TUCAN EDM

TRIUMF Ultra-Cold Advanced Neutron project

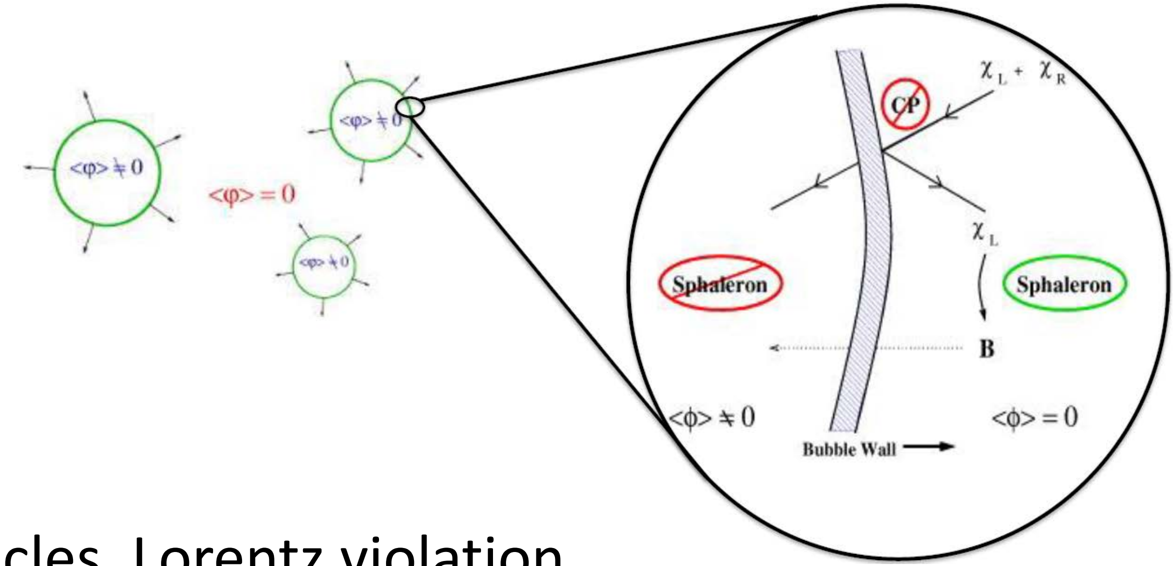
Jeff Martin

TUCAN Collaboration

TRIUMF PP-EEC, April 22, 2021

Physics of Neutron Electric Dipole Moment

- Search for new sources of CP violation beyond the standard model.
- Motivated by:
  - New physics for electroweak baryogenesis
  - SUSY CP problem / new TeV-scale physics
  - Strong CP problem / Peccei-Quinn, axions
  - Other new physics scenarios
- Ancillary measurements:
  - Precision clock comparison (axion-like particles, Lorentz violation, background cosmic field, …)
  - Time-dependent EDM's (axionlike dark matter)



Adapted from Morrissey & Ramsey-Musolf New J. Phys. 2012

Frequency measurement requiring many neutrons and stable magnetic field

Electric dipole moments and CP violation

- Hamiltonian of neutron in an electromagnetic field (non-relativistic limit)

$$H = -\mu\vec{\sigma}\cdot\vec{B} - \underline{d\vec{\sigma}\cdot\vec{E}}$$

$$\rightarrow \not{T} \rightarrow \not{CP}$$

- Experiment: precise measurement of neutron spin precession frequency to determine *d*.

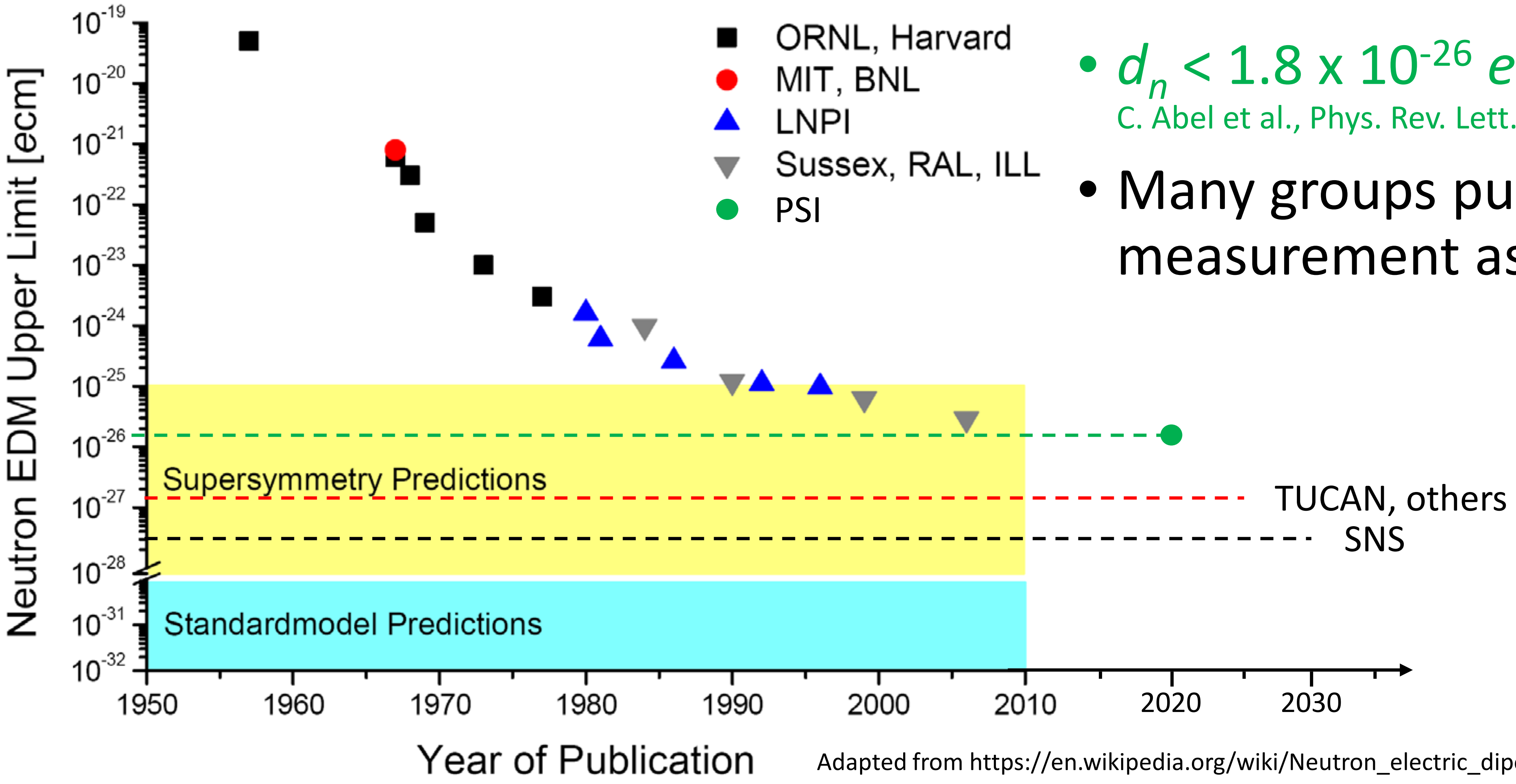
$$h\nu = 2\mu B \pm 2dE$$

- Statistical uncertainty:

$$\sigma_d = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

TUCAN goal:
$\sigma_d = 1 \times 10^{-27}$ ecm
in 400 days of running.

Neutron EDM – experimental status



- $d_n < 1.8 \times 10^{-26}$ *ecm* (90% C.L.)
  C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
- Many groups pursuing ~ 10^{-27} *ecm* measurement as next step

New UCN source technology

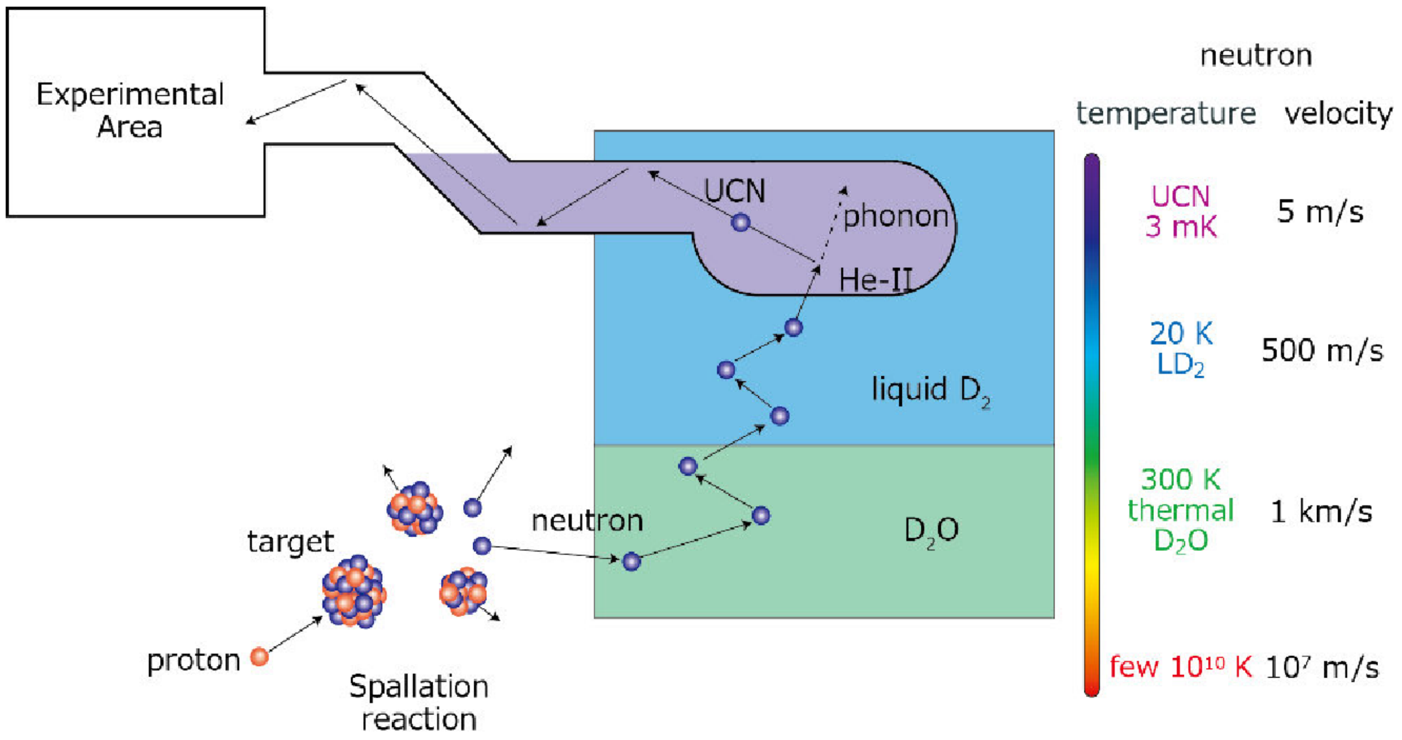
Adapted from https://en.wikipedia.org/wiki/Neutron_electric_dipole_moment

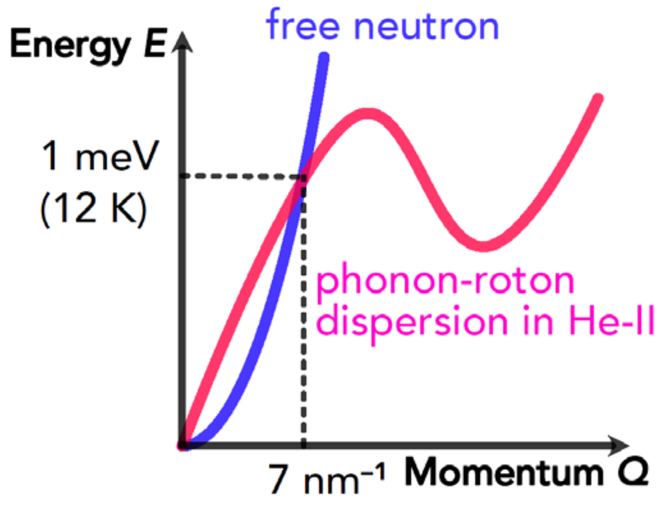
Planned Neutron EDM Experiments

• PSI n2EDM	spallation so-D_2, magnetic fields	upgrading, 2021-	Room temperature EDM experiments coupled to cryogenic UCN sources
• PanEDM (ILL/Munich)	reactor He-II, 1st MSR	installing, 2022-	
• ILL/PNPI/Gatchina	dual cell, previous nEDM meas't	upgrading	
• LANL	spallation so-D_2 UCN source	2022-	
• TUCAN (Japan/Canada)	spallation He-II, MSR	upgrading, 2023-	
• SNS	fully cryogenic source/experiment	2026-	Within superfluid He
• ILL/ESS n-beam	intense pulsed neutron beam	R&D, 2025-	Neutron beam expts.
• J-PARC crystal	high E in crystal	R&D	

Most room-temperature UCN EDM experiments aim for 10^{-27} *e*cm precision.

Spallation-driven superfluid helium UCN source



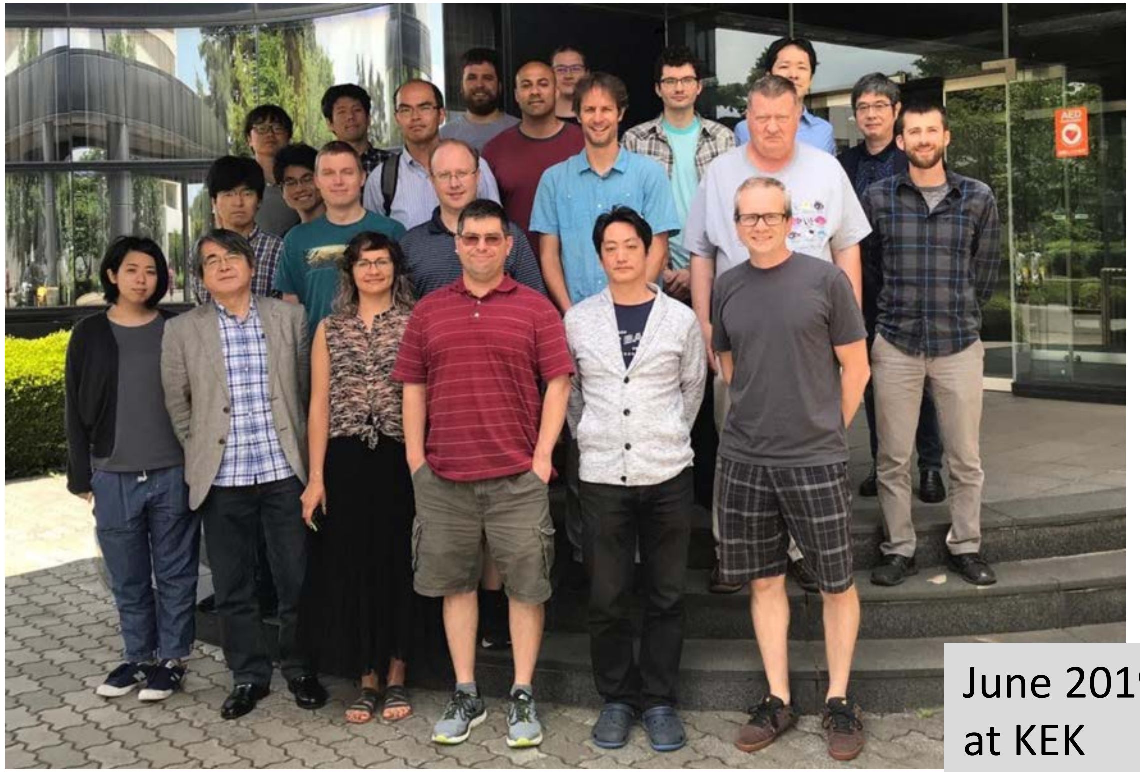


- Competitors:
  - Reactor sources of neutrons (ILL, Gatchina, FRM2)
  - Solid deuterium crystal instead of He-II (LANL, PSI, FRM2)

TUCAN: Uniqueness and competitive edge

- Spallation-driven He-II UCN source can surpass competing so-D_2 UCN sources (longer UCN storage times) and reactor-driven He-II sources (lower heating per unit neutron flux).
- Proven technology of room-temperature neutron EDM experiment. Low risk with window of opportunity to surpass fully cryogenic experiments.
- Unique features of our neutron EDM experiment:
  - Self-shielded B_0 coil.
  - NMOR-based magnetometers.
  - R&D on possible Xe comagnetometer (farther future).
- And are building on the R&D of other groups:
  - Magnetically shielded room (MSR).
  - Dual measurement cells.

TUCAN Collaboration



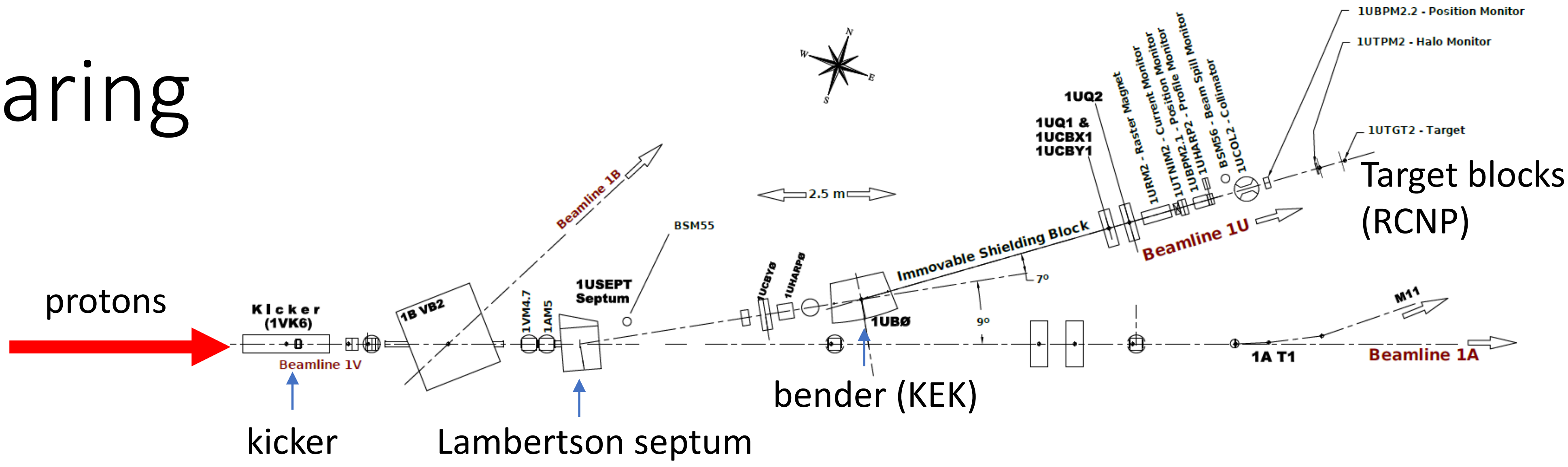
June 2019, at KEK

H. Akatsuka[1], C. Bidinosti[2], C. Davis[3], B. Franke[3,4], M. Gericke[5], P. Giampa[3], R. Golub[6], S. Hansen-Romu[5,2], K. Hatanaka[7,*], T. Hayamizu[9], T. Higuchi[7], G. Ichikawa[8], S. Imajo[7], B. Jamieson[2], S. Kawasaki[8], M. Kitaguchi[1], W. Klassen[4,5,2], A. Konaka[3,10], E. Korkmaz[11], E. Korobkina[6], F. Kuchler[3], M. Lavvaf[5,2], T. Lindner[3,2], K. Madison[4], Y. Makida[8], J. Mammei[5], R. Mammei[2,3], J. Martin[2,*], R. Matsumiya[3], M. McCrea[2], E. Miller[4], K. Mishima[8], T. Momose[4], T. Okamura[8], H. J. Ong[7], R. Picker[3,12], W. D. Ramsay[3], W. Schreyer[3], A. Sher[3], H. Shimizu[1], S. Sidhu[12], S. Stargardter[5,2], I. Tanihata[7], S. Vanbergen[4], W.T.H. van Oers[5,3], Y. Watanabe[8]

[1]Nagoya University, [2]The University of Winnipeg, [3]TRIUMF, [4]The University of British Columbia, [5]University of Manitoba, [6]North Carolina State University, [7]RCNP Osaka, [8]KEK, [9]RIKEN, [10]Osaka University, [11]University of Northern BC,[12]Simon Fraser University

*cospokespersons (K. Hatanaka and J. Martin)

Beam sharing



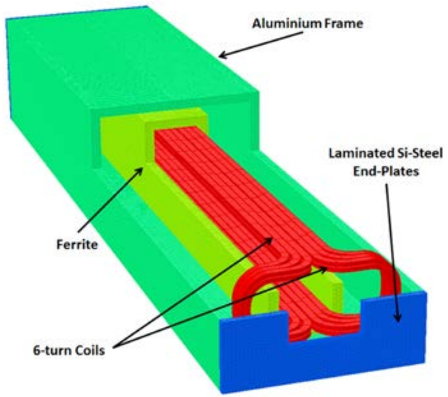
- Key enabling technology is kicker magnet.

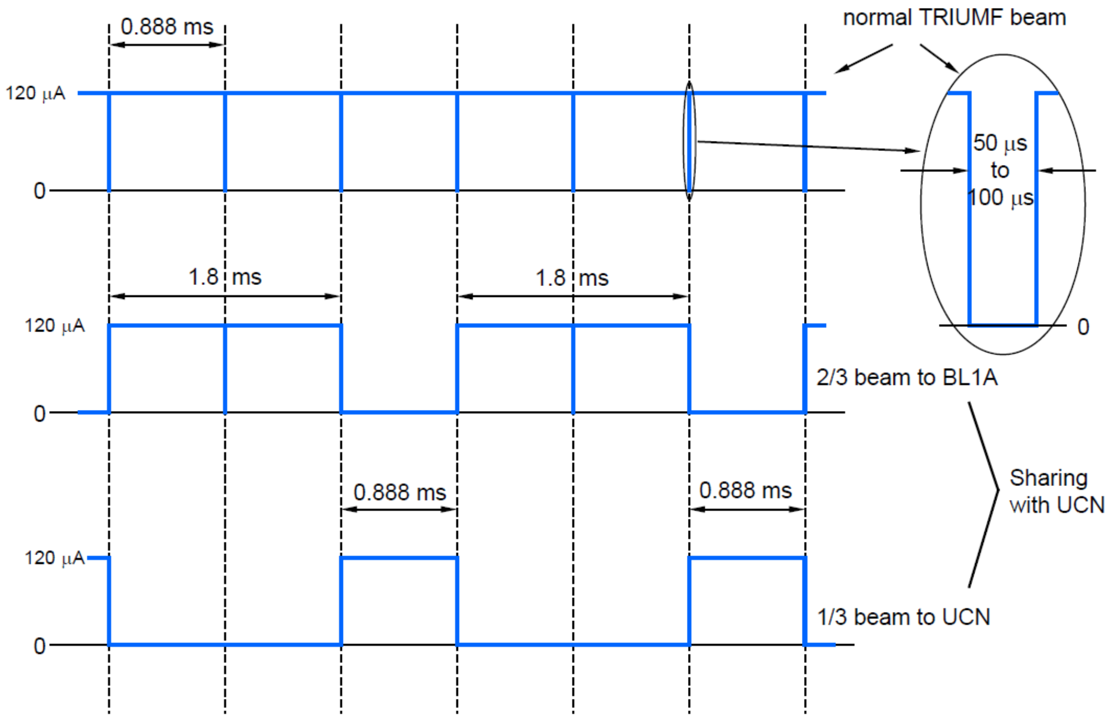
S. Ahmed et al., Nucl. Instrum. Meth. A 927, 101 (2019)

S. Ahmed et al., Phys. Rev. Accel. Beams 22, 102401 (2019)

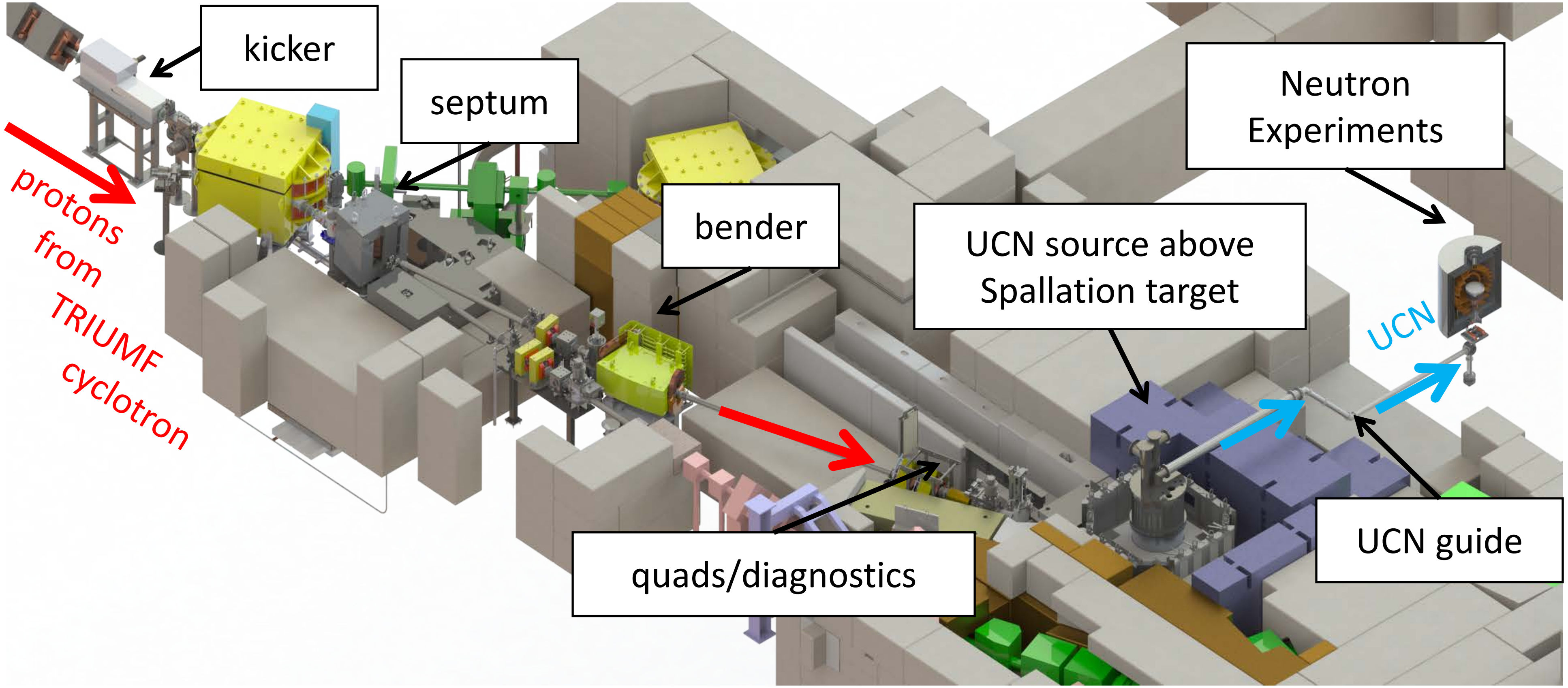
UCN source uses 483 MeV proton beam @ 40 µA current, producing neutrons by spallation.

Beam on for typ. 1 minute, off for typ. 3 minutes.



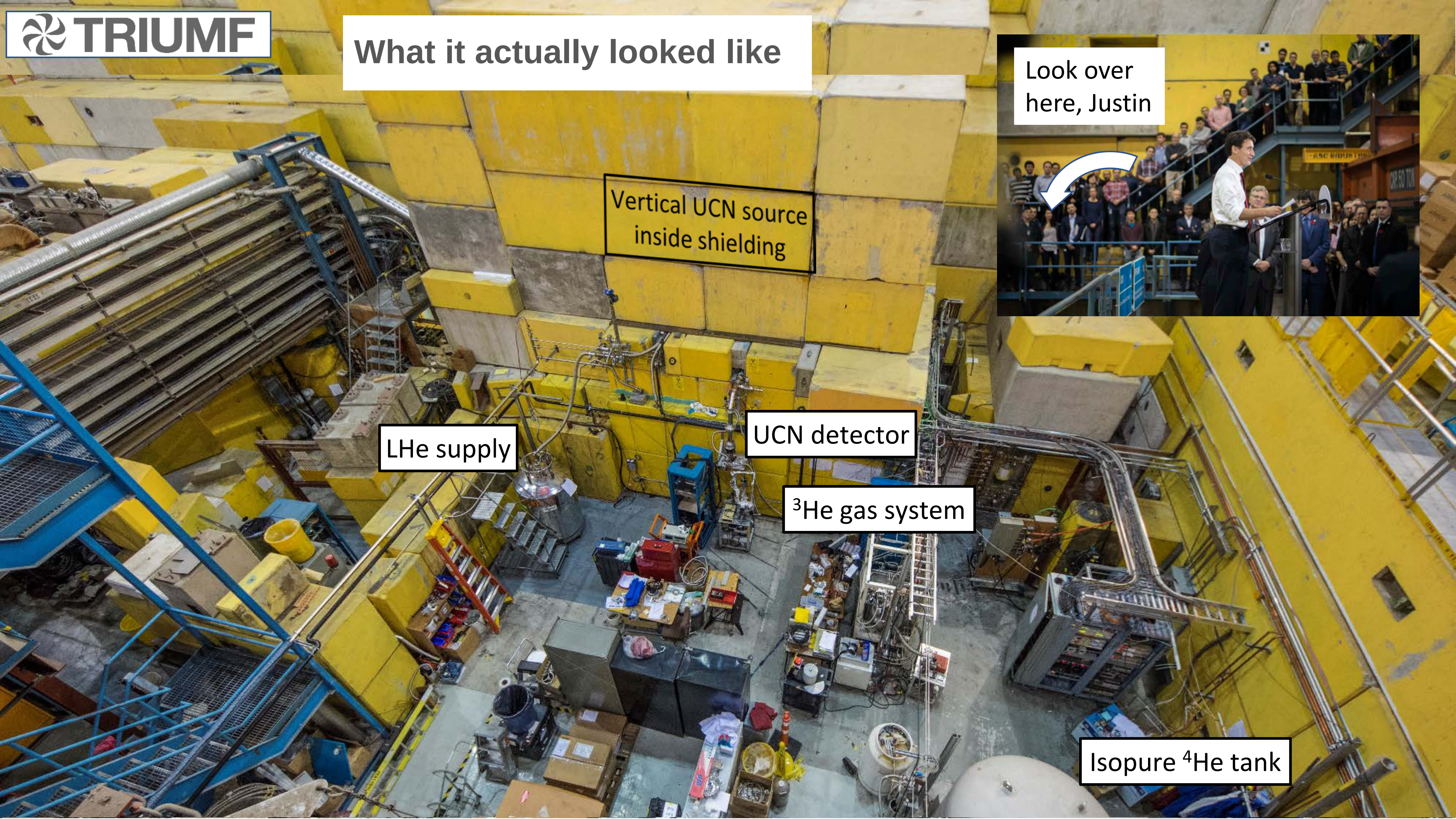


TUCAN – Prior to December 2020



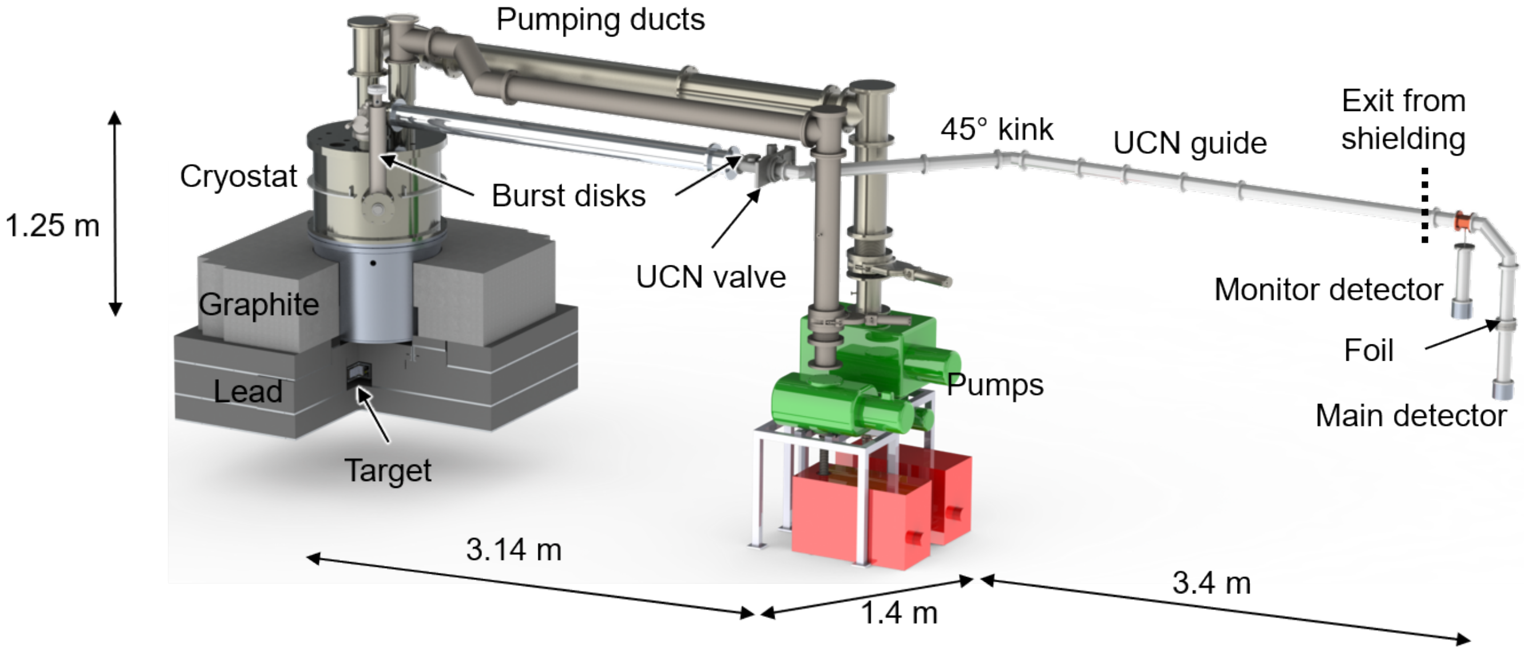
Facility as of 2020 – shielding blocks removed for clarity.
“Vertical” UCN source installed

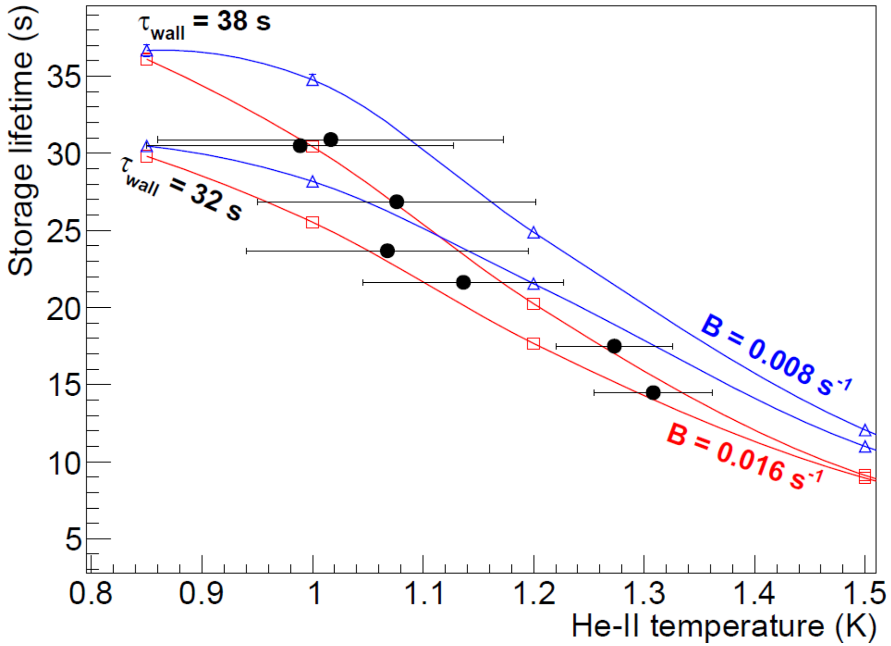
What it actually looked like



First UCN for TRIUMF

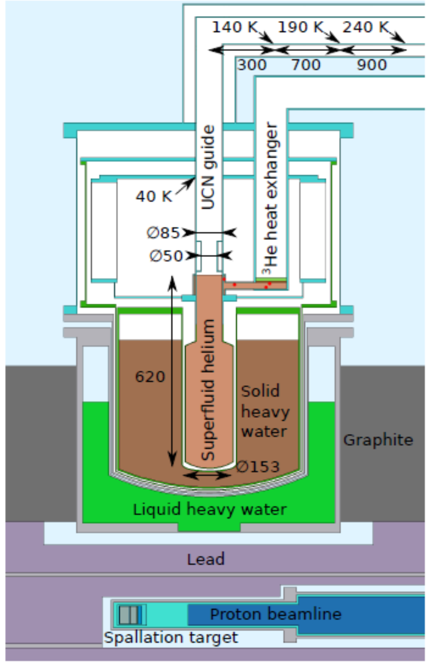
S. Ahmed *et al.* (TUCAN Collaboration)
Phys. Rev. C **99**, 025503 (2019)

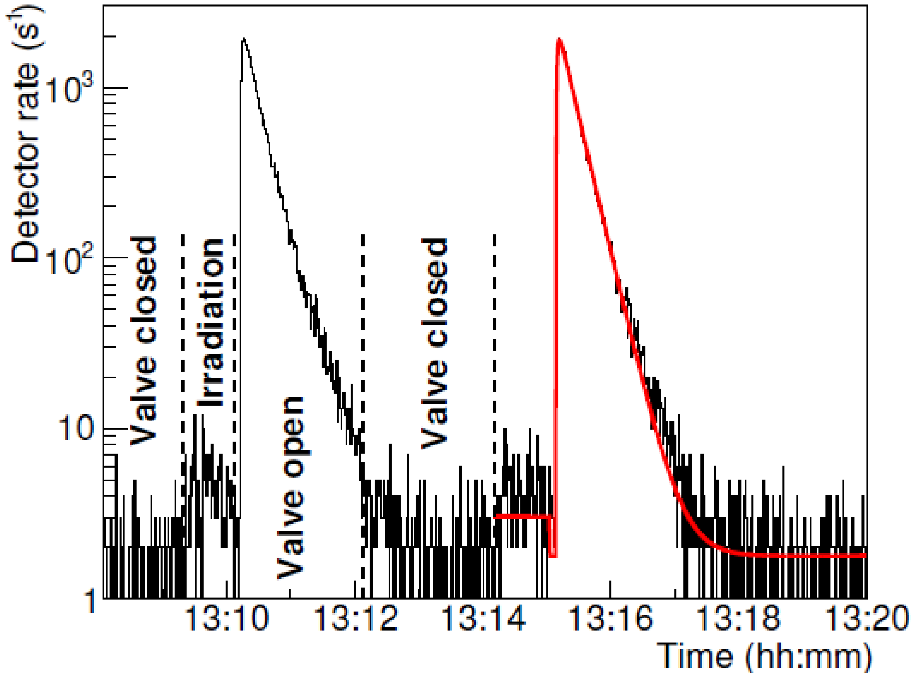


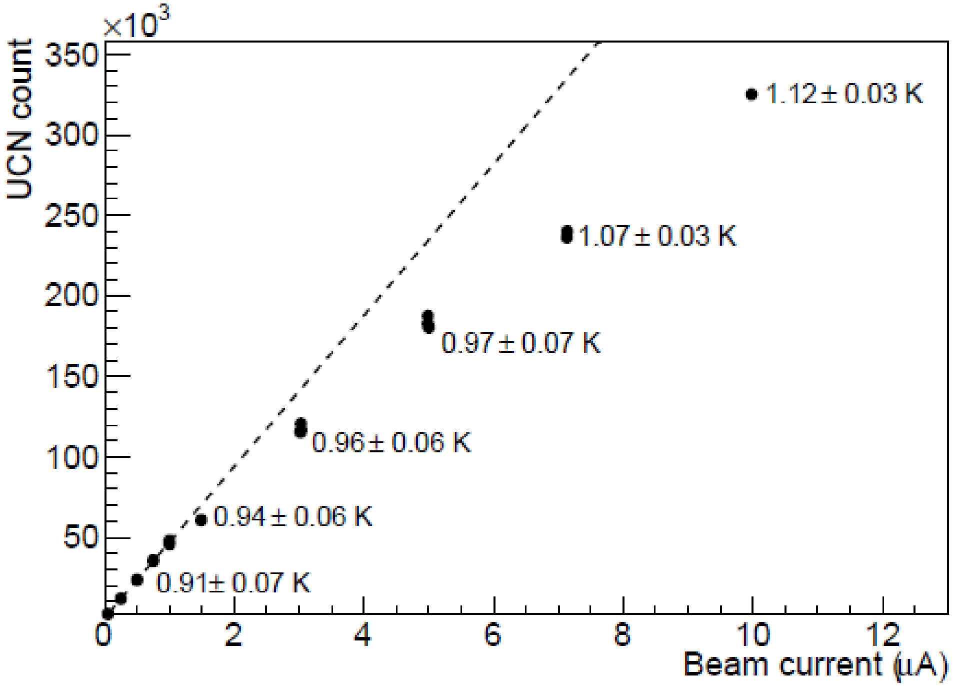


- UCN rate and source lifetime vs. temp, beam power, time, etc. show good agreement with simulation.
- UCN transport parameters studied in detail using rise/fall/transport time measurements.
- Thermometry and He-II thermal conductivity also investigated (F. Rehm, BSc thesis)
- Results used to benchmark simulations for UCN source upgrade.

First UCN for TRIUMF





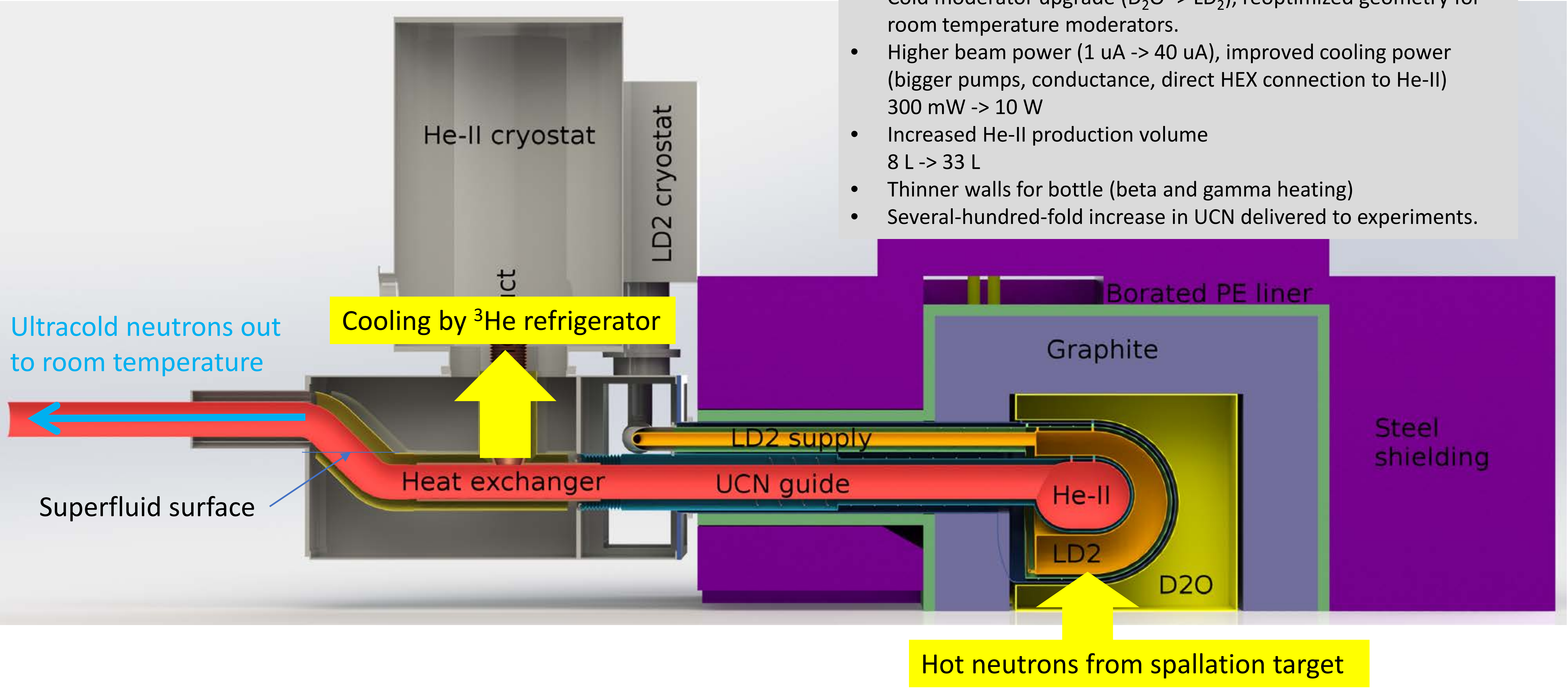


- The source was also used for a host of UCN guide, UCN polarization, UCN detection experiments in 2018 and 2019.
- Established TRIUMF facility as a focal point for collaboration to gather and develop the project.

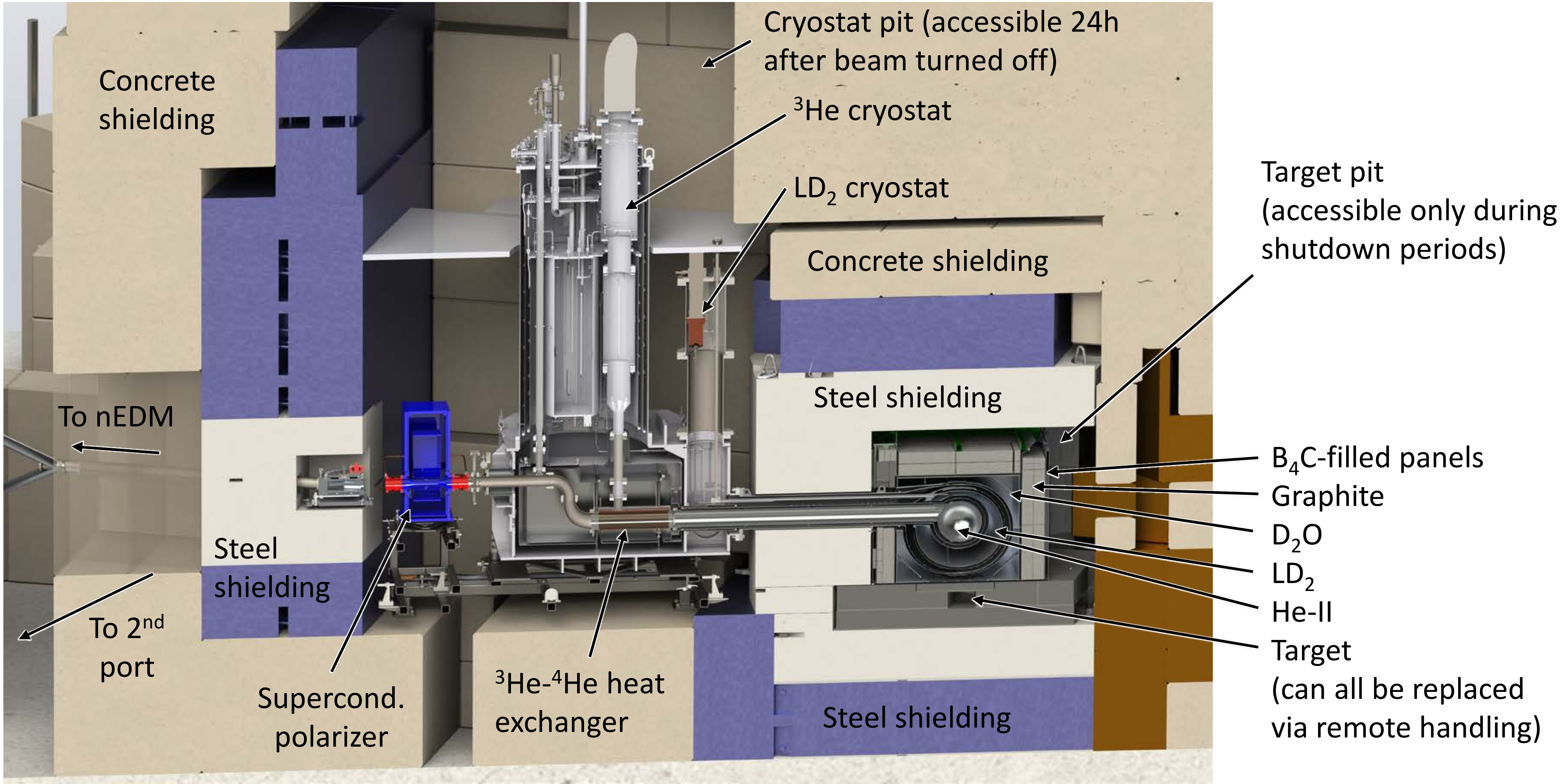
Ongoing upgrade: Next generation He-II cryostat (the “horizontal source”)

Improvements compared to “vertical” source

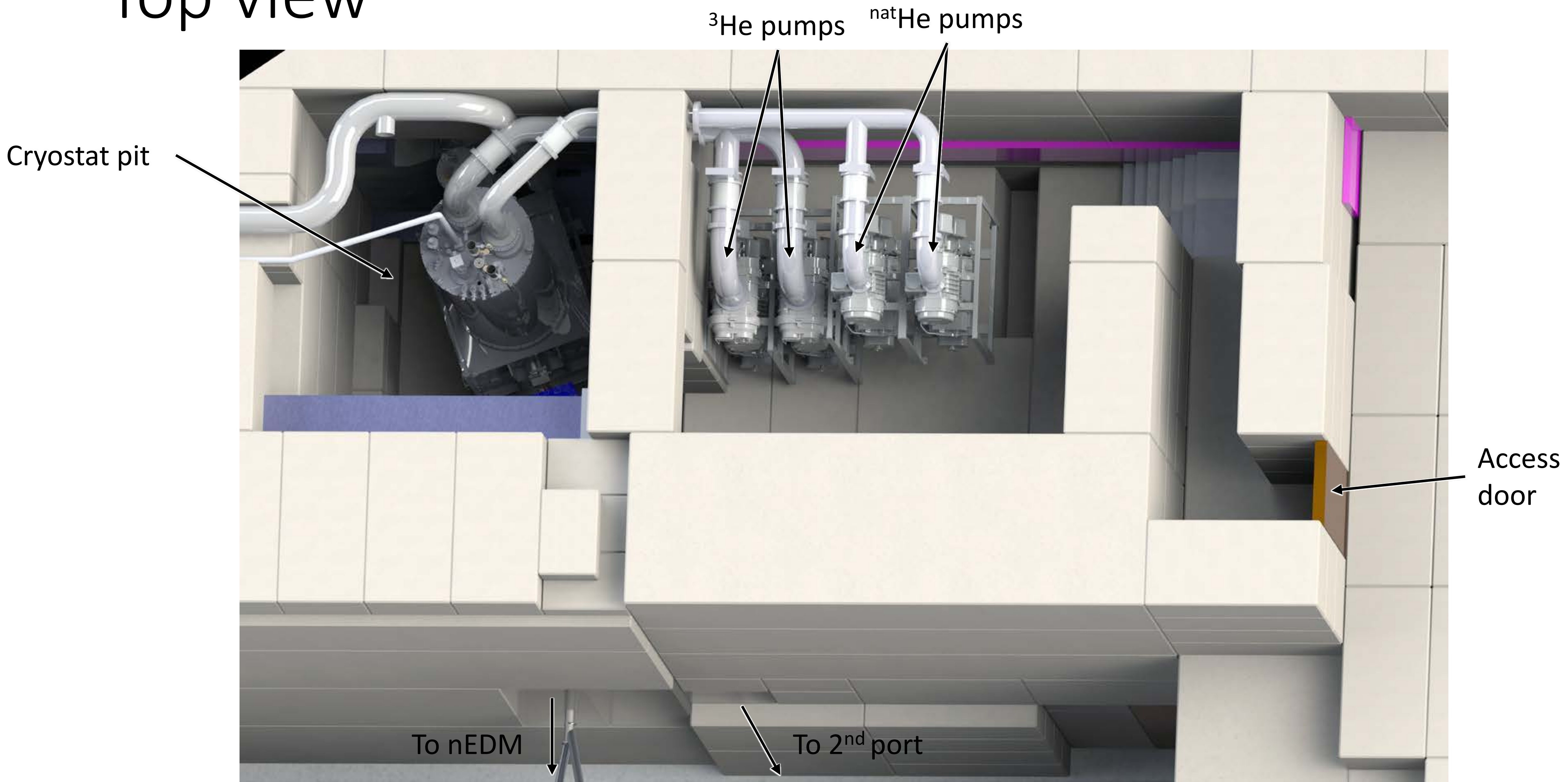
- Material potential He-II is 18 neV, use near-horizontal extraction
- Cold moderator upgrade (D_2O -> LD_2), reoptimized geometry for room temperature moderators.
- Higher beam power (1 uA -> 40 uA), improved cooling power (bigger pumps, conductance, direct HEX connection to He-II) 300 mW -> 10 W
- Increased He-II production volume 8 L -> 33 L
- Thinner walls for bottle (beta and gamma heating)
- Several-hundred-fold increase in UCN delivered to experiments.



Horizontal source and shielding detail



Top view



Cryostat pit
^{3}He pumps
^{nat}He pumps
Access door
To nEDM
To 2nd port

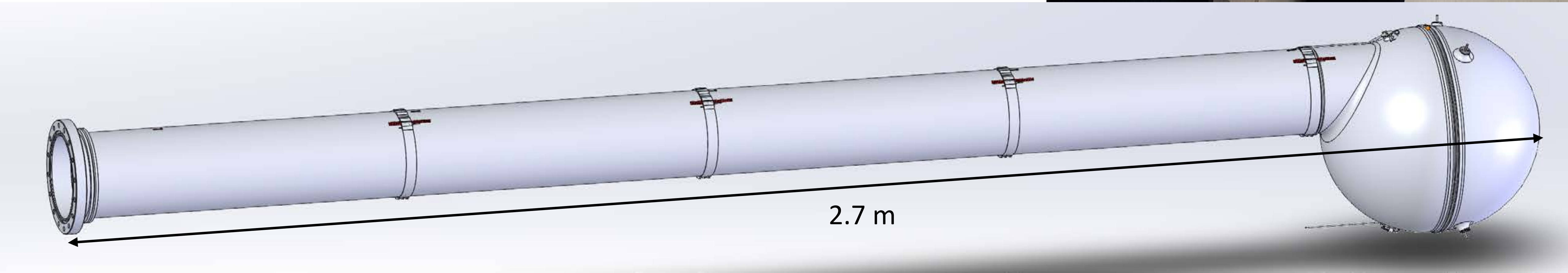
He-II cryostat tests in Japan (2020-21)


Shinsuke Kawasaki, KEK

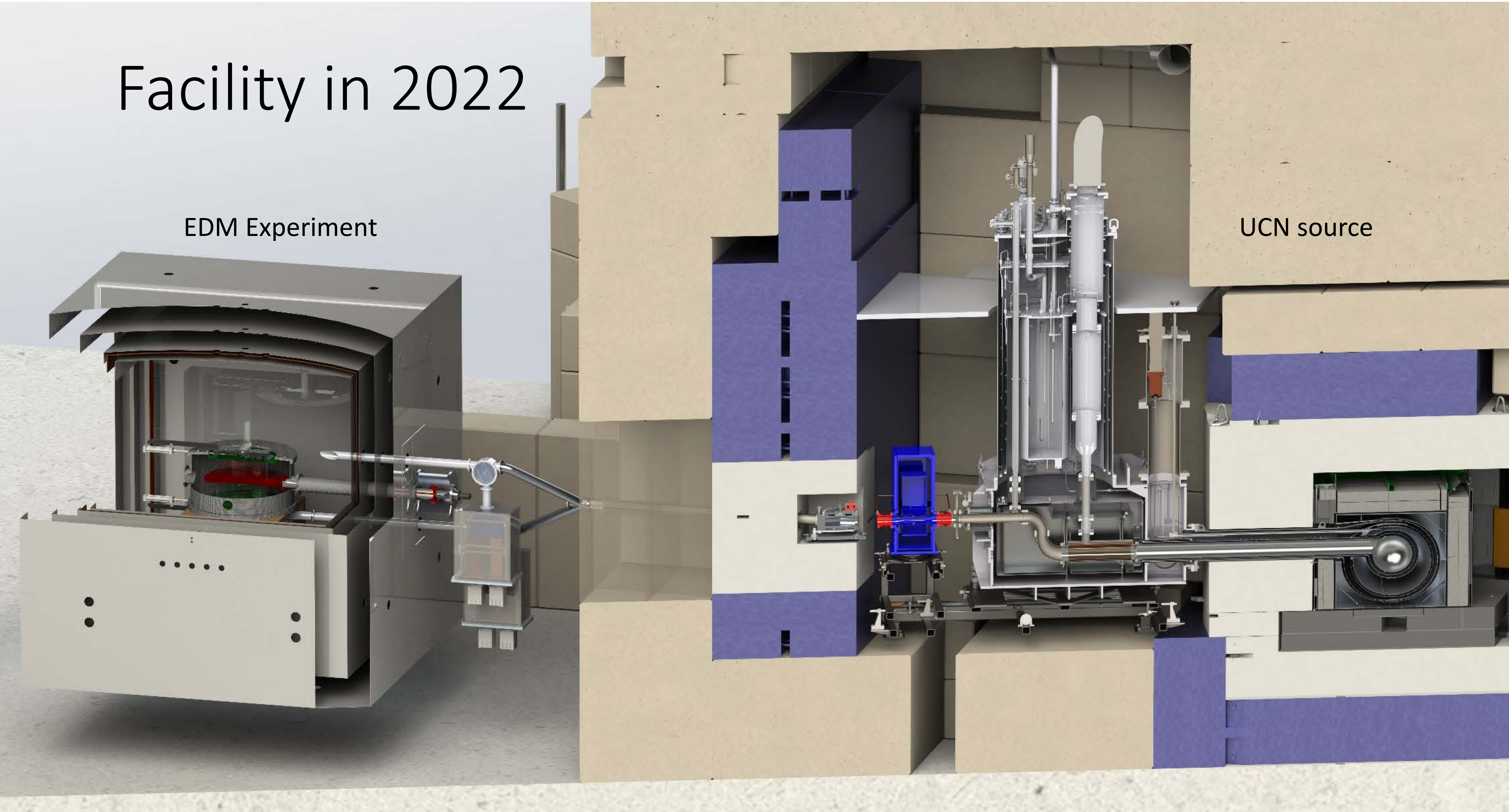
- Cryostat performs well with He-II (to 1.4 K), testing with ^{3}He to be done in 2021 at TRIUMF.

He-II vessel construction in Canada

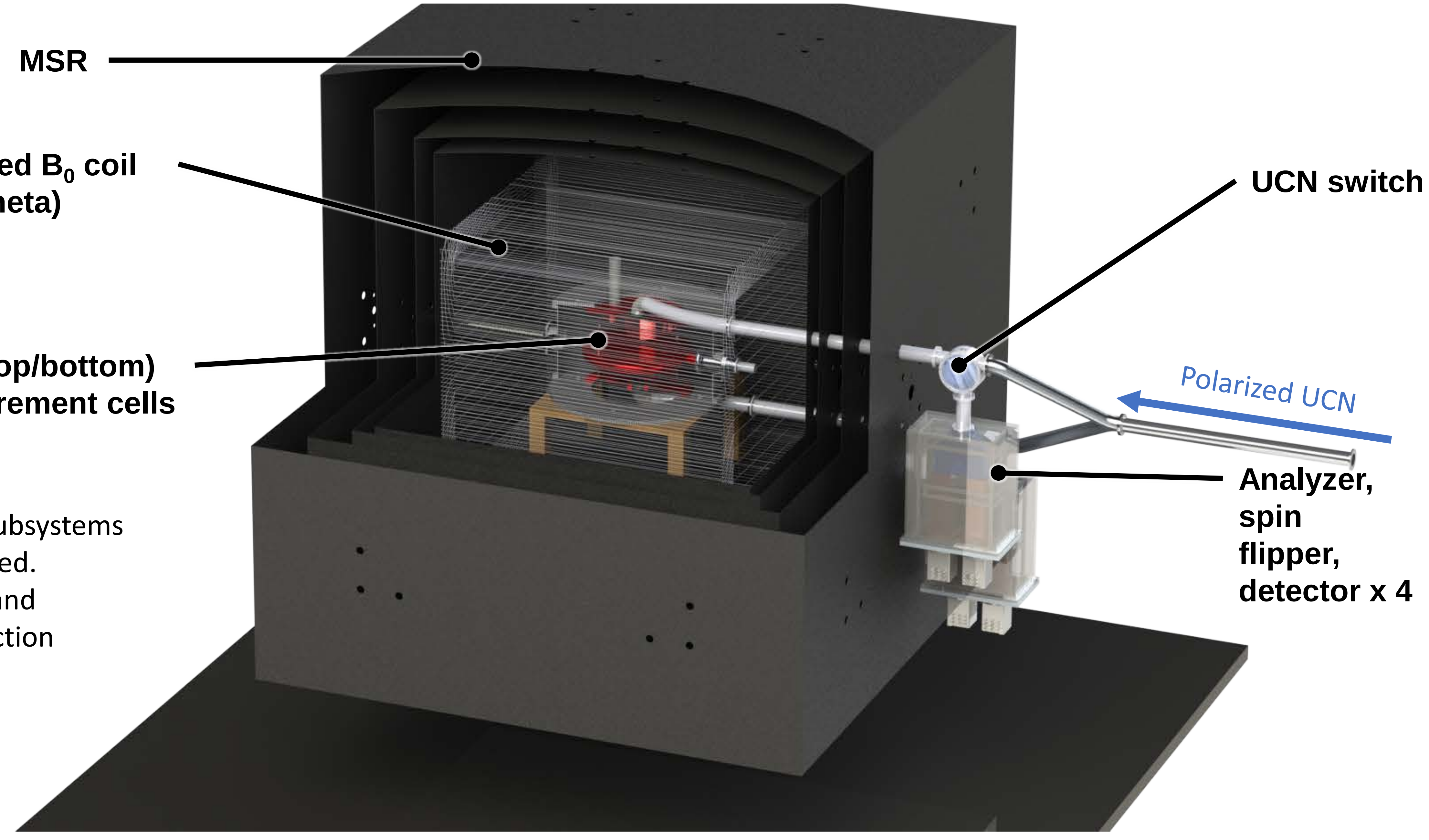
- Dome fabrication, welding.
- Coat with Ni-plating for UCN compatibility.
- Test with UCN (J-PARC and/or LANL).
- Integrate into “tail-section” cryostat, 2021.



Facility in 2022



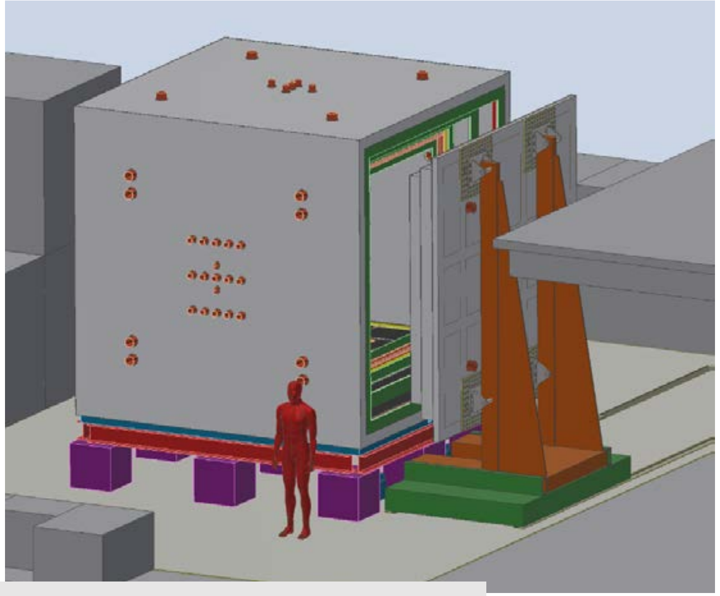
TUCAN EDM experiment layout



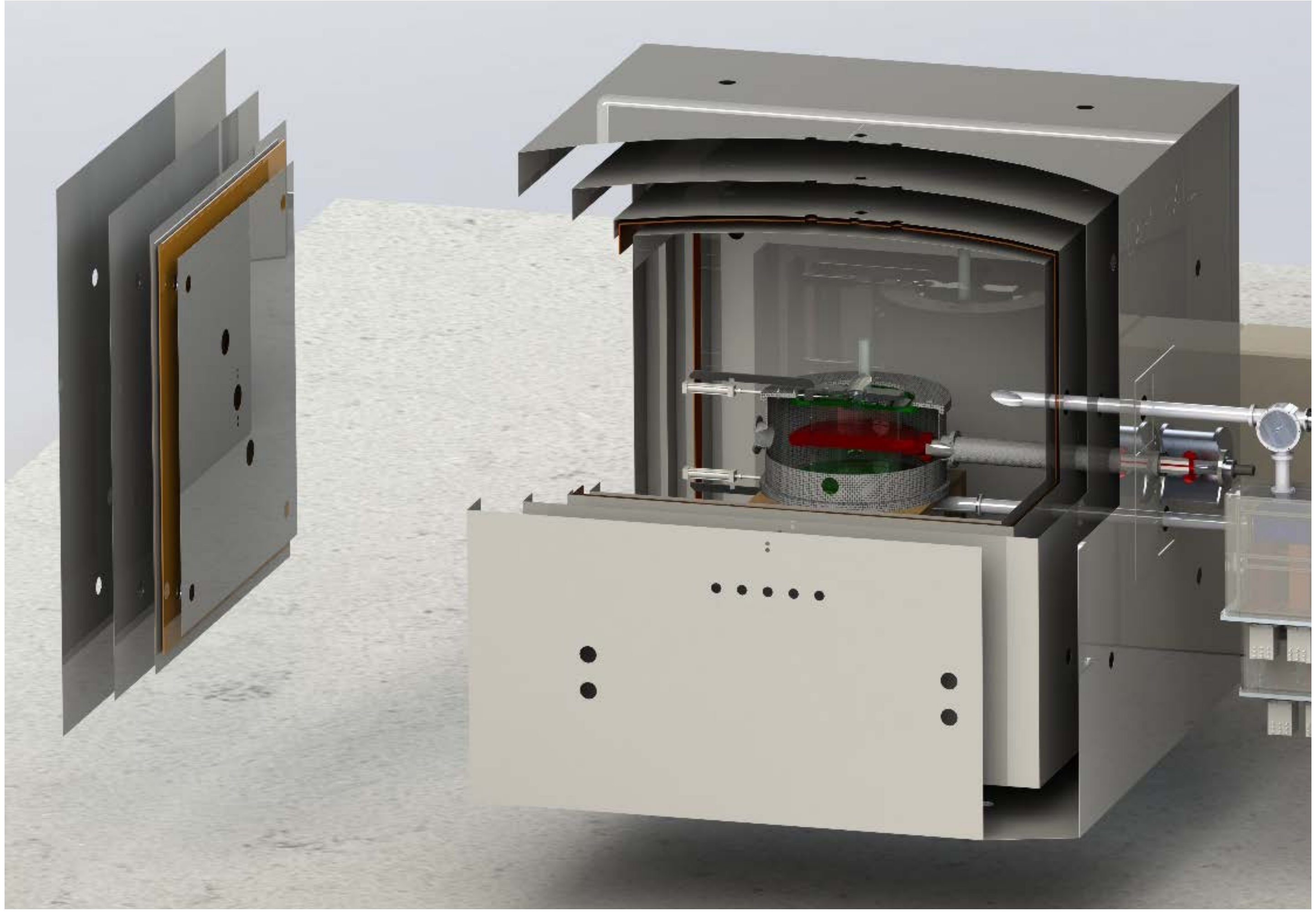
- Major subsystems developed.
- Design and construction phase.

Magnetically shielded room (MSR)

- contract with Magnetic Shields Ltd. (UK)
- Installation April 2022



Door motion mechanism



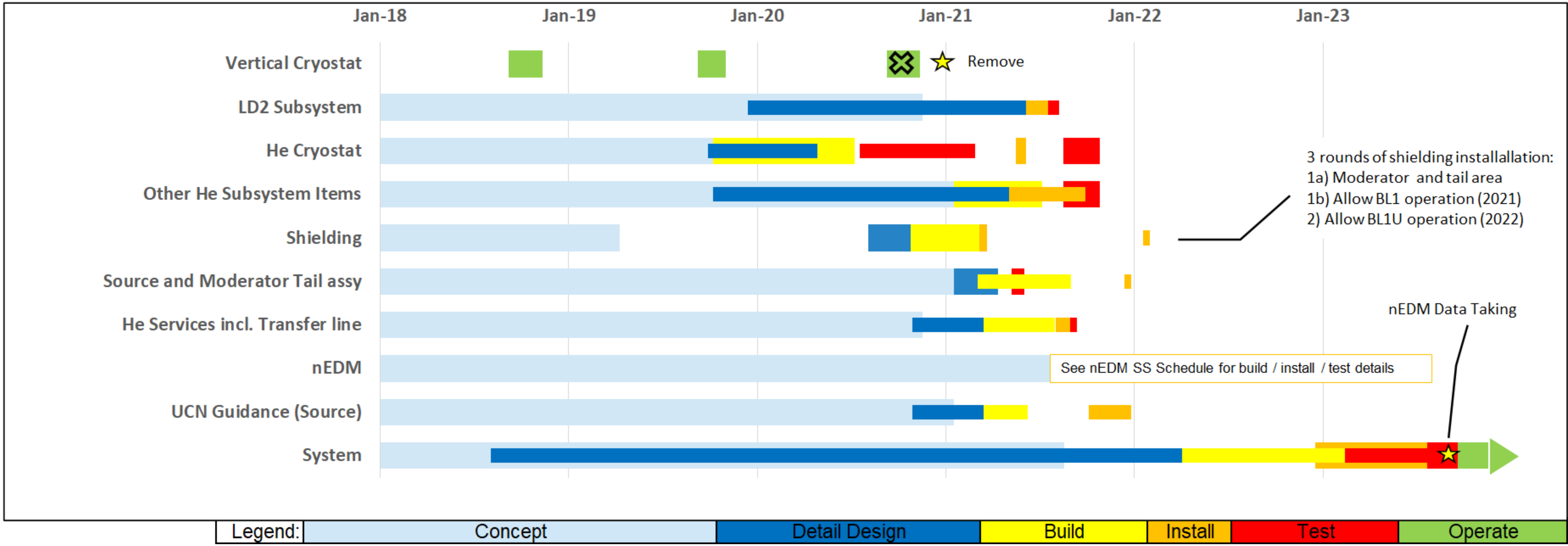
More progress, and work breakdown

- Equipment in the mechanical design/construction phase:
  - External field compensation (RCNP Osaka, TRIUMF)
  - Internal coils (Winnipeg)
  - UCN detector (Winnipeg)
  - UCN spin analysis (Winnipeg, RCNP Osaka, TRIUMF)
  - HV/cell/valves/central region (TRIUMF)
  - Hg comagnetometer and Xe development lab (UBC)
  - NMOR-based Cs magnetometers (Winnipeg)
  - UCN guides (Winnipeg, KEK, TRIUMF)
  - HEX development (KEK, TRIUMF)
- Challenges: integration and interfaces

TUCAN Plans

- Next two years (2021-2022):
  - Complete the upgrade of the UCN source
  - Design and build the nEDM experiment
  - Commission UCN source with beam (2022)
- 2023:
  - First beam to nEDM experiment (commissioning)
- Beyond (2024-):
  - Run the nEDM experiment for statistics, and systematics studies
  - Develop user facility and other experiments
- Detailed project planning and professional project management (next slides are a high-level summary)

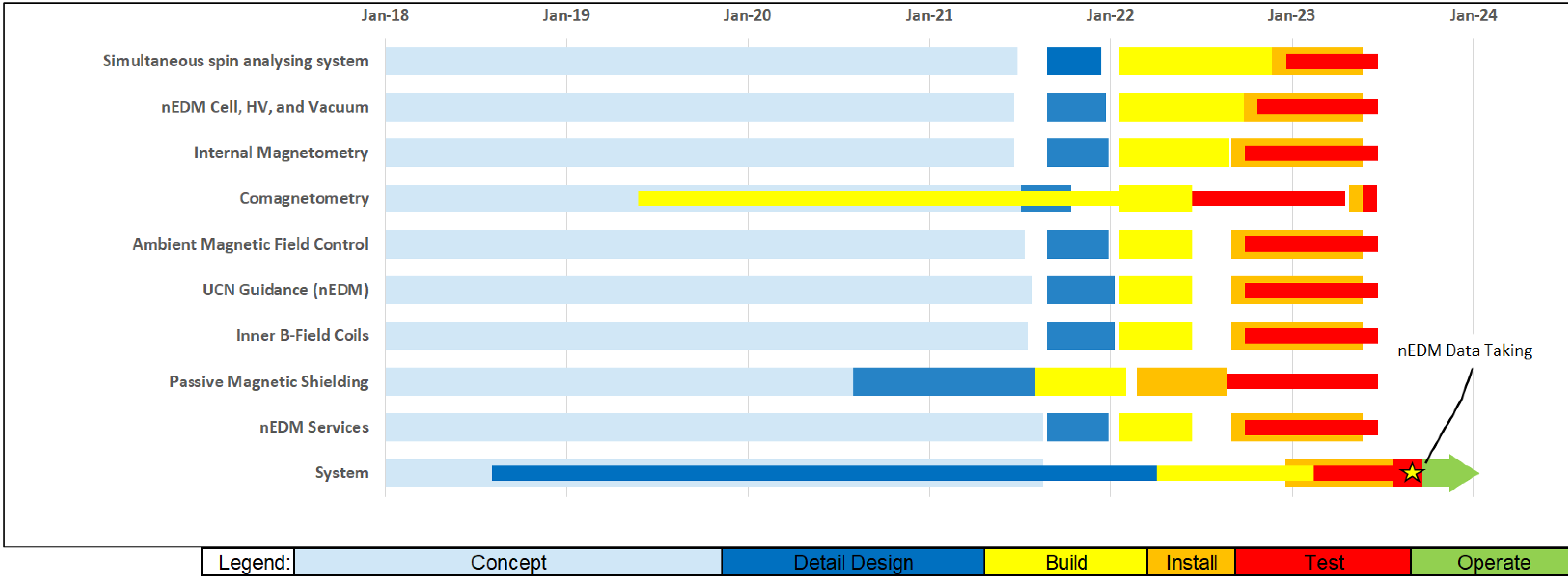
UCN Source schedule



Challenge: engineer and designer FTE's.

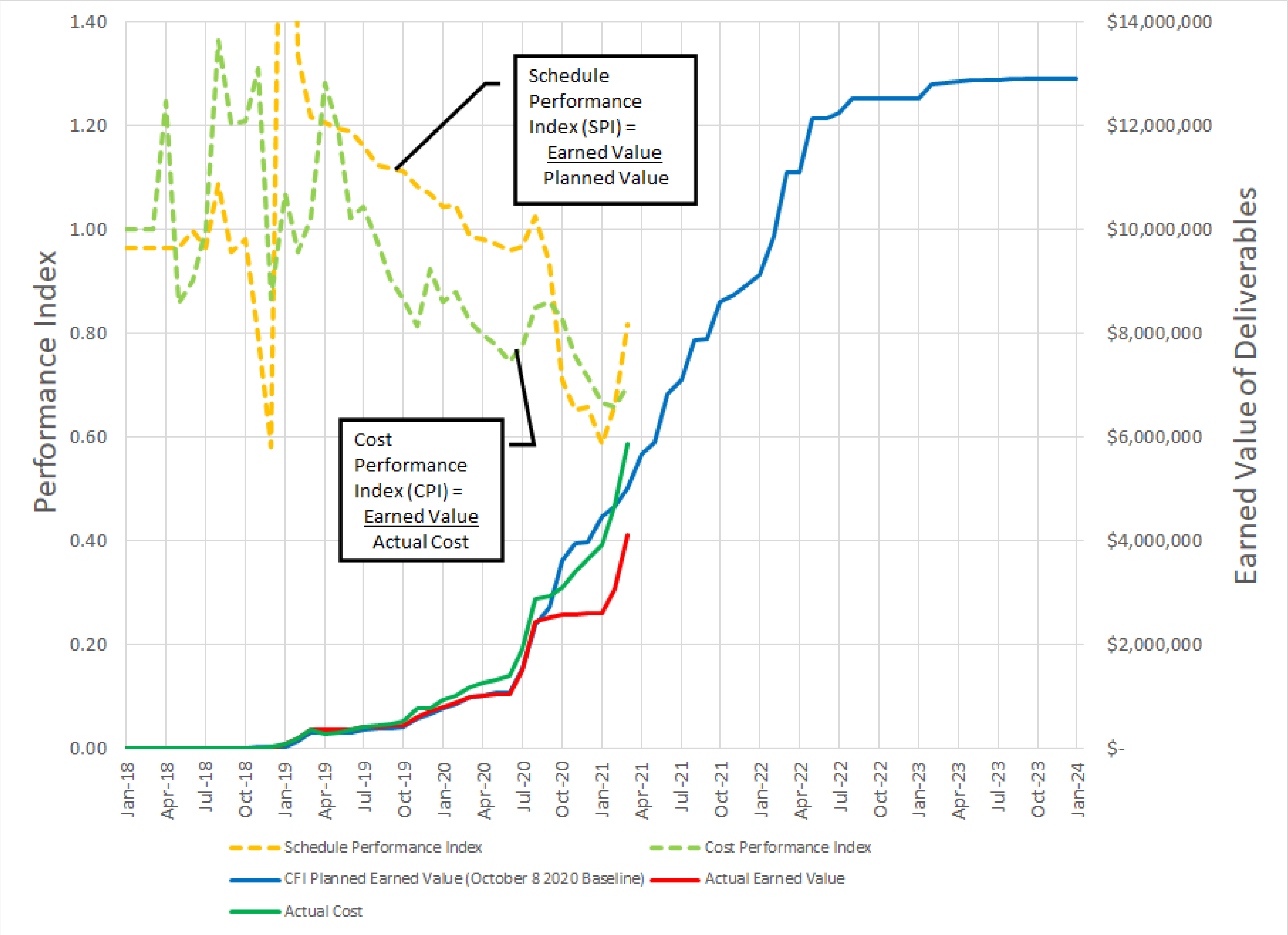
While our project engineer (Cam Marshall) is excellent, our main schedule risk arises because we need more engineering support.

nEDM schedule



nEDM experiment also needs engineering support, after the UCN source (same engineering personnel do both, so hard to proceed in parallel)

CFI spending metrics



Conclusions

- Strong physics interest with tight constraint placed on CP violation.
- Highly competitive field with many new ideas, technologies.
  - Community holds nEDM workshops every 2-4 years
    - October 2017: TRIUMF, Harrison Hot Springs, BC http://nedm2017.triumf.ca
    - February 2021: U. Grenoble-Alpes https://lpsc-indico.in2p3.fr/event/2584/
- Next generation of experiments aims at 10^{-27} e-cm uncertainty, order of magnitude improvement.
- TUCAN has made good progress making first UCN at TRIUMF using a unique superfluid helium UCN source
- TUCAN source upgrade and EDM experiment installation happening in the next two years.

Thank you!

Research Manitoba

Chaires de recherche du Canada
Canada Research Chairs
Canada

NSERC CRSNG

BC Knowledge Development Fund

Japan Society for the Promotion of Science • Founded 1932 •

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Backups

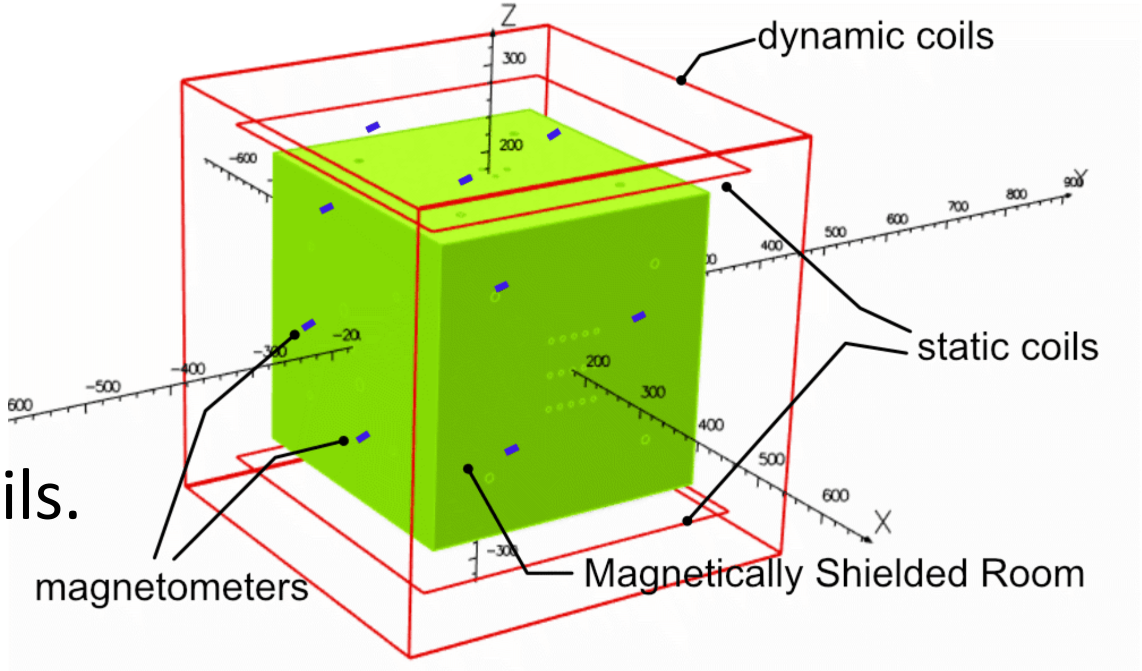
Some examples of recent progress

Unique challenge for TRIUMF: high ambient field of 3 Gauss

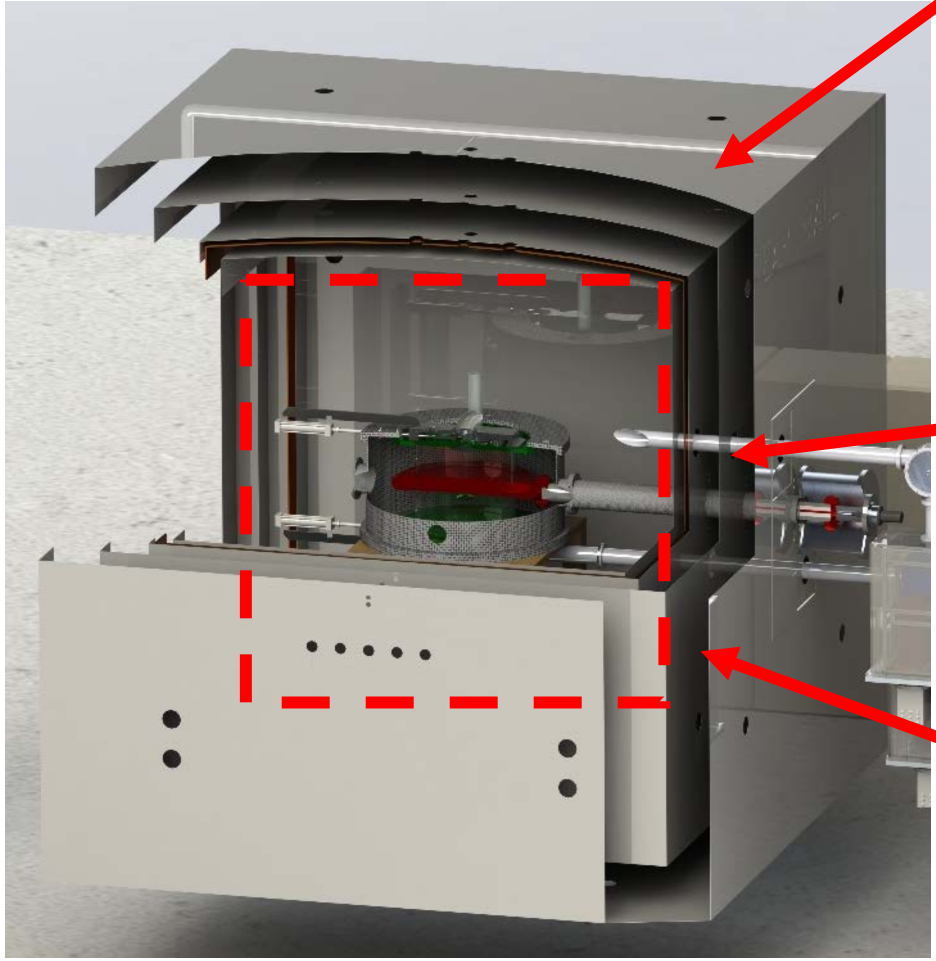
- Experiment located adjacent to the TRIUMF cyclotron

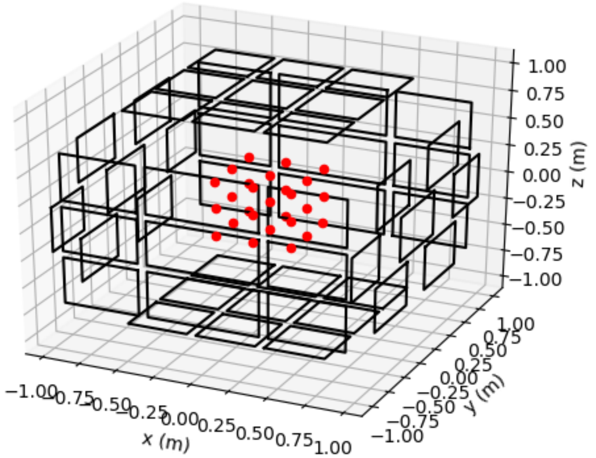
1. Field mapping campaign (2019-20)
2. Fitting the field maps
3. Input to FEA calculation to design coils.

Field in mu-metal reduced below saturation with safety factor of 10, with relatively simple bucking coil design.

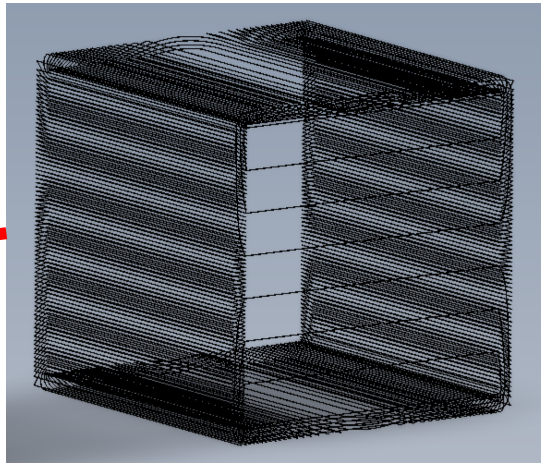


Internal coil systems

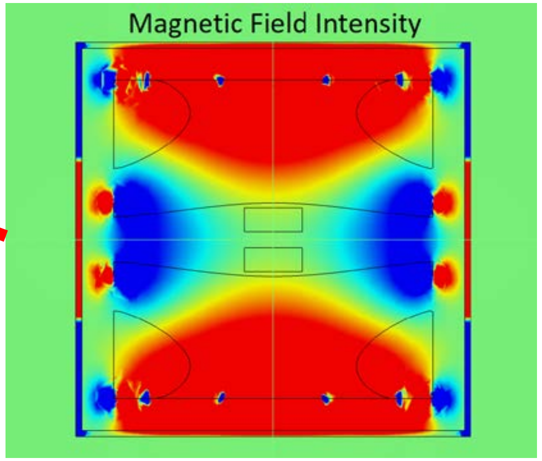




Highly flexible shim coils



Self-shielded, highly uniform main B_0 coil

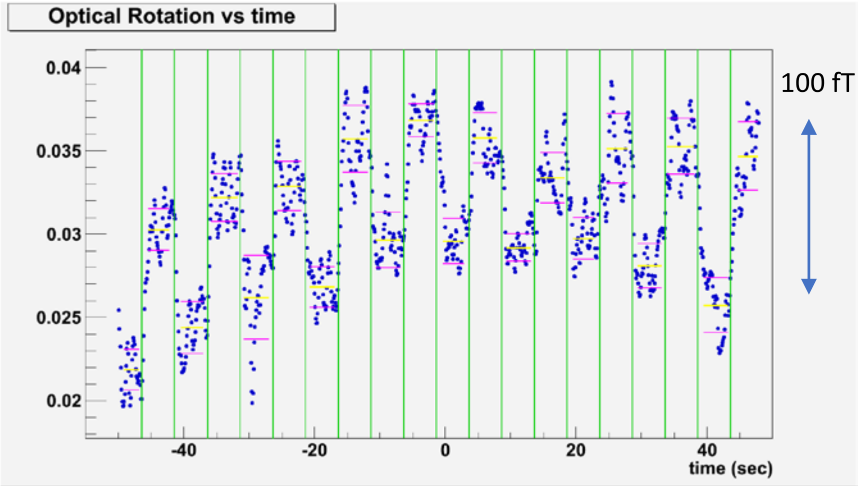


Special harmonics for systematic studies

Challenge: interfaces and integration

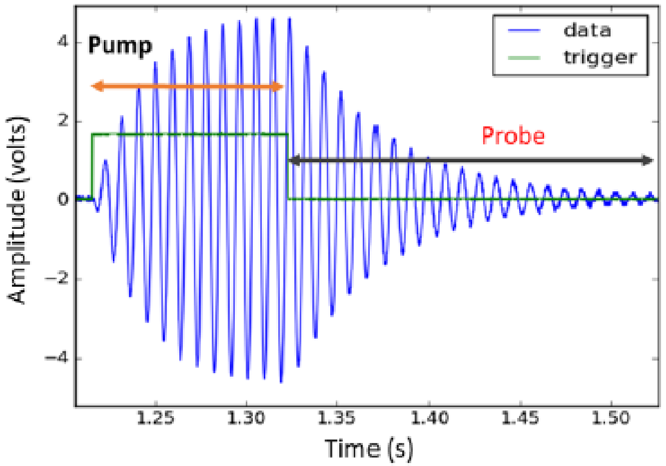
NMOR magnetometry

- "All optical" pump-probe technique involving alkali atoms.
- Requires paraffin-coated Rb or Cs cells.

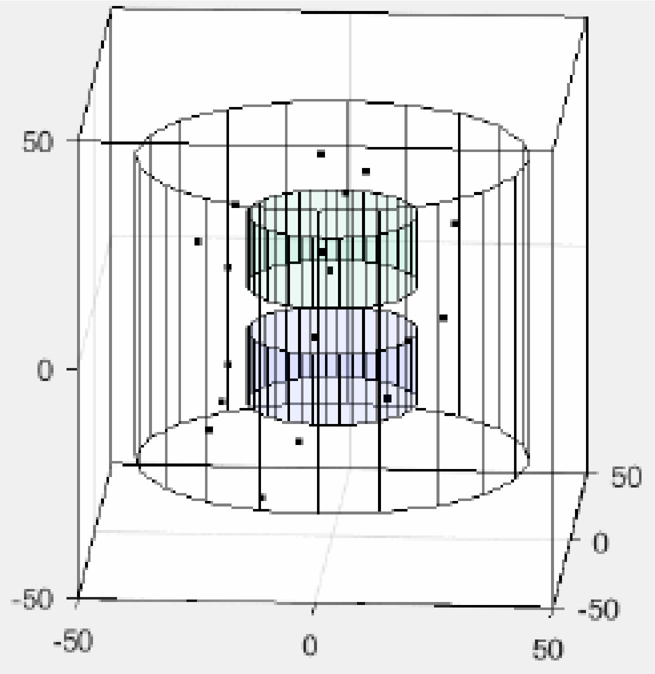


J.W. Martin et al. NIM A 778, 61 (2015).

Achieved 20 fT precision in ~ 1 Hz bandwidth near zero field.



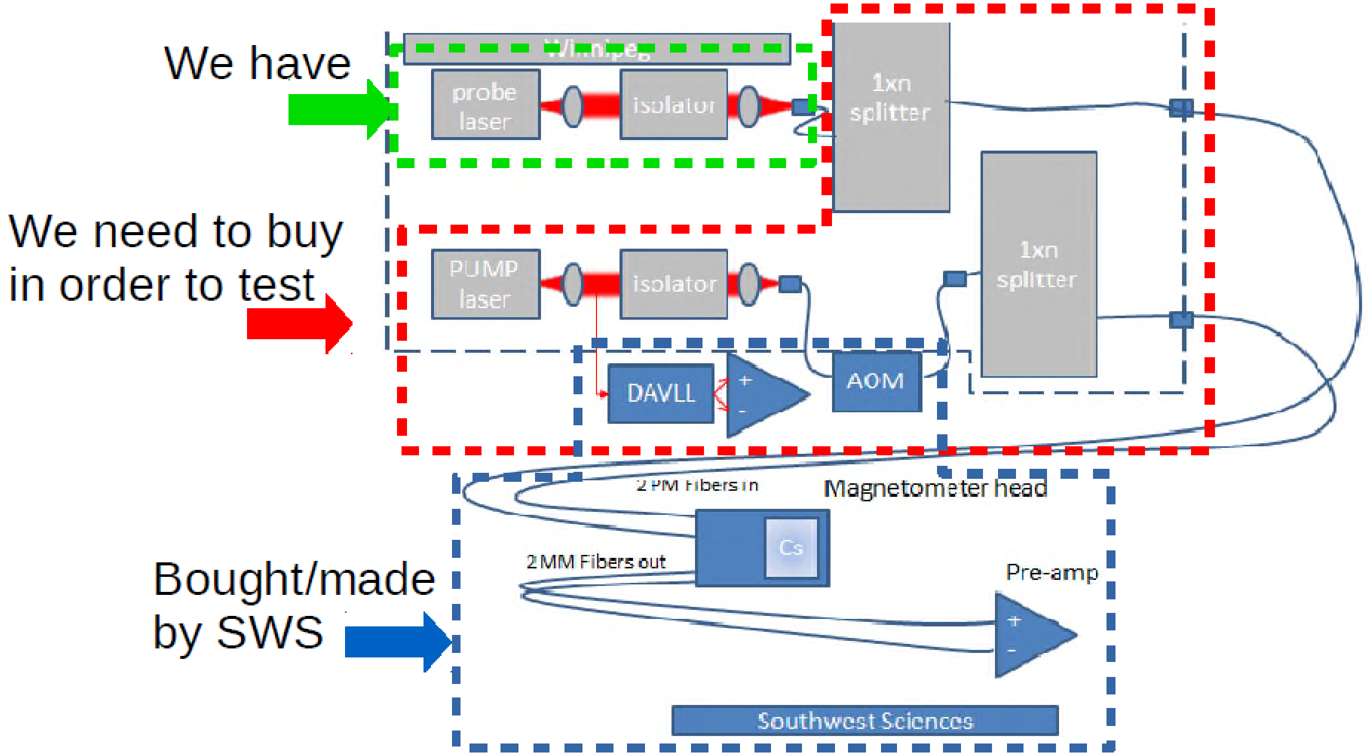
M. Das, MSc (U. Manitoba, 2019) Rb FID mode a chieves ~ 2pT in single shot, ~100 fT after 10 s averaging (Allan standard deviation)



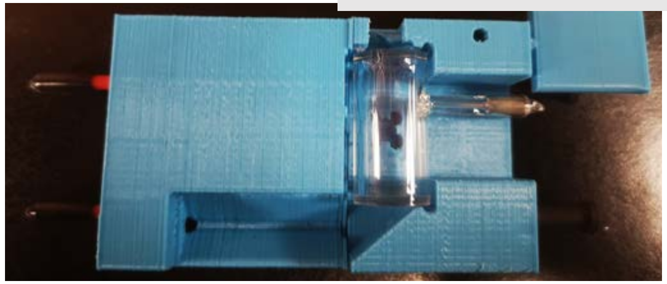
W. Klassen, MSc (U. Manitoba, 2020) Cs-based system, fiber optics, and positioning in nEDM expt.

"Wigner-Eckart theorem and the false EDM of ^{199}Hg"
W. Klassen, J.W. Martin, G. Pignol NIM A 922, 322 (2019).

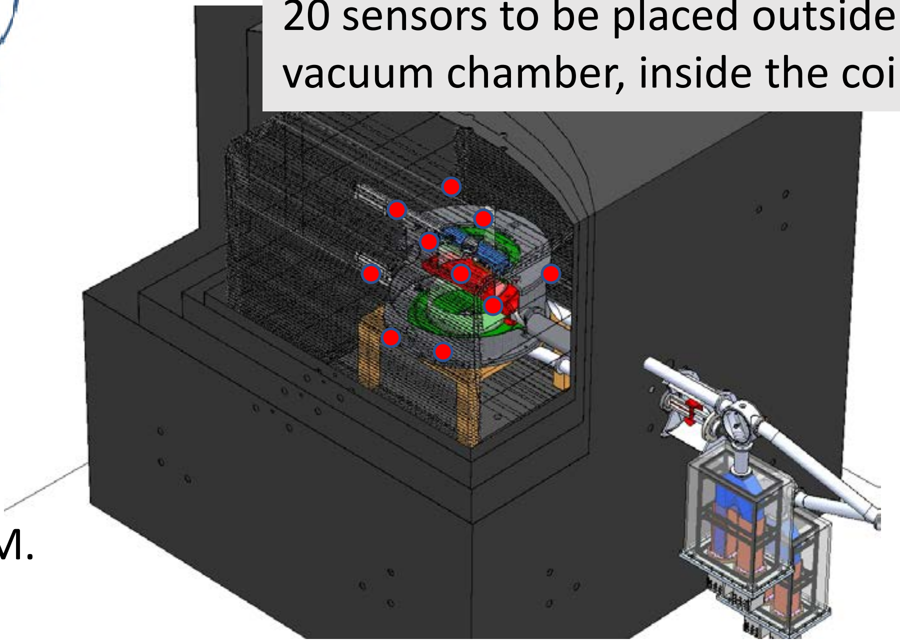
NMOR magnetometry in the EDM experiment



Fiberized sensor mock-up



20 sensors to be placed outside the vacuum chamber, inside the coils



- Cells tested in Winnipeg, integrated into sensors by SWS, Santa Fe, NM.
- First five cells tested and ready for integration.

More progress

- Other ongoing design/construction:
  - UCN detector (Winnipeg)
  - UCN spin analysis (RCNP Osaka, TRIUMF, Winnipeg)
  - HV/cell/valves/central region (TRIUMF)
  - Hg comagnetometer (UBC)
  - UCN guides (Winnipeg, KEK, TRIUMF)
  - HEX development (KEK, TRIUMF)

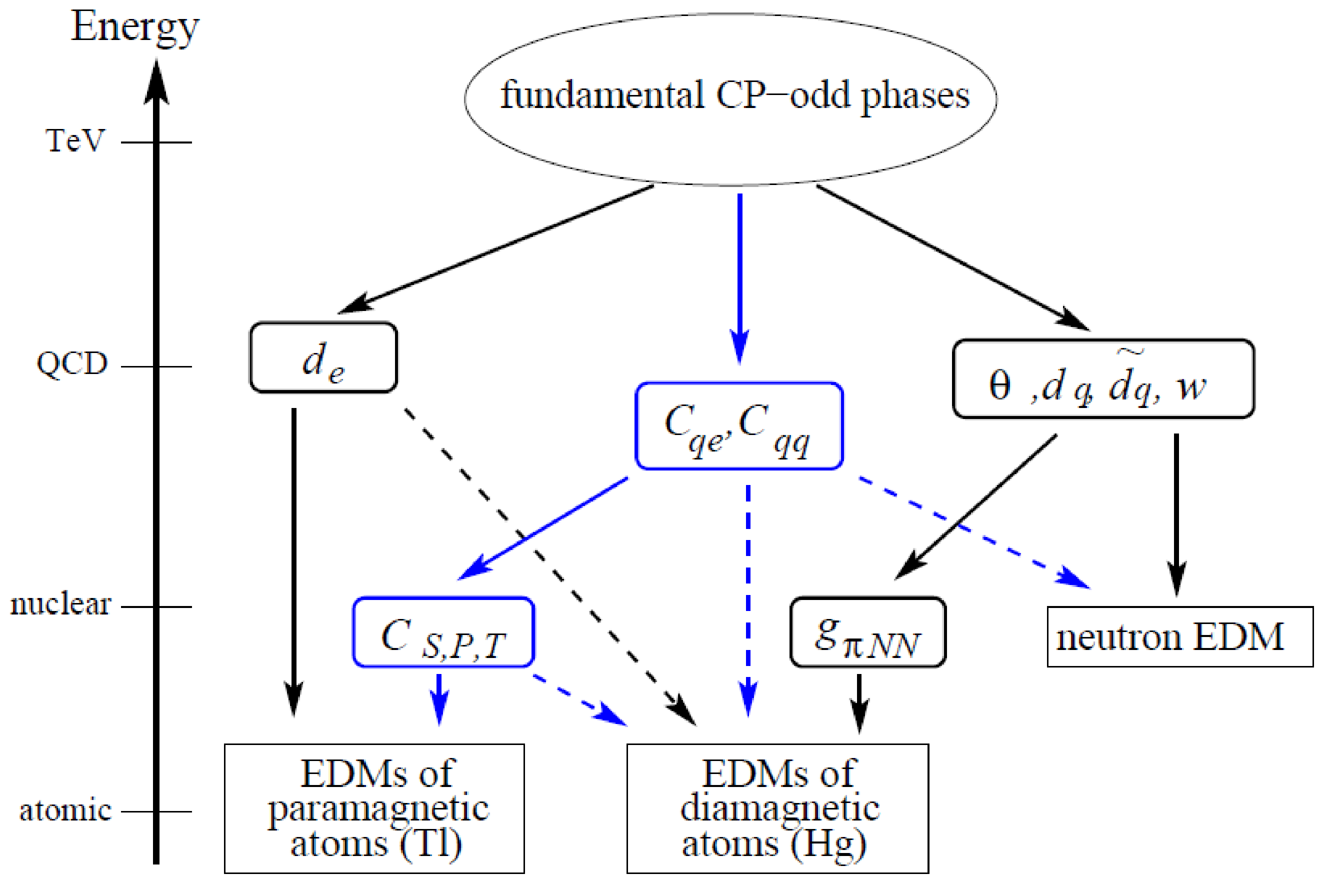
Backups

Competitiveness of nEDM vs. other EDM’s

and recent theoretical predictions specifically for nEDM

Heritage of EDM’s – how New Physics enters

$d_e < 1.1 \times 10^{-29}$ e-cm
(ACME ThO)

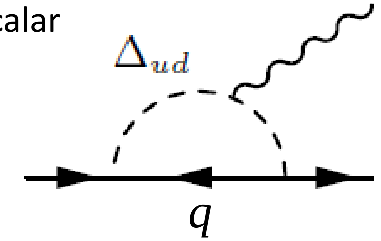


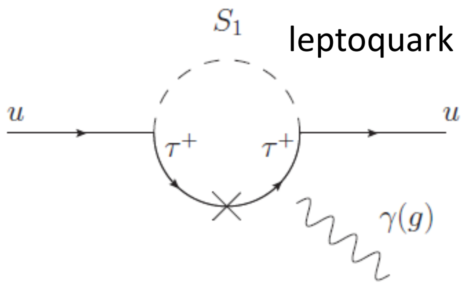
$d_n < 1.8 \times 10^{-26}$ e-cm
(PSI)
$d_n < 1.6 \times 10^{-26}$ e-cm
(U. Wash Hg-199)

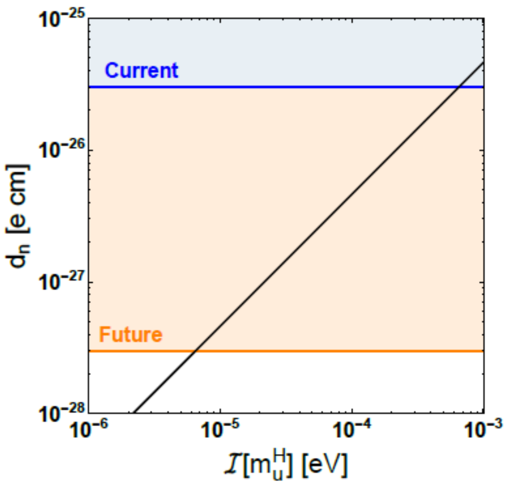
- Figure: Pospelov & Ritz, Ann. Phys. **318**, 119 (2005).
- See also: J. Engel, M. Ramsey-Musolf, U. van Kolck, Prog. in Part. and Nucl. Phys. **71**, 21 (2013).
  T. Chupp, P. Fierlinger, M. Ramsey-Musolf, and J. Singh, Rev. Mod. Phys. 91, 015001 (2019).

Survey of recent theoretical progress (focusing on d_n, recent arXiv)

Post-sphaleron uses new scalar







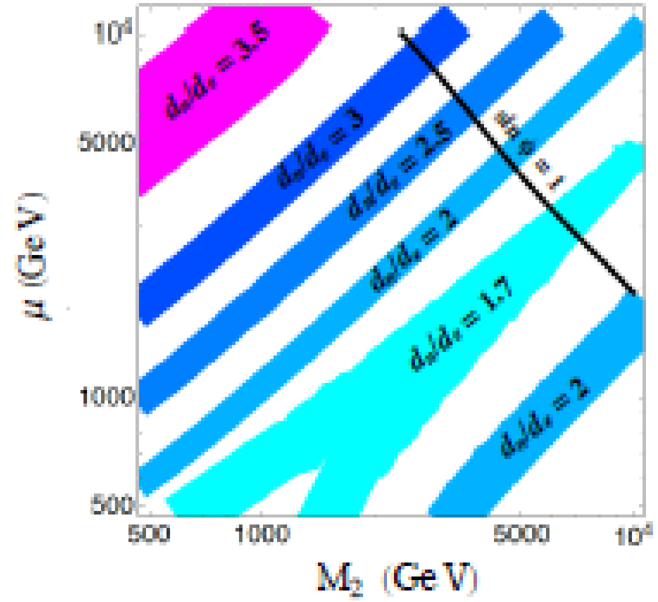
- Scalar leptoquark, relationship to B-decay
  - Crivellin & Saturnino arXiv:1905:08059
  - Dekens, de Vries, Jung & Vos arXiv: 1809.09114
- CP violation/baryogenesis in dark sector – generally doesn't predict large d_n (or d_e provides more stringent constraint/motivation)
  - Okawa, Pospelov & Ritz arXiv:1905.05219; Fuyuto, He, Li & Ramsey-Musolf arXiv:1902.10340; Carena, Quiros & Zhang PRL 122, 201802 (2019).
- $d_n \sim \mathrm{Im}[m_u]$, relating strong CP problem to seesaw mechanism of neutrino mass
  - Carena, Liu, Shah, Wagner & Wang, arXiv:1904.05360.
- Other new physics scenarios motivated by baryogenesis
  - Vector dileptons give enough CP violation in EWBG (d << present bound) Bell, Dolan, Friedrich, Ramsey-Musolf & Volkas arXiv:1903.11255
  - Post-sphaleron ΔB=2 requires more CP violation ($d_n \sim$ present bound) Bell, Corbett, Nee & Ramsey-Musolf, PRD 99, 015034 (2019).
- GUT -> θ (strong CP) -> observable d_n
  - Mimura, Mohapatra & Severson PRD 99, 115025 (2019).
- Time-dependent nEDM induced by axions
  - E.g. Flambaum & Tran Tan extend to atoms, molecules arXiv:1904.07609

Themes:

- New CP violation beyond SM
- Strong CP problem, axions
- Baryogenesis (especially EWBG)

Survey of theoretical progress (focusing on d_n, recent arXiv)

- CPV Higgs couplings, relationship to LHC
  - Cirigliano, Crivellin, Dekens, de Vries, Hoferichter, Mereghetti, arXiv:1903.03625
- How quark EDM's relate to neutron EDM (lattice QCD)
  - Gupta, Yoon, Bhattacharya, Cirigliano, Jang, Lin, Phys. Rev. D 98, 091501 (2018)
  - $d_n < 4 \times 10^{-29}$ e-cm in split SUSY (quite an experimental challenge!)



Backups

Competitiveness and physics of superfluid helium UCN source

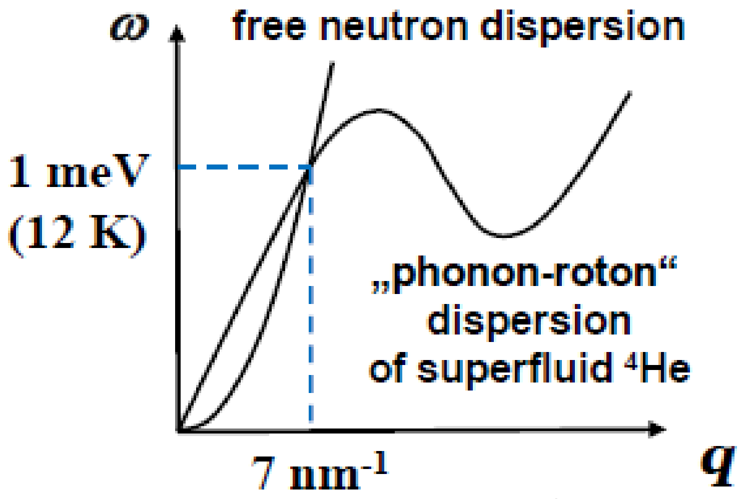
Survey of UCN Sources Worldwide

Place	Neutrons	UCN converter	Status
ILL	Reactor, CN	Turbine	Running
J-PARC	Spallation	Doppler shifter	Running
ILL SUN-2	Reactor, CN	Superfluid He	Running
ILL SuperSUN	Reactor, CN	Superfluid He	Upgrading
RCNP/KEK/TRIUMF	Spallation	Superfluid He	Upgrading
Gatchina WWR-M	Reactor	Superfluid He	Future
LANL	Spallation	Solid D2	Running
Mainz	Reactor	Solid D2	Running
PSI	Spallation	Solid D2	Running
NSCU Pulstar	Reactor	Solid D2	Commissioning
FRM-II	Reactor	Solid D2	Future

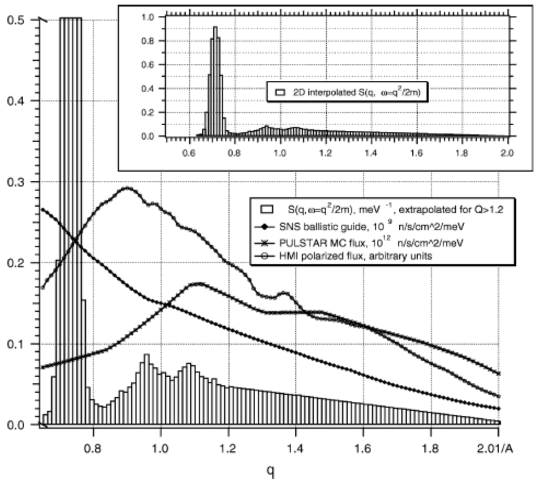
TUCAN combination of spallation target and superfluid helium is unique.
Upgrade schedule is competitive with other leading sources of UCN.

Superfluid ^{4}He production of UCN

- Incident CN @ 1 meV excites one phonon
  Golub and Pendlebury, 1975, 1977
- Multiphonon excitation give additional production
- Pressurizing superfluid shifts dispersion curve
  Schmidt-Wellenburg et al., PRC **92**, 024004 (2015)



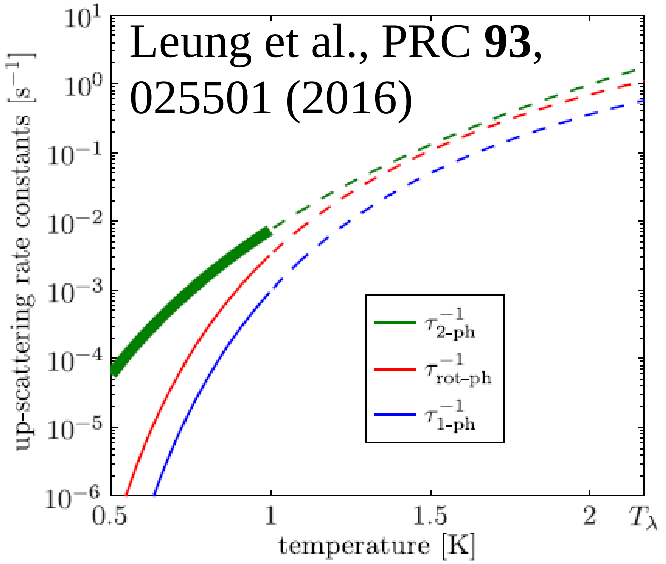
Courtesy of O. Zimmer

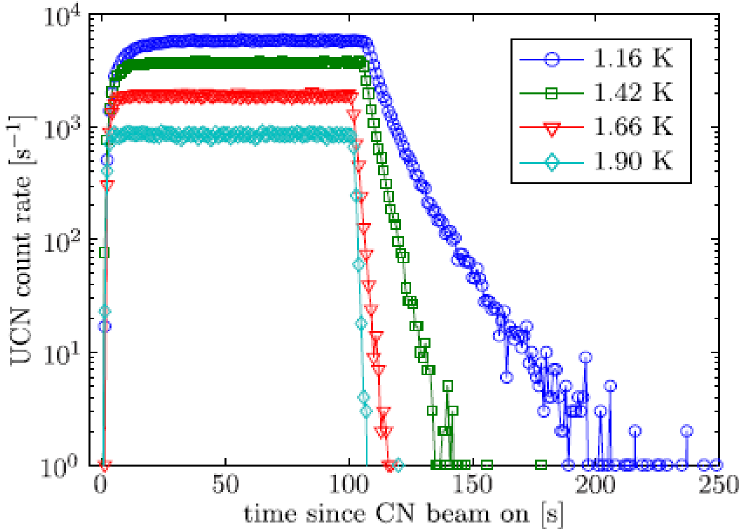


Korobkina et al.,
PLA **301**, 462 (2002)

Superfluid ^{4}He losses of UCN

- Losses dominated by 2-phonon upscattering loss rate ~ T^7
- Recent measurements establish this up to T ~ 2.2 K
- T < 0.8 K gives τ_{UCN} > 300 s
- Challenge:
    - T < 0.8 K
    - Extraction (concept of SNS-nEDM, NIST n-lifetime)





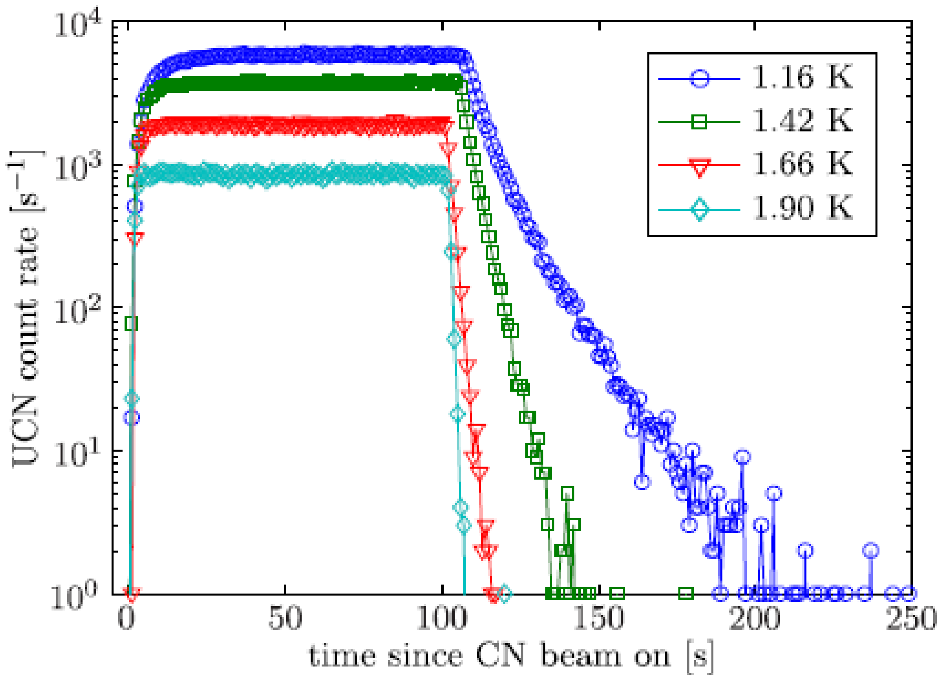
UCN Losses in Superfluid Helium (He-II)

- Key question for this project:
  - At design beam current 10 Watts of heat enter the He-II
  - Can we keep the He-II cold enough, at far end of long channel?

UCN are always far from thermal equilibrium:

$T_{neutron} < 0.003$ K

$T_{superfluid} \sim 1$ K



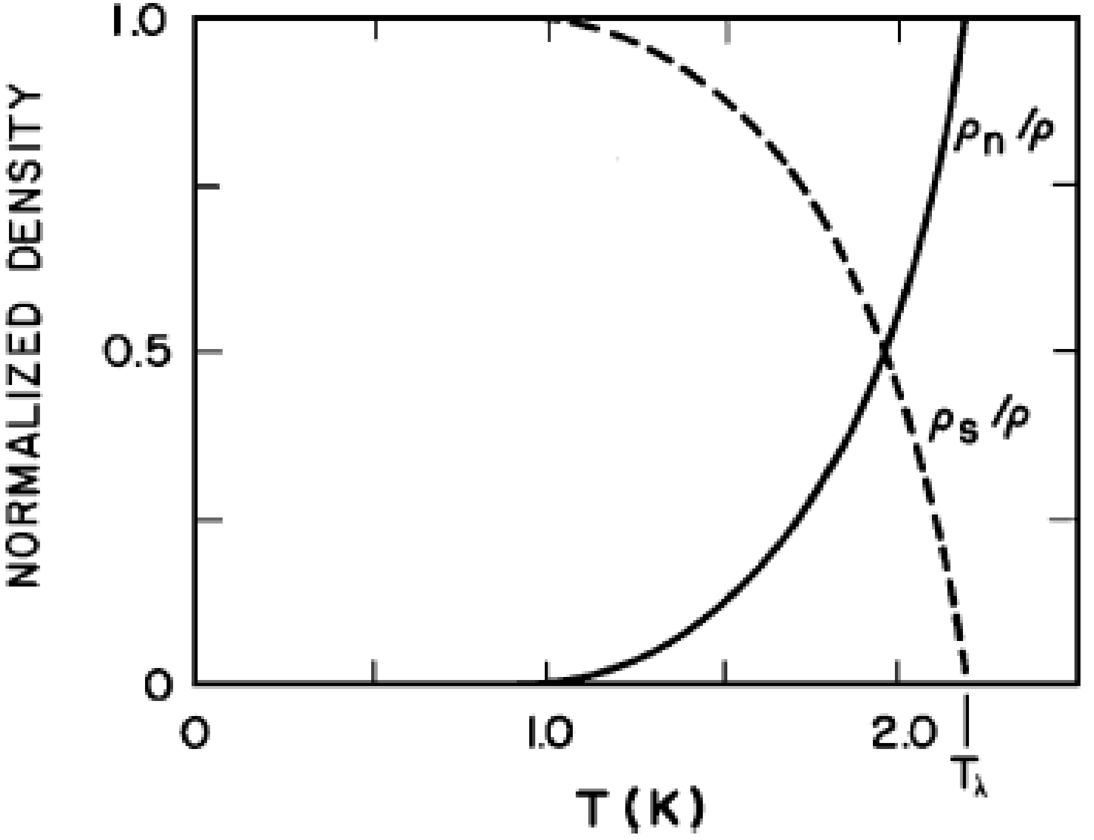
Leung et al., PRC **93**, 025501 (2016) measurements from ILL Grenoble

Losses dominated by 2-phonon UCN upscattering

loss rate ~ $T^7_{superfluid}$

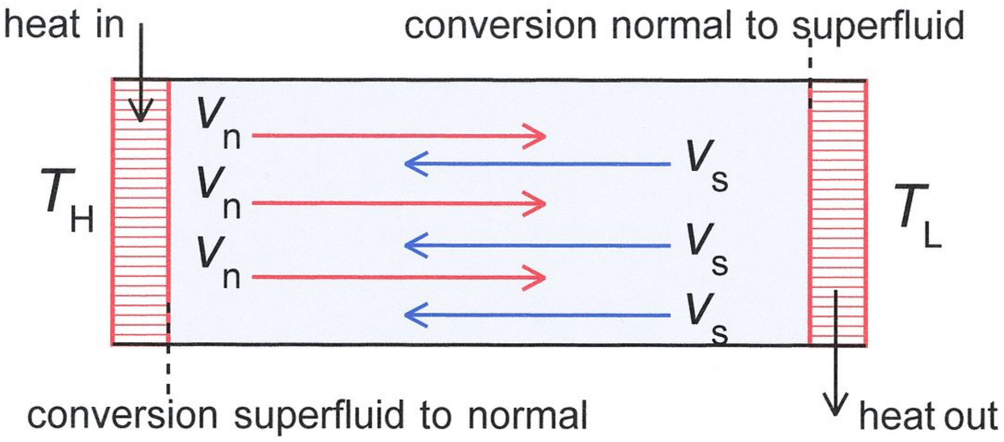
Two-fluid model of He-II

- He-II is made up of
  - Superfluid component ρ_s (entropy = 0, viscosity = 0)
  - Normal fluid component ρ_n
- Good at explaining viscosity contradictions, thermal transport properties, second sound, …

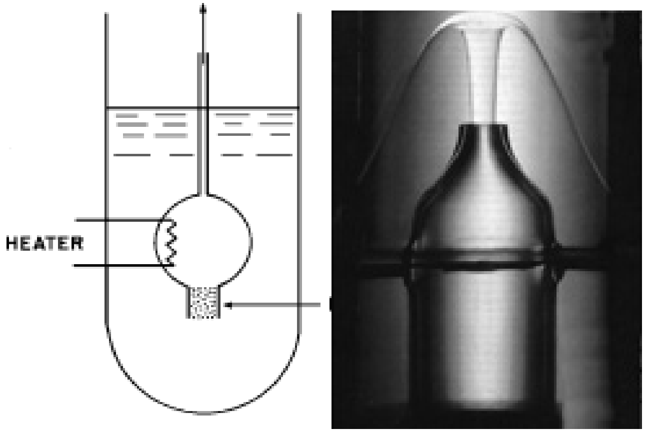


Thermal “Counterflow”

- Superfluid component flows towards heat source, normal component flows away.
- Normal component carries away entropy.
- Basis of heat transport is thermal counterflow of normal vs. superfluid components.

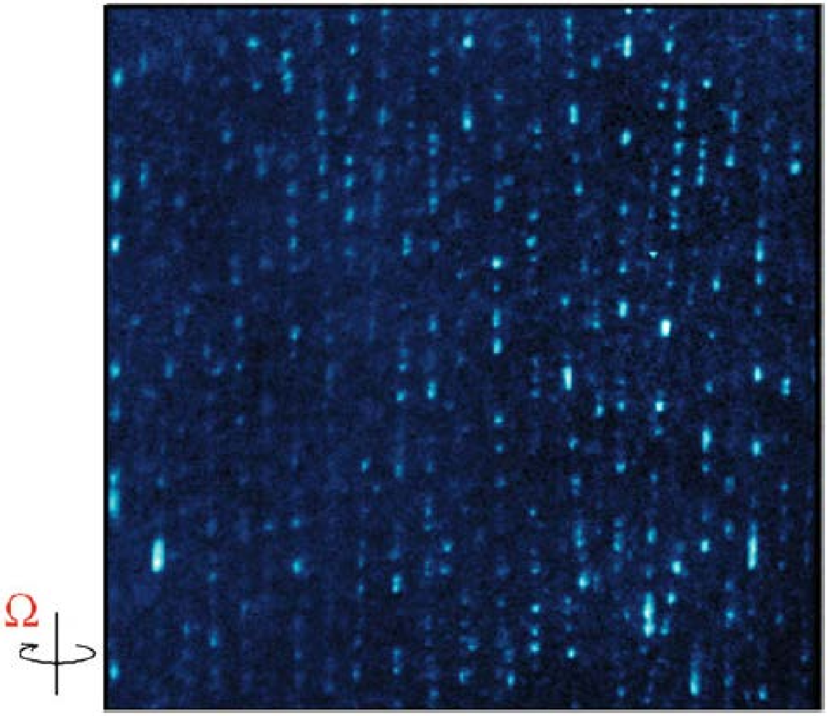


Nature **141,** 243-244 (1938)

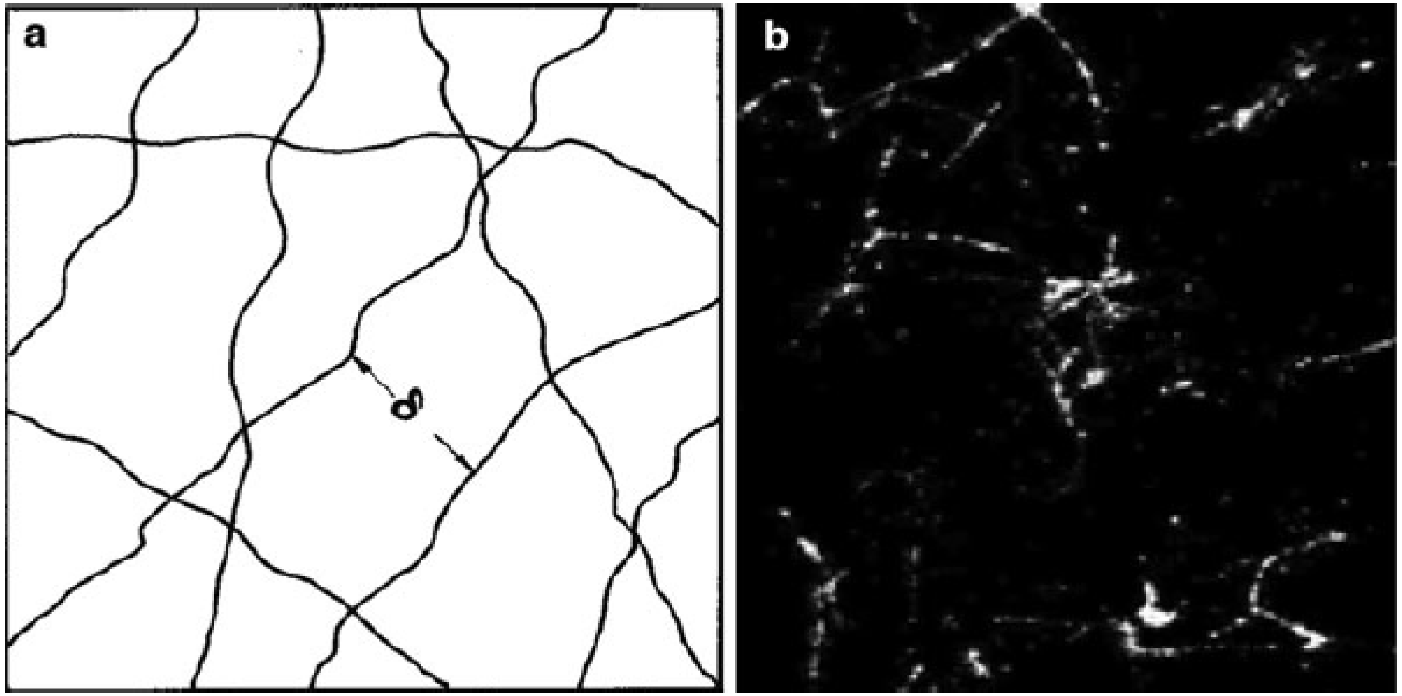


Fountain Effect

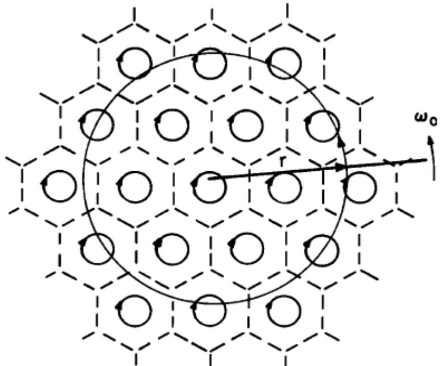
Turbulent He-II and Quantum Vortices



Vortices in rotating He-II



Vortices in thermal counterflow



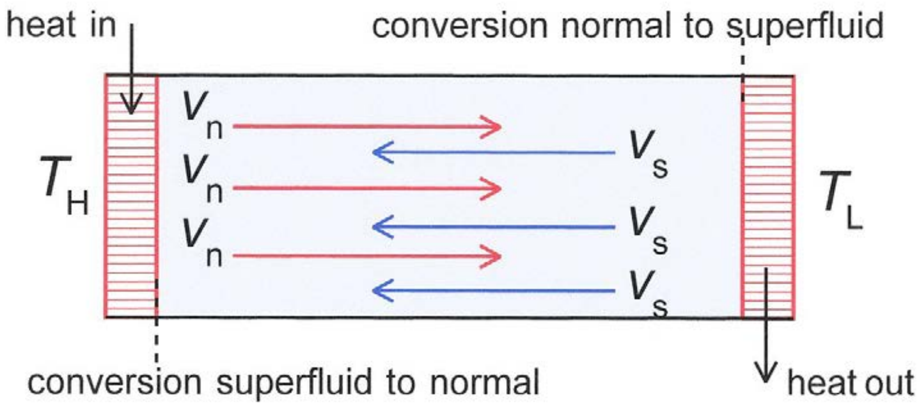
Circulation is quantized.

$$\oint \vec{p} \cdot d\vec{q} = nh$$

Images from van Sciver, *Helium Cryogenics*.
Hydrogen particles attached to vortices.

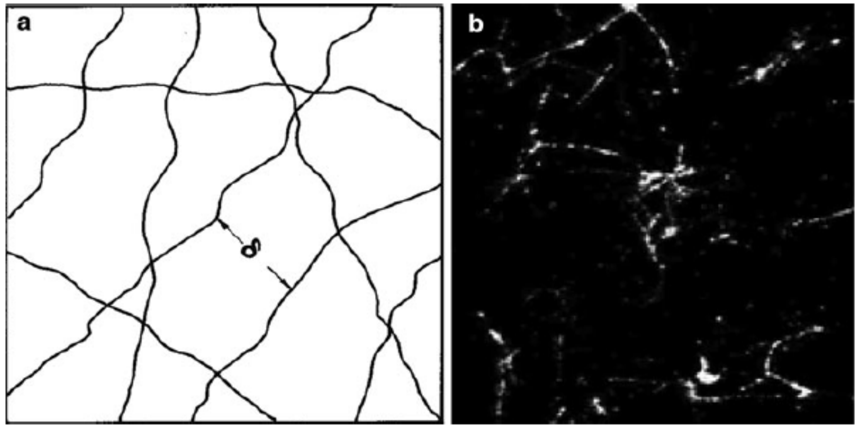
Turbulence in Thermal Counterflow

- For large heat flux, $|v_n - v_s|$ is large.
- Friction force between normal and superfluid creates vortex tangles.
- Normal component, which carries away heat, is impeded by mutual friction with vortices.



$$\frac{dT}{dx} = -\frac{\beta \mu_n q}{d^2(\rho s)^2 T} - \frac{A_{GM}\rho_n}{\rho_s^3 s^4 T^3} q^3$$

viscous turbulent



Conclusion: Turbulent He-II does not conduct heat like a usual material ~ q^3, indicates presence of vortices.

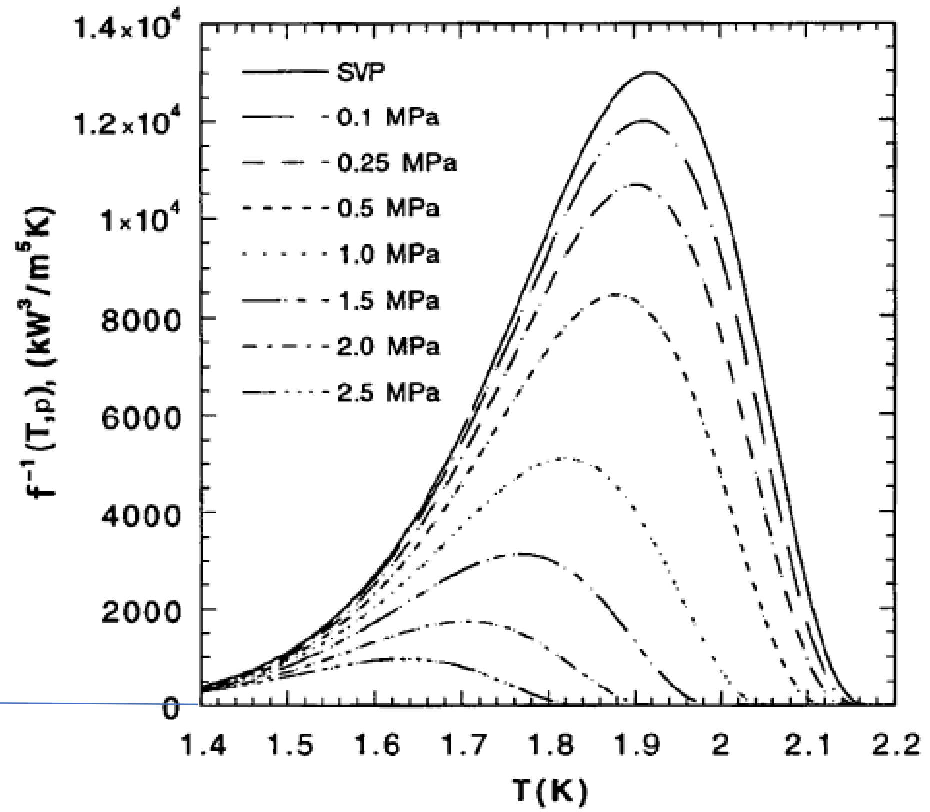
Heat conduction of turbulent He-II

- Empirical fits to data for "thermal conductivity function"
- Strong

$$\frac{dT}{dx} = -f(T, p)q^m$$

m =~ 3
According to expt.

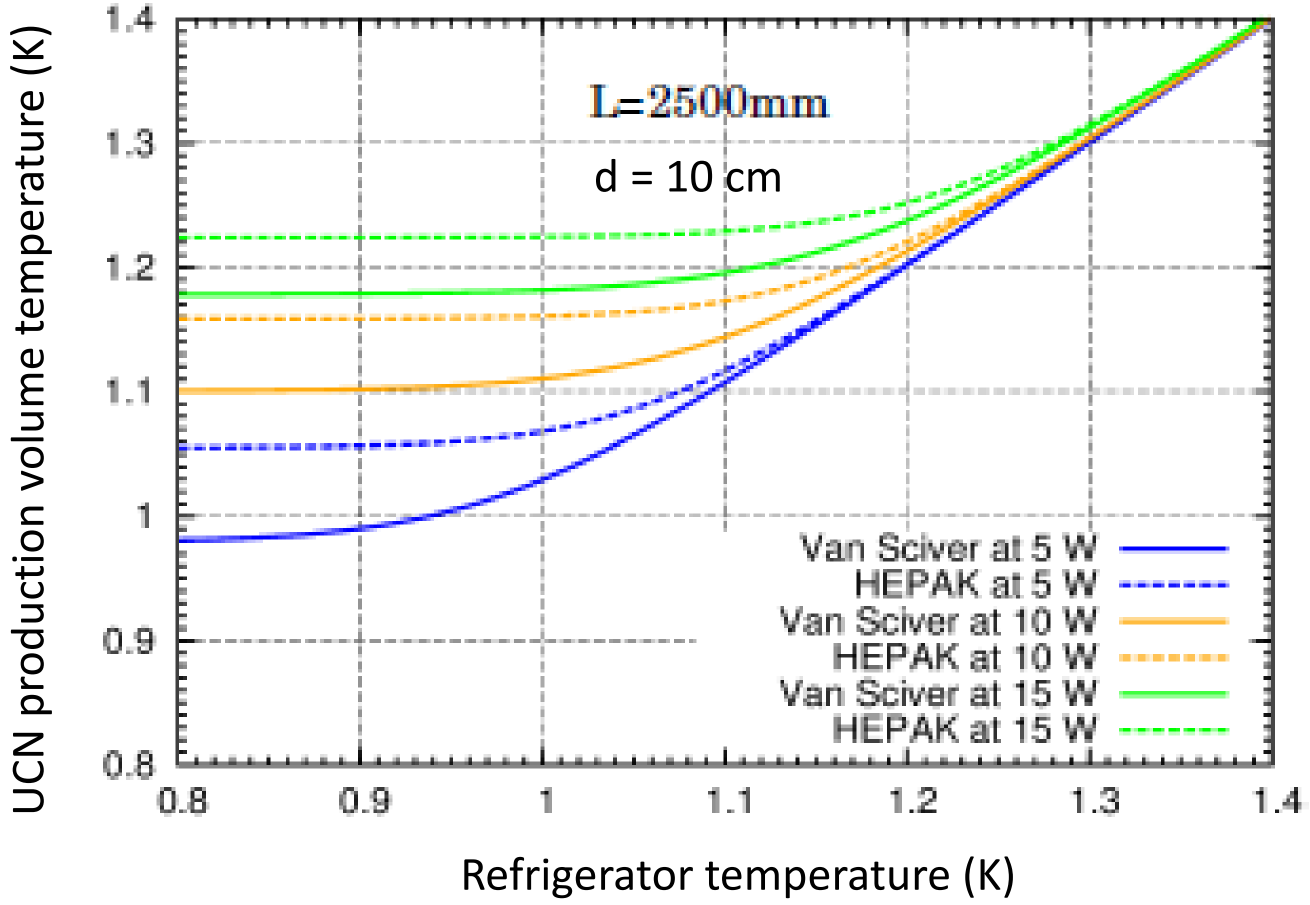
  - Basis of e.g. LHC
- Small "conductivity" at lower temperatures.



Our experiment
0.8 – 1.0 K

Most measurements

Calculation for our UCN Source based on Gorter-Mellink fits

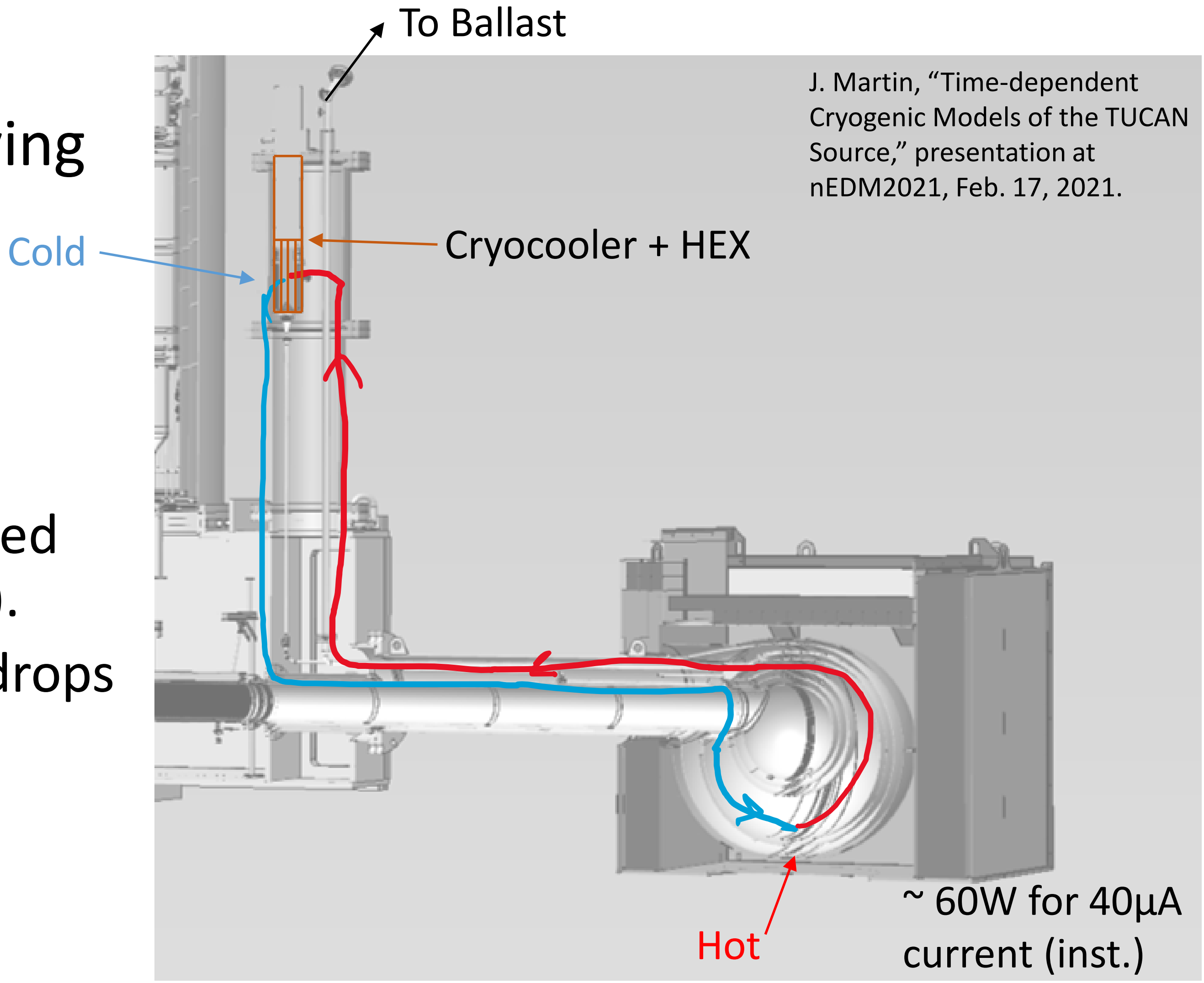


Example of calculations by T. Okamura, KEK

- For 10 W heat input, UCN production volume cannot be cooled below 1.1 K, no matter how much refrigeration power available.
- Strongly dependent on channel diameter ~ d^6

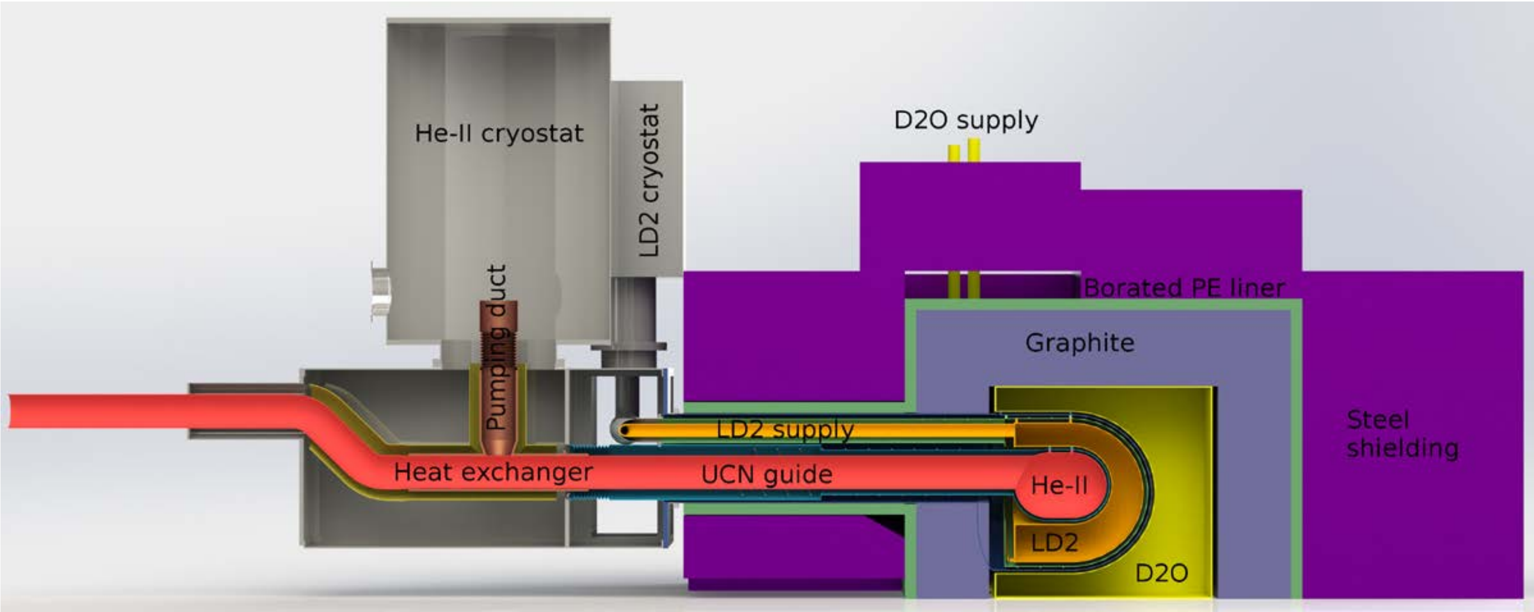
LD_2 thermosyphon (natural circulation system)

- Features: single-phase, no moving parts
- Engineering studies completed:
  - 1D time-dependent model of circulation.
  - HEX studies (fins vs. multi-threaded helix, heat xfer vs. pressure drop).
  - Detailed accounting of pressure drops around the whole loop.



He-II time-dependent thermal modeling

10x faster thermal response and smaller temperature gradient, with x40 increase in beam power



J. Martin, "Time-dependent Cryogenic Models of the TUCAN Source," presentation at nEDM2021, Feb. 17, 2021.

t = 10 sec.