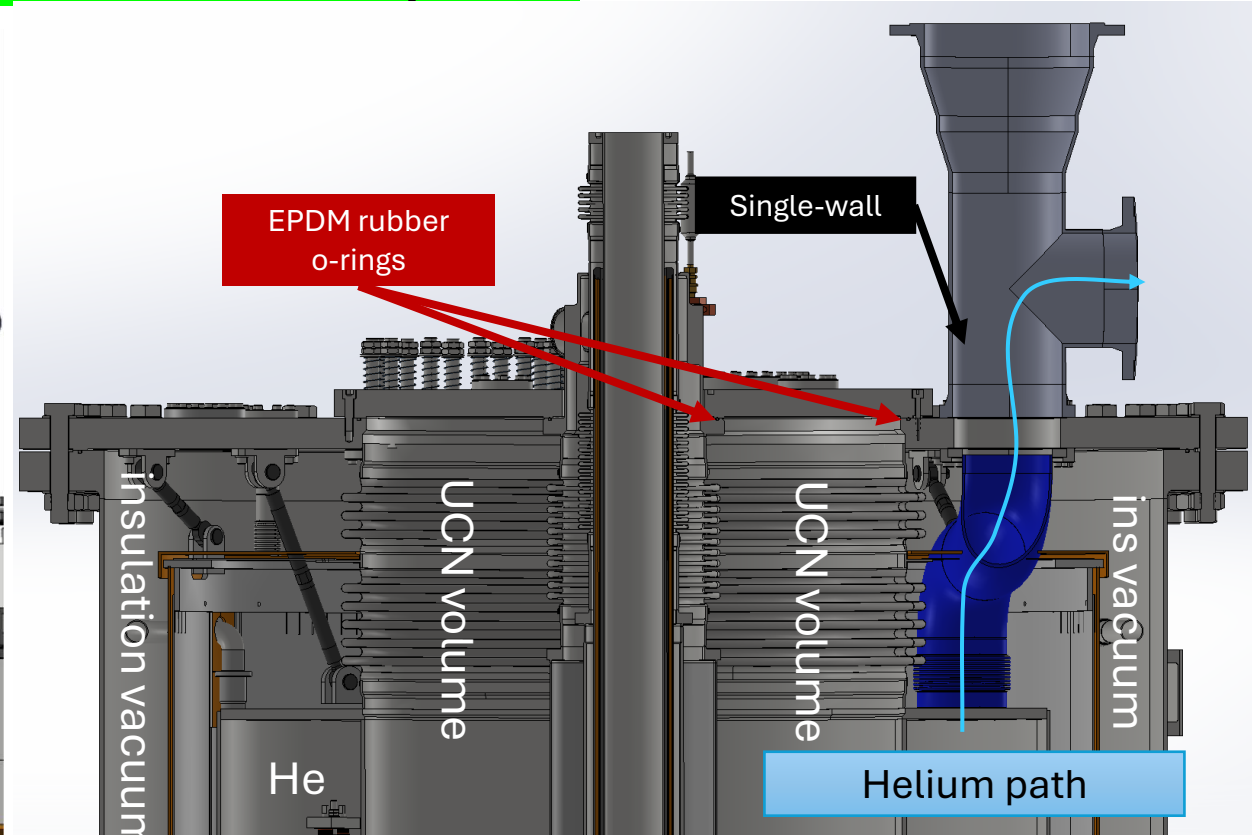
Outer Turret

PENeLOPE Cryostat Issues

- Single wall He vents -> Icing -> nearby o-rings compromised -> **vacuum deteriorates**
- **The icing issues have been resolved with Helium path modifications.**
- Leak checked o-rings at RT and at 140 K, **No leak checker response!**

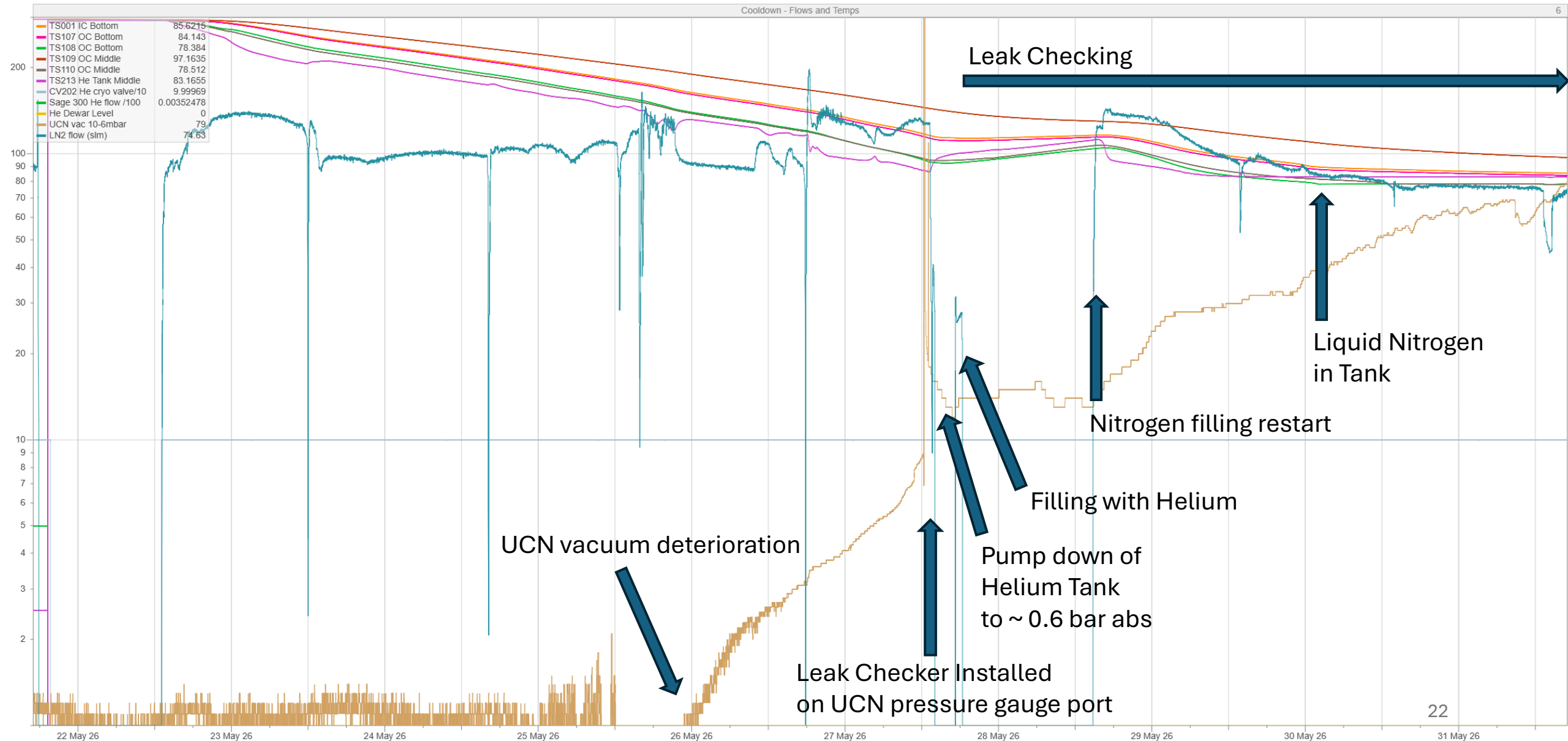


Central Channel



Outer Turret

PENeLOPE 2nd Cooldown 2026 (w/Nitrogen)

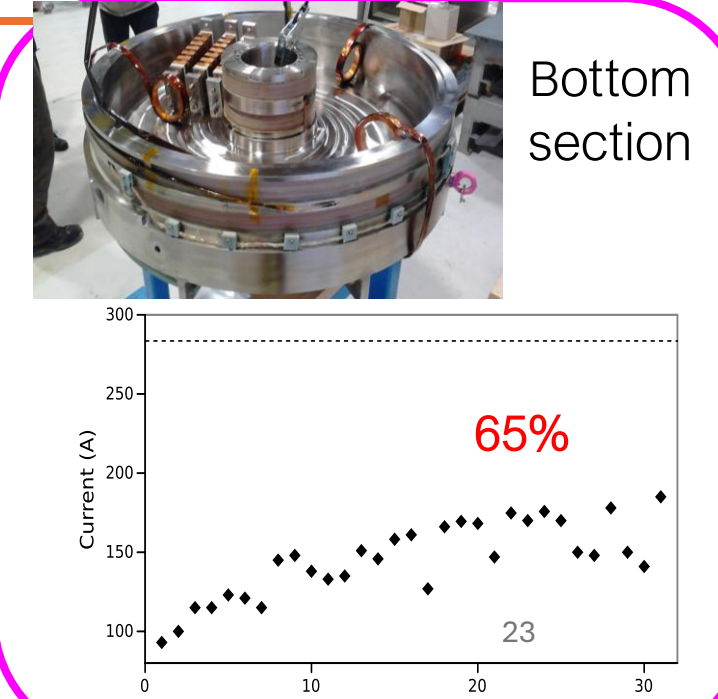
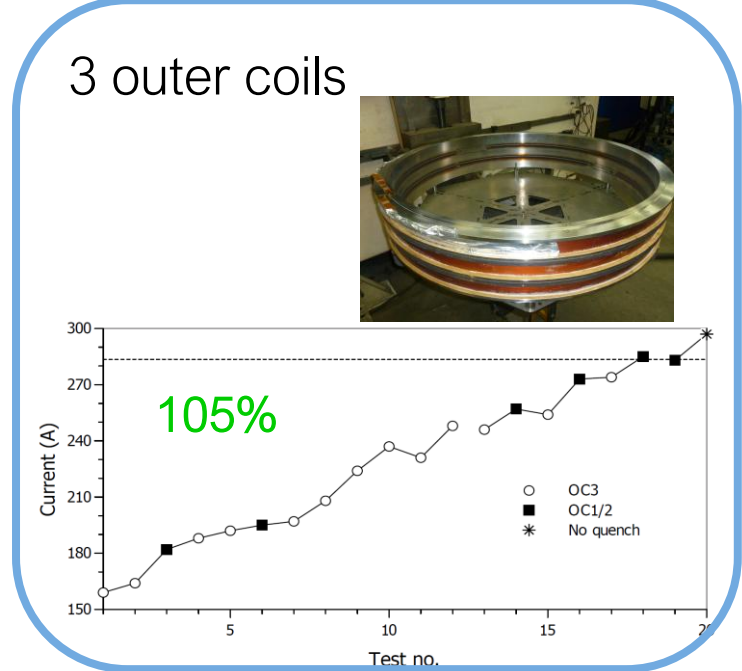
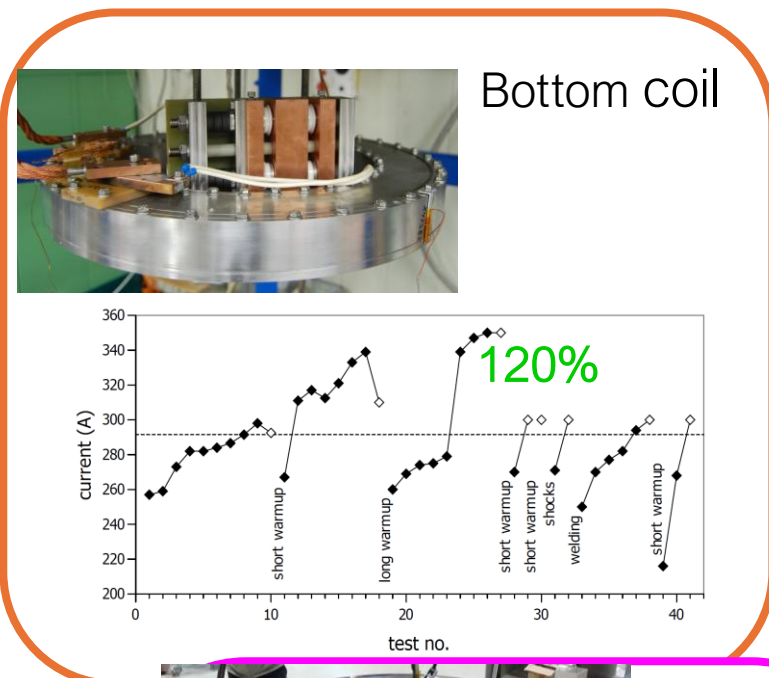
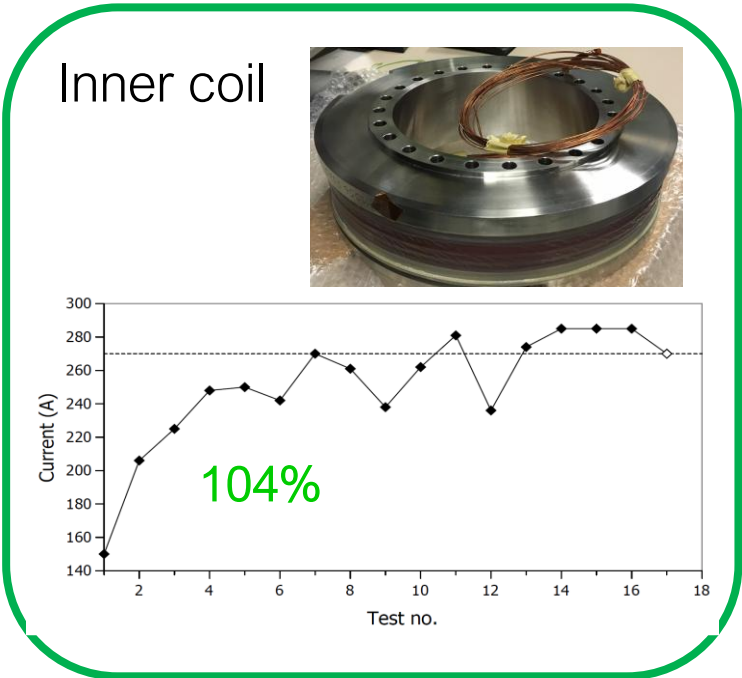


PENeLOPE: Past Developments

- Prototype coil tests
 - Quench training – coil conditioning
 - Cooldown coils to operating temperature (< 4.7 K)
 - Energize coils so they are physically stable
 - Finds maximum operating current reachable by hitting a quench plateau

- Ideal operating current is 283 A
 - Maximum magnetic field of 5.5 T at coils
 - Produces usable 1.8 T magnetic field in UCN storage volume

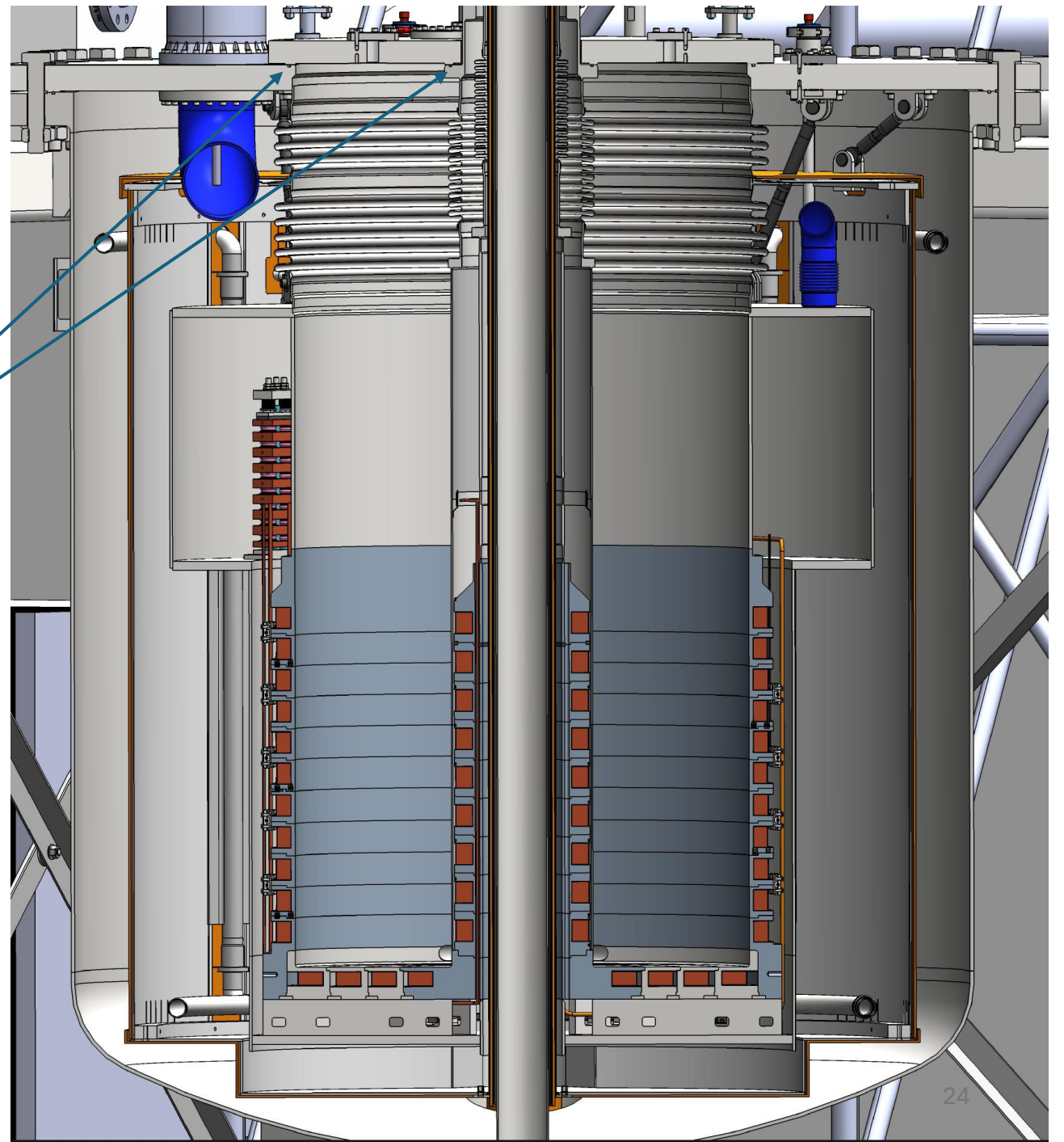
• The Bottom Section plateaued at 65 % of ideal operating current



PENeLOPE Ice on Lid

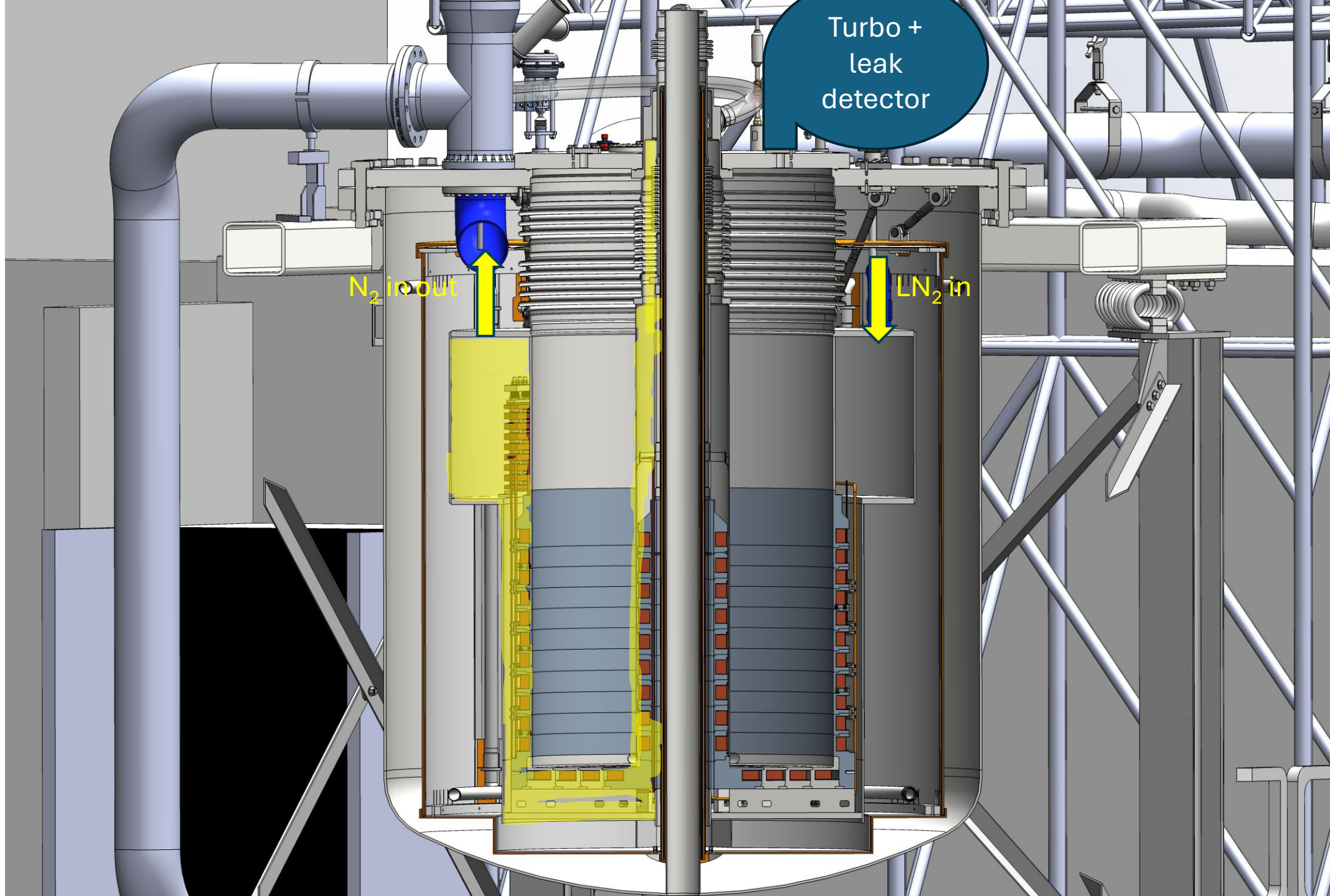
UCN Volume lid

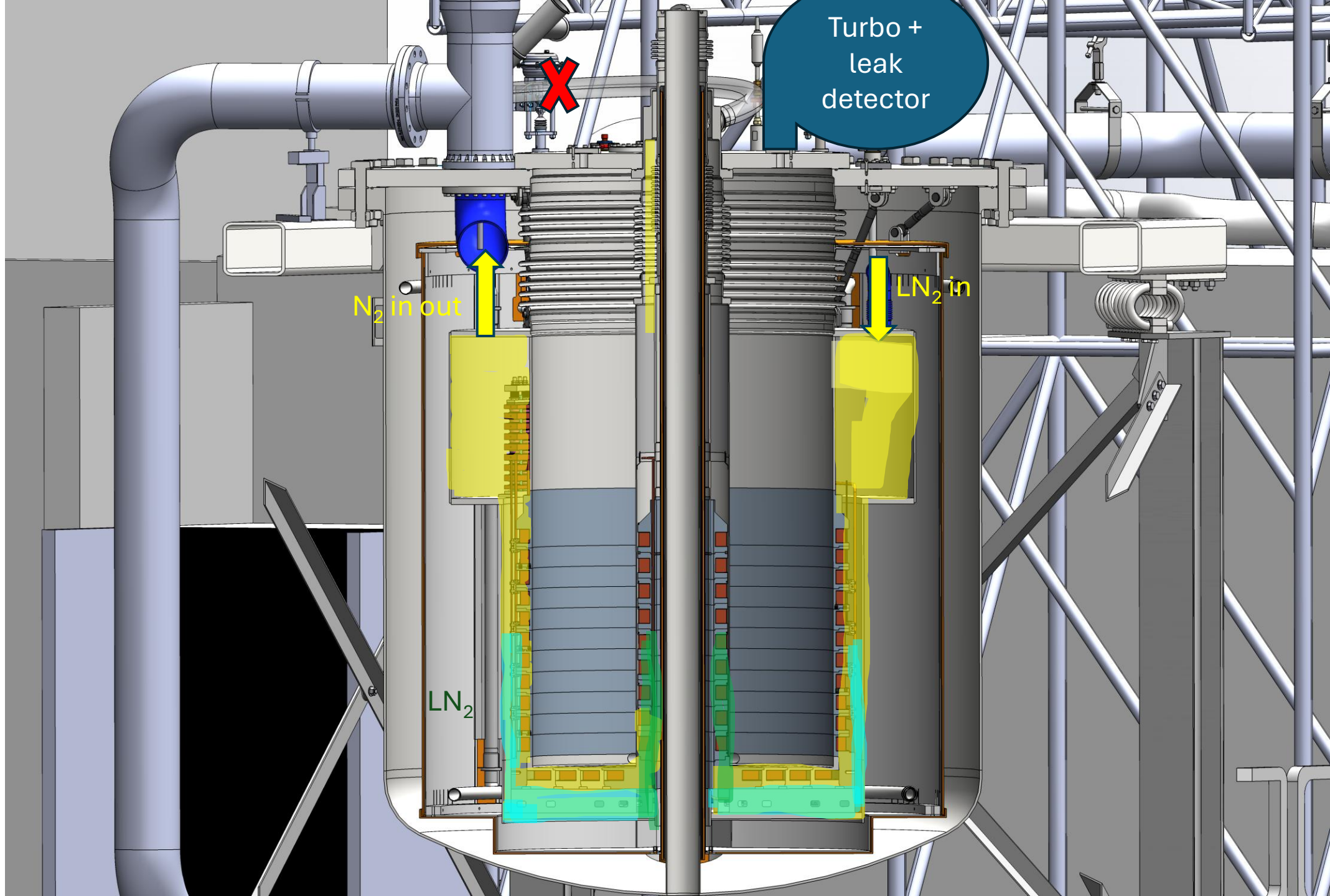
- Inner and outer seals
- EPDM o-rings



Outline

- Why study neutron lifetime precisely?
 - CKM unitarity test
 - Big bang nucleosynthesis (narrowing down the scale of early universe light element abundance)
 - Beam vs bottle discrepancy (neutron lifetime puzzle)
- PENeLOPE high level
 - UCN volume, UCN feeding, storing with magnetic fields in the volume, need liquid helium to get to superconducting levels of magnetization
- PENeLOPE low level
 - Operating magnet, ~260 A current in NbTi coils, chosen operating temp 4.7 K, UCN volume evacuation, Helium Tank filling.
- Previous Cooldowns – TUM, TRIUMF, precooling stage
- Cryostat Failure + Fixes
- 2026 Cryostat cooldown (LN2 in HeTank = Precooling with condensing)
- 2026 Cooldown and UCN volume vacuum failure – possible cold leak
- Current Tests while cold, leak checking.
- (Extra: trapping UCN, CKM unitarity, beta asymmetry parameters for lambda measurement ($g_A = g_a/g_v$), UCNtau, # of PENeLOPE runs needed to 0.1s, Beam vs bottle, previous studies on energizing coils with CoTEX)





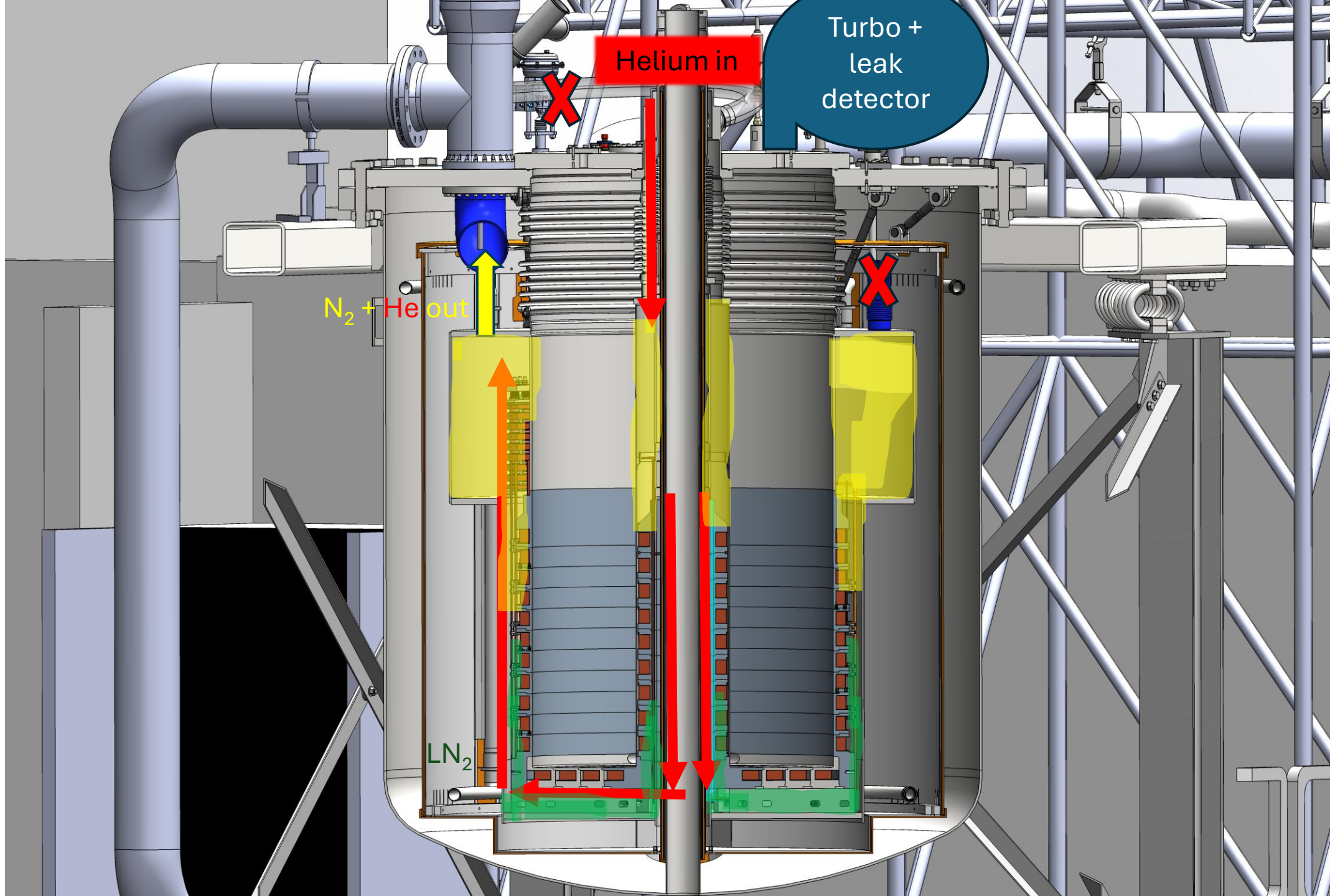
Turbo +
leak
detector

X

N₂ in out

LN₂ in

LN₂



Leak Checking @ 140 K Coil Temperatures

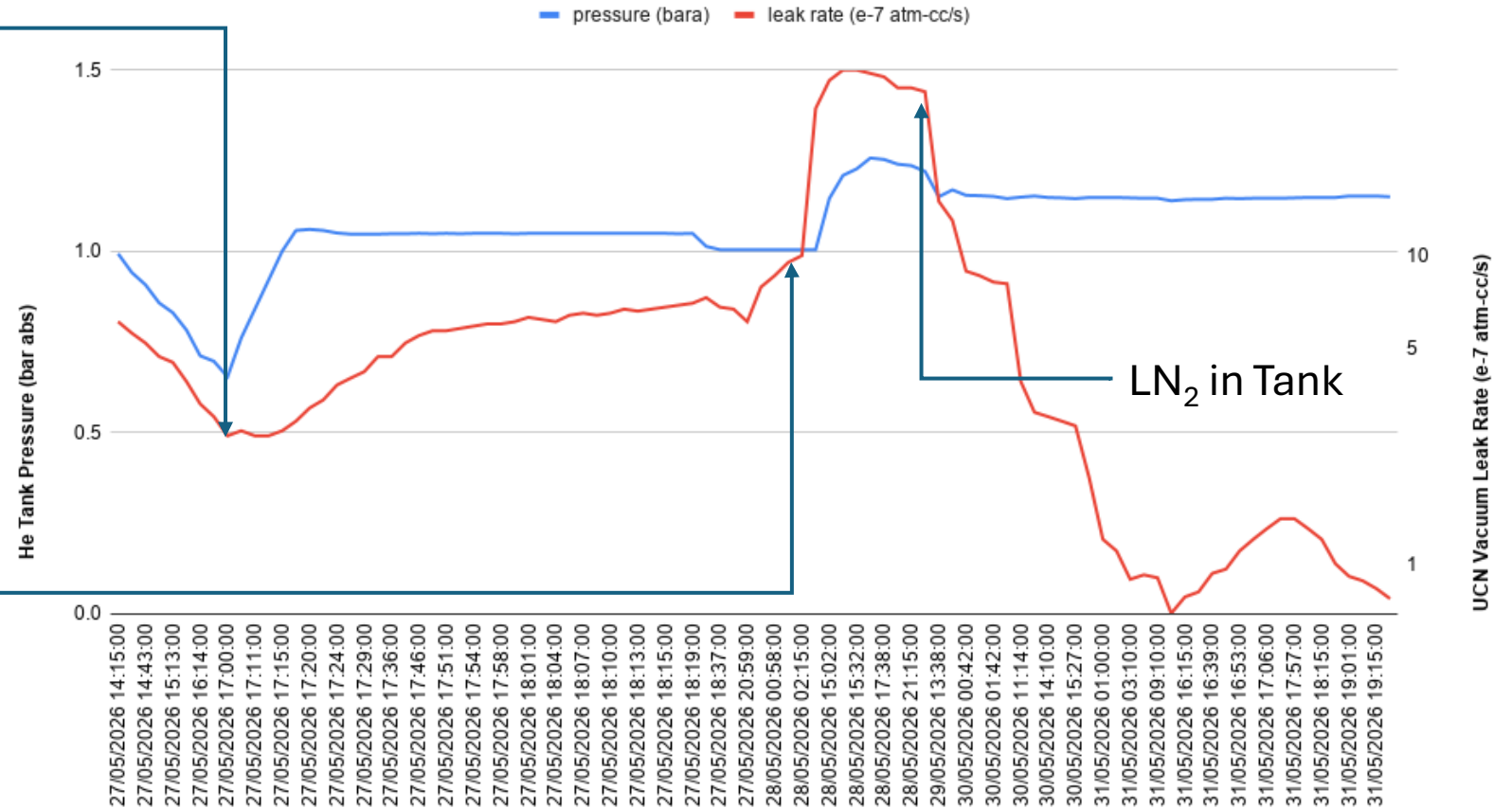
- Helium Injection

- May 27 17:00
~1000 l

- LN2 Filling Restart

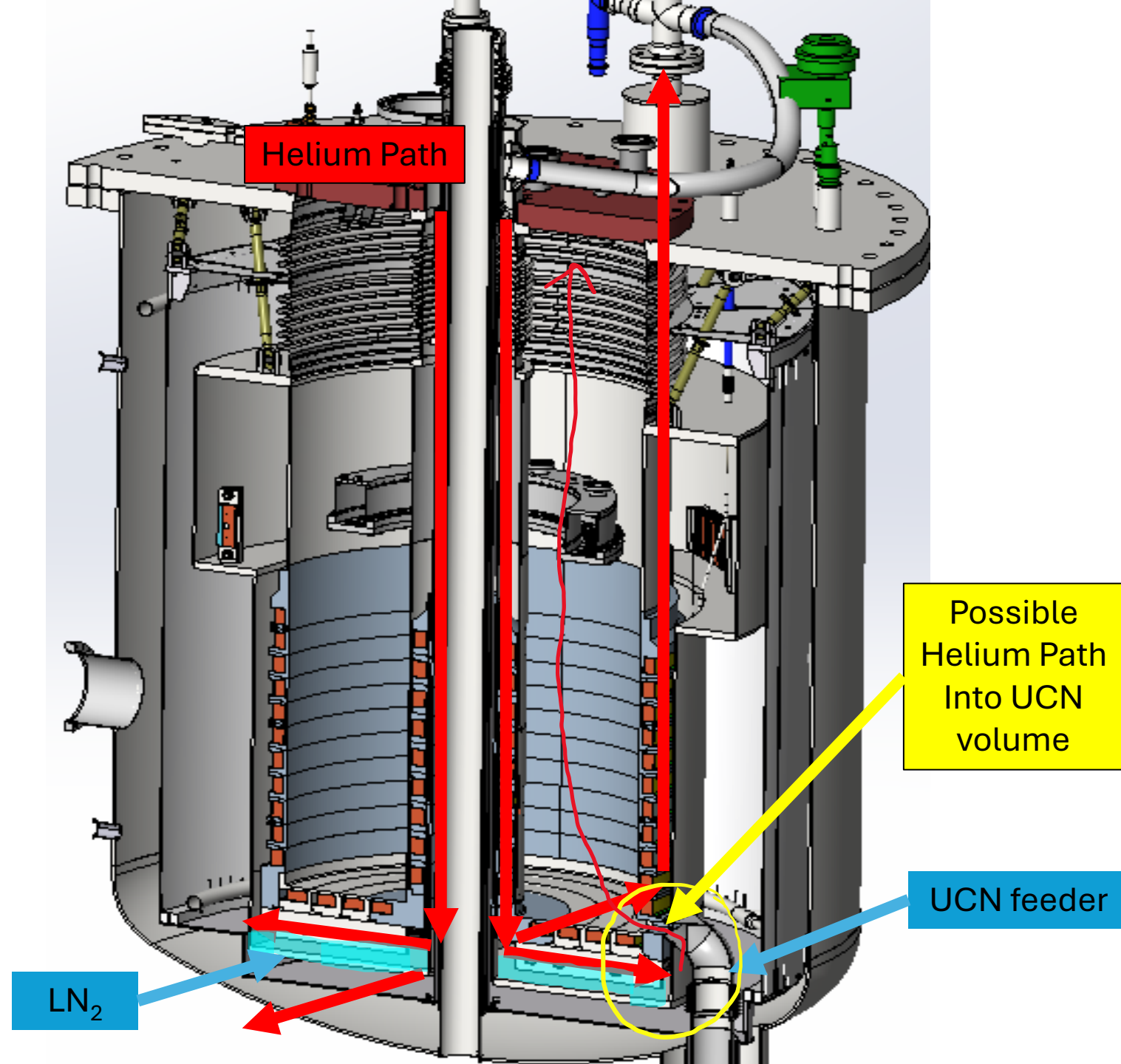
- May 28 14:40

Leak Rate and HeTank Pressure vs Time

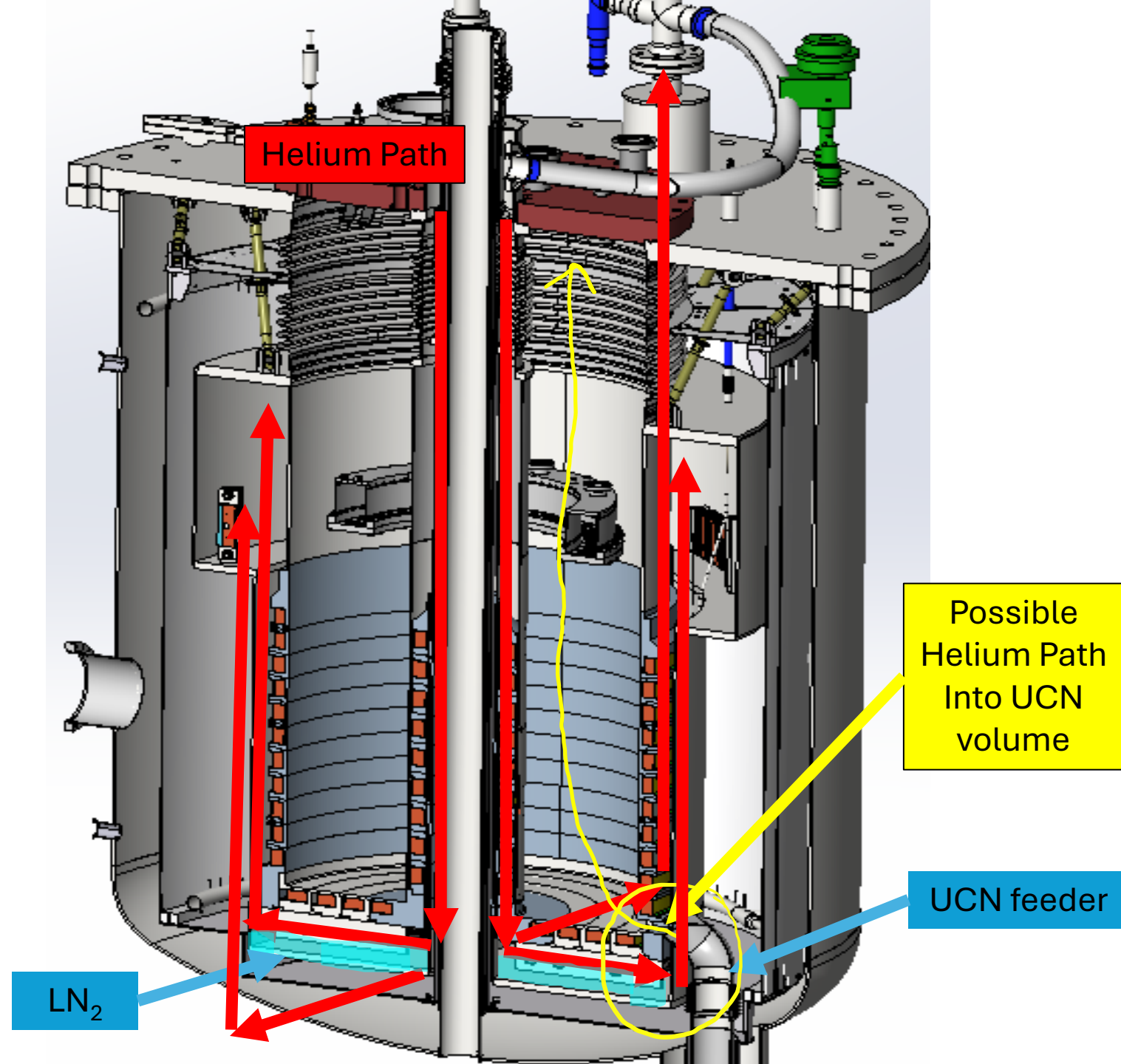


*Leak Checker Installed in parallel to turbo pump

- Liquid Level under UCN Feeder
- Lower initial BG leak rate of $2.6e-8$ atm-cc/s
- UCN Volume pressure decreasing slowly from $1.1e-3$ mbar abs
- Helium Injection = BG leak rate rise
 - 1st injection into central channel, max leak rate = $1.7e-7$ atm-cc/s
 - 1st injection into helium tank inlet (outer coils), max leak rate = $3.0e-8$ atm-cc/s
 - 2nd injection into central channel, max leak rate = $8.1e-7$ atm-cc/s



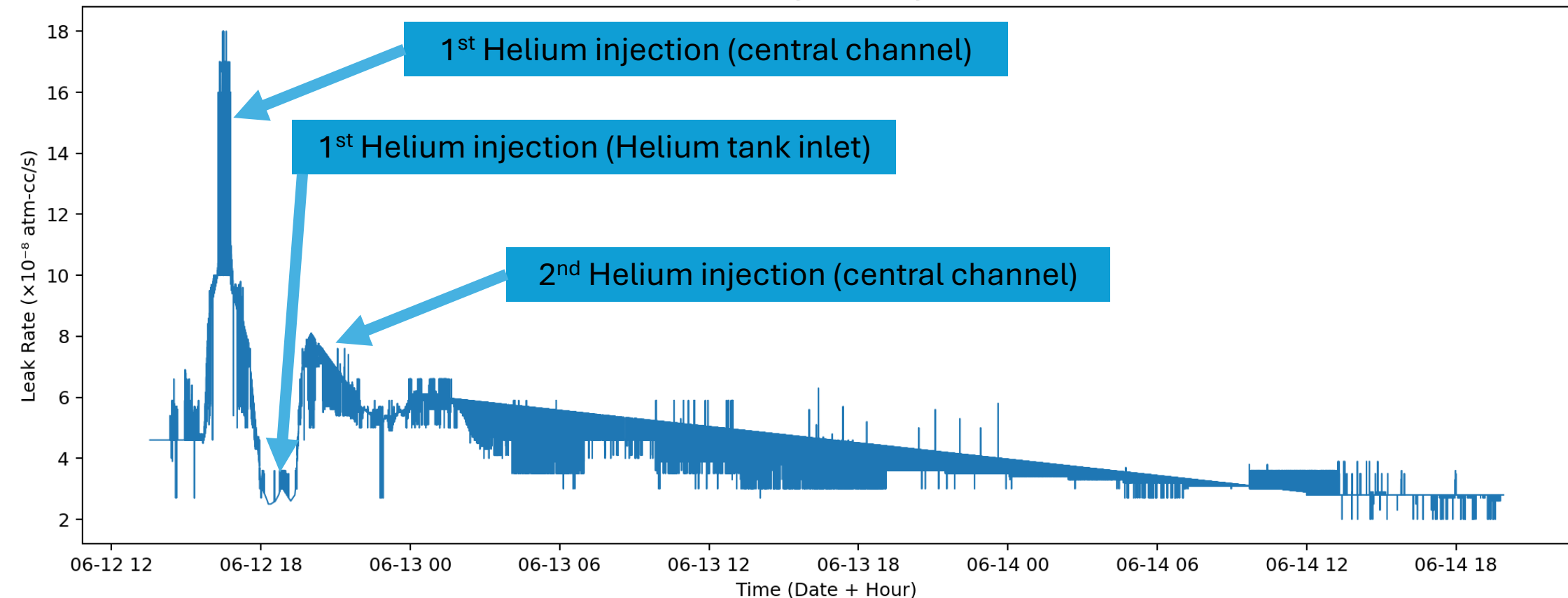
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 - 2nd injection into central channel, max leak rate = $8.1e-7$ atm-cc/s



Helium Injection on June 12th 2026

- Helium Injections = background leak rate rise
 - LN2 height = 15.5 cm to 11.5 cm from bottom of Helium tank
 - 1st injection into central channel, max leak rate = $1.7e-7$ atm-cc/s
 - 1st injection into helium tank inlet (outer coils), max leak rate = $3.0e-8$ atm-cc/s
 - 2nd injection into central channel, max leak rate = $8.1e-7$ atm-cc/s

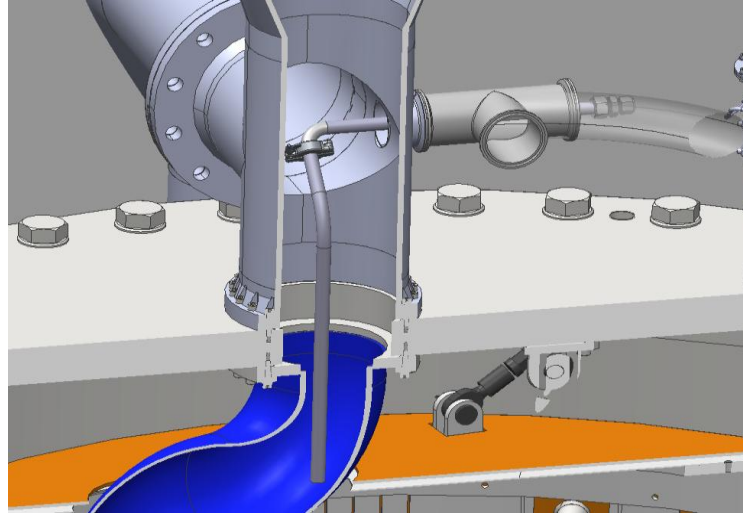
Leak Rate of June 12 to June 14



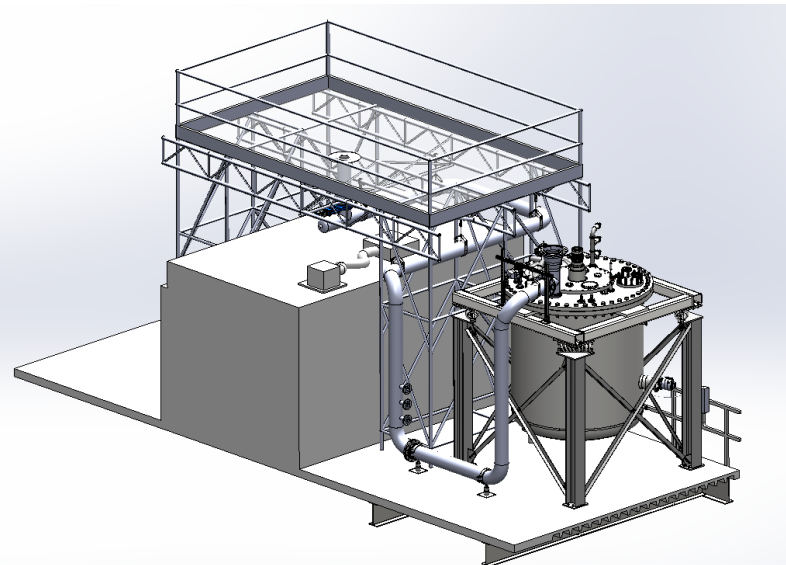
PENeLOPE: Planned Cryostat Improvements (2026)

- Prevent icing on the lid
 - Add new hardware to exhaust line
 - Implement double wall retrofit
 - Planned for Spring 2026

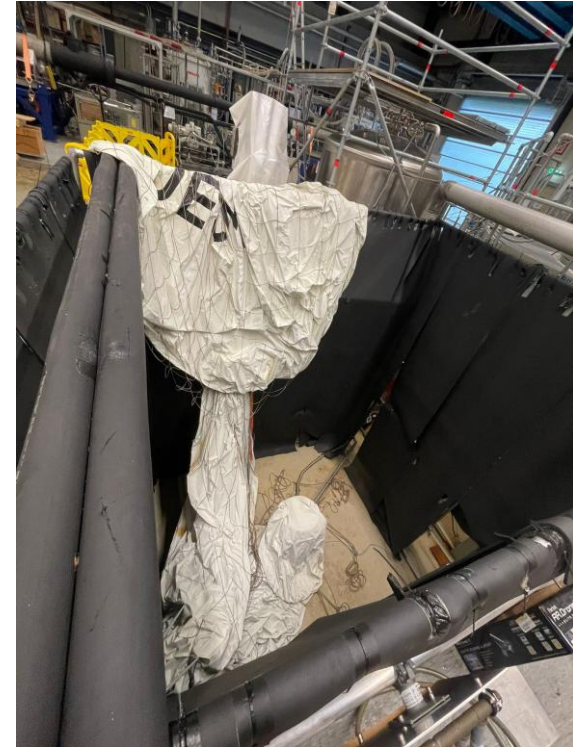
- Include the Helium recovery balloon into exhaust line
 - Essential for quench training
 - Implement by summer 2026



Above: Plan for improving Helium exhaust turret
Below: CAD design of piping and support for He balloon



PENeLOPE Helium Recovery Balloon at TUM

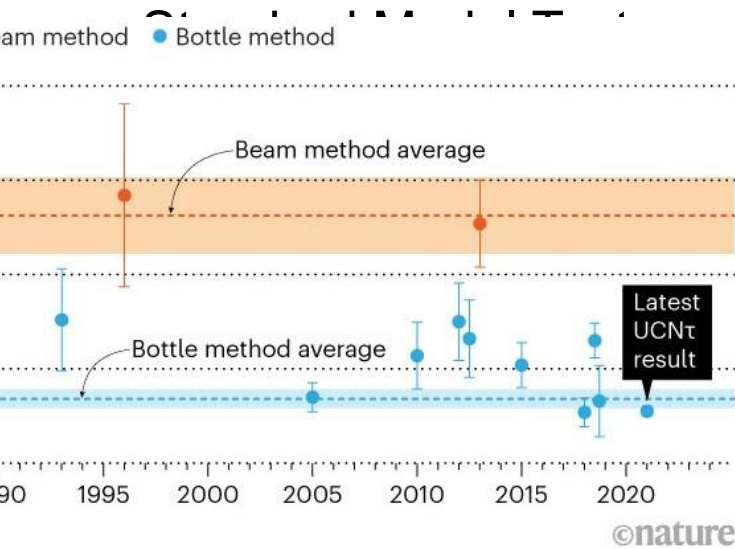


Why Measure a Precise Neutron lifetime?

- Free neutron β^- Decay:

- $n \rightarrow p + e^- + \bar{\nu}_e + 0.783\text{MeV}$
- Weak interaction process \rightarrow determines CKM element V_{ud}

Motivations:



urity

ial light-element abundances

Helium-3

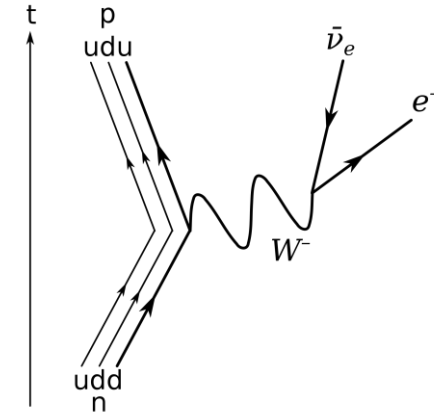
lifetime Puzzle

measured neutron lifetime values

2015)

- PDG 2026:** $\tau_n = 878.3 \pm 0.4 \text{ s}$ (PDG average 2026)
 - 4-5 σ discrepancy (~ 9 s) separation between these values**
- Daide Castelvecchi, 'Physicists make most precise measurement ever of neutron's lifetime', Nature Magazine (2018)

β^- Decay Feynman Diagram



CKM Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

