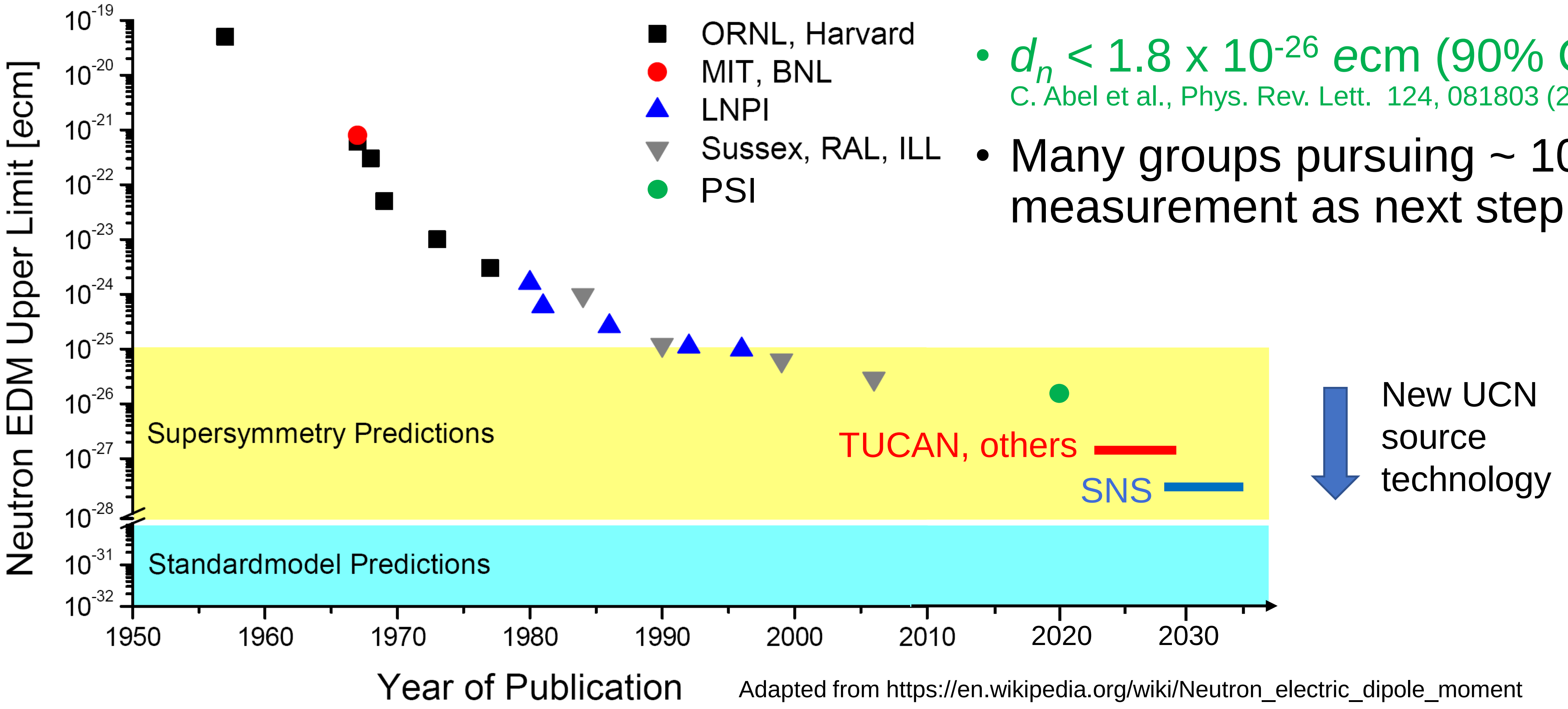
Progress towards a measurement of the neutron electric dipole moment using a world-leading ultracold-neutron source at TRIUMF + Magnetics

TUCAN
TRIUMF Ultra Cold Advanced Neutron source

Wolfgang Schreyer
Given by Russell Mammei
on behalf of the TUCAN collaboration

CIPANP 2022

A great way to annoy theorists

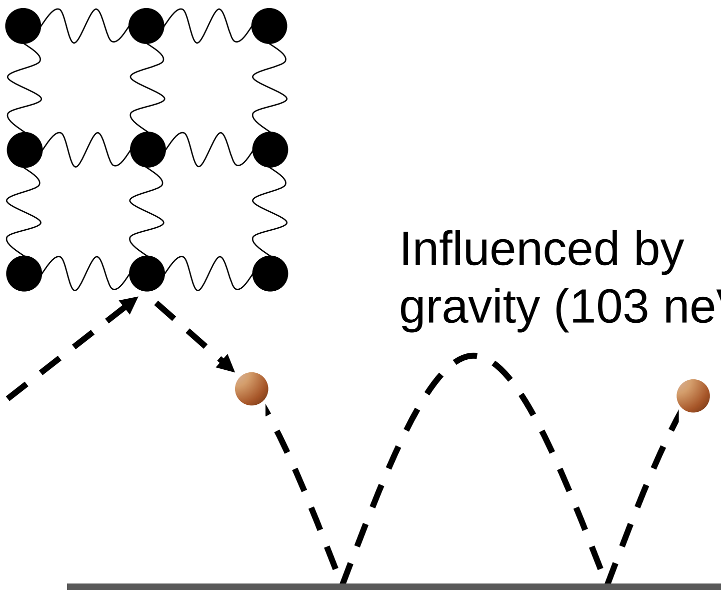


- $d_n < 1.8 \times 10^{-26}$ *e*cm (90% C.L.)
  C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
- Many groups pursuing ~ 10^{-27} *e*cm measurement as next step

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

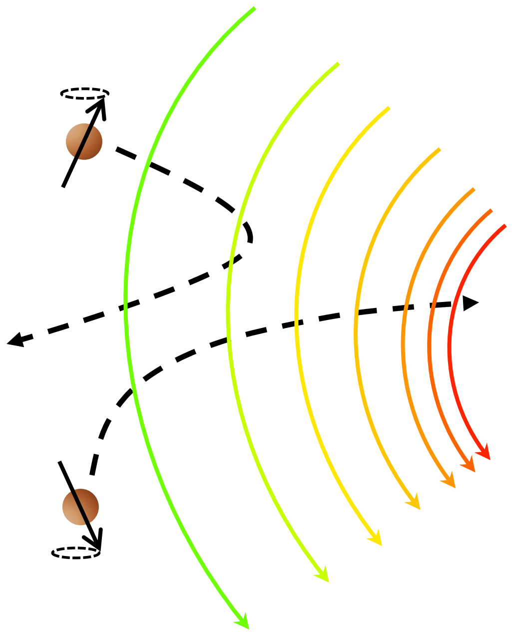
Ultracold neutrons are the ideal tool for nEDM searches

Convert cold neutrons to ultracold through phonon-scattering
1 meV → 100 neV



Influenced by gravity (103 neV/m)

Totally reflected by many materials (Fe: 209 neV, Ni: 245 neV)



Interact with magnetic field (60.3 neV/T)

- $\sigma_d = \frac{\hbar}{2\alpha ET\sqrt{N}}$
- $T \approx 200$ s ☺
- $\alpha \approx 0.7$ ☺
- $N \approx 10^4$ per cycle ☹
- $E \approx 10$ kV/cm

Sensitivity of an EDM measurement

TRIUMF Ultra Cold
Advanced Neutron source

Sensitivity of nEDM experiment $\sigma(d_n) \propto \dfrac{1}{E\tau\sqrt{N}}$

E : strength of applied electric field
τ : interaction time
N : neutron counts

	Free flight metod	Crystal diffraction method	UCN method
interaction tome τ [s]	$\sim 10^{-1}$	$\sim 10^{-3}$	$\sim 10^{2}$
electric field E [V/cm]	$\sim 10^{4}$	$\sim 10^{8}$	$\sim 10^{4}$
neutron counts n [n/s]	$\sim 10^{8}$	$\sim 10^{4}$	$\sim 10^{2}$ $\Rightarrow 10^3$
sensitivity σ(d_n)	$\sim 10^{-25}/\sqrt{\mathrm{Day}}$	$\sim 10^{-25}/\sqrt{\mathrm{Day}}$	$\sim 10^{-25}/\sqrt{\mathrm{Day}}$ $\Rightarrow 2\text{x}10^{-26}/\sqrt{Day}$

TUCAN

Each value is regulated to be same sensitvity for the purpose of making characteristc of each method clear

All methods have the possibility to get the sensitivity at the same level.

Slide by Shigeyasu Itoh

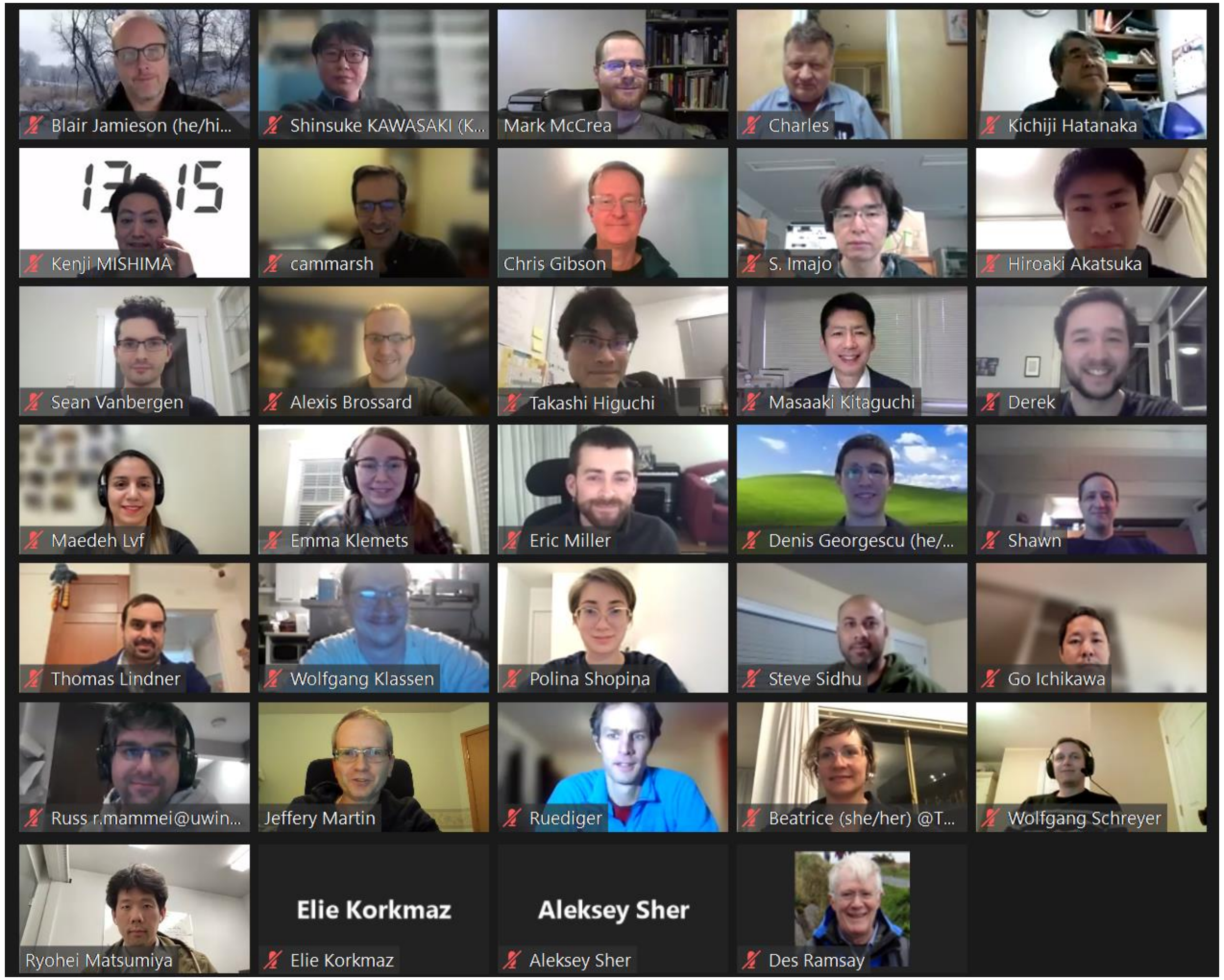
TUCAN

Advanced Neutron source

TUCAN collaboration and goals

TRIUMF

TRIUMF UltraCold Advanced Neutron Collaboration



Jan. 2022 virtual collaboration meeting

TUCAN collaboration goals:

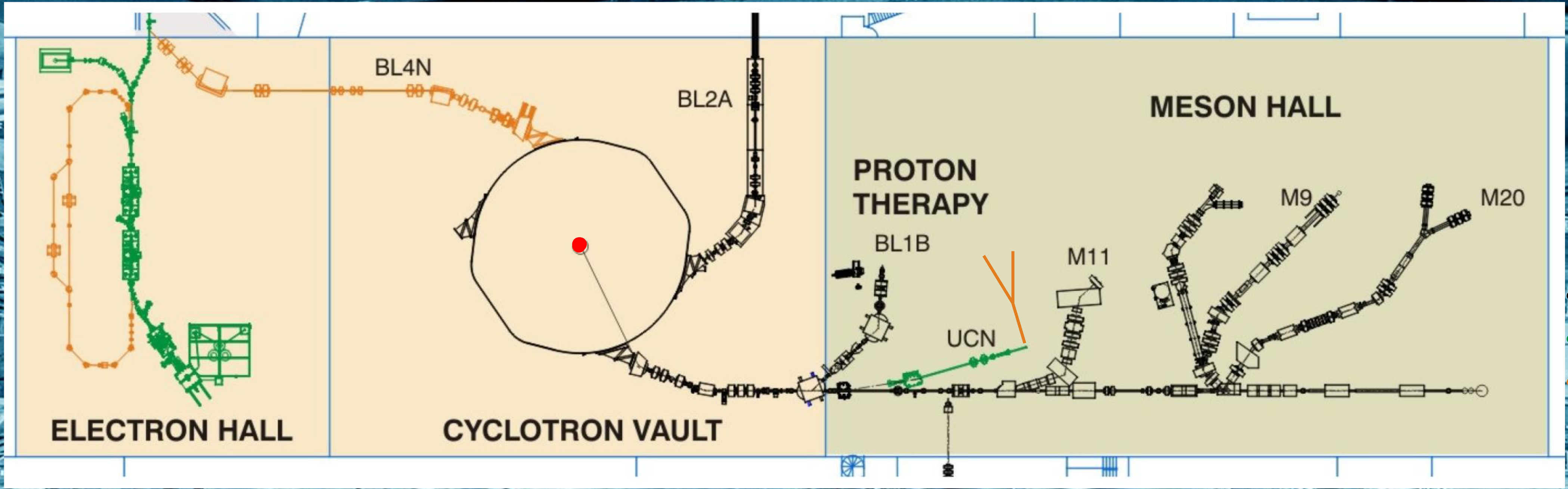
1. Create the world's **strongest ultracold neutron source** **using the TRIUMF cyclotron**.
2. **Search for a neutron electric dipole moment** with a **sensitivity of 10-27 e cm (1-σ) in 400 beam days.**
3. Create an **international user facility** for fundamental research using ultracold neutrons.

H. Akatsuka[1], C. Bidinosti[2], A. Brossard[3], C. Davis[3], B. Franke[3,4], D. Fujimoto[3], M. Gericke[5], P. Giampa[6], R. Golub[7], S. Hansen-Romu[5,2], K. Hatanaka[8,*], T. Higuchi[8], G. Ichikawa[9], S. Imajo[8], B. Jamieson[2], S. Kawasaki[9], M. Kitaguchi[1], W. Klassen[4,5,2], E. Klemets[4], A. Konaka[3,10], E. Korkmaz[11], E. Korobkina[7], F. Kuchler[3], M. Lavvaf[5,2], T. Lindner[3,2], K. Madison[4], Y. Makida[9], J. Mammei[5], R. Mammei[2,3], J. Martin[2,*], R. Matsumiya[3], M. McCrea[2], E. Miller[4], K. Mishima[9], T. Momose[4], T. Okamura[9], H.J. Ong[8], 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[9]

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

*co-spokespersons (K. Hatanaka and J. Martin)

The TRIUMF beam delivery system



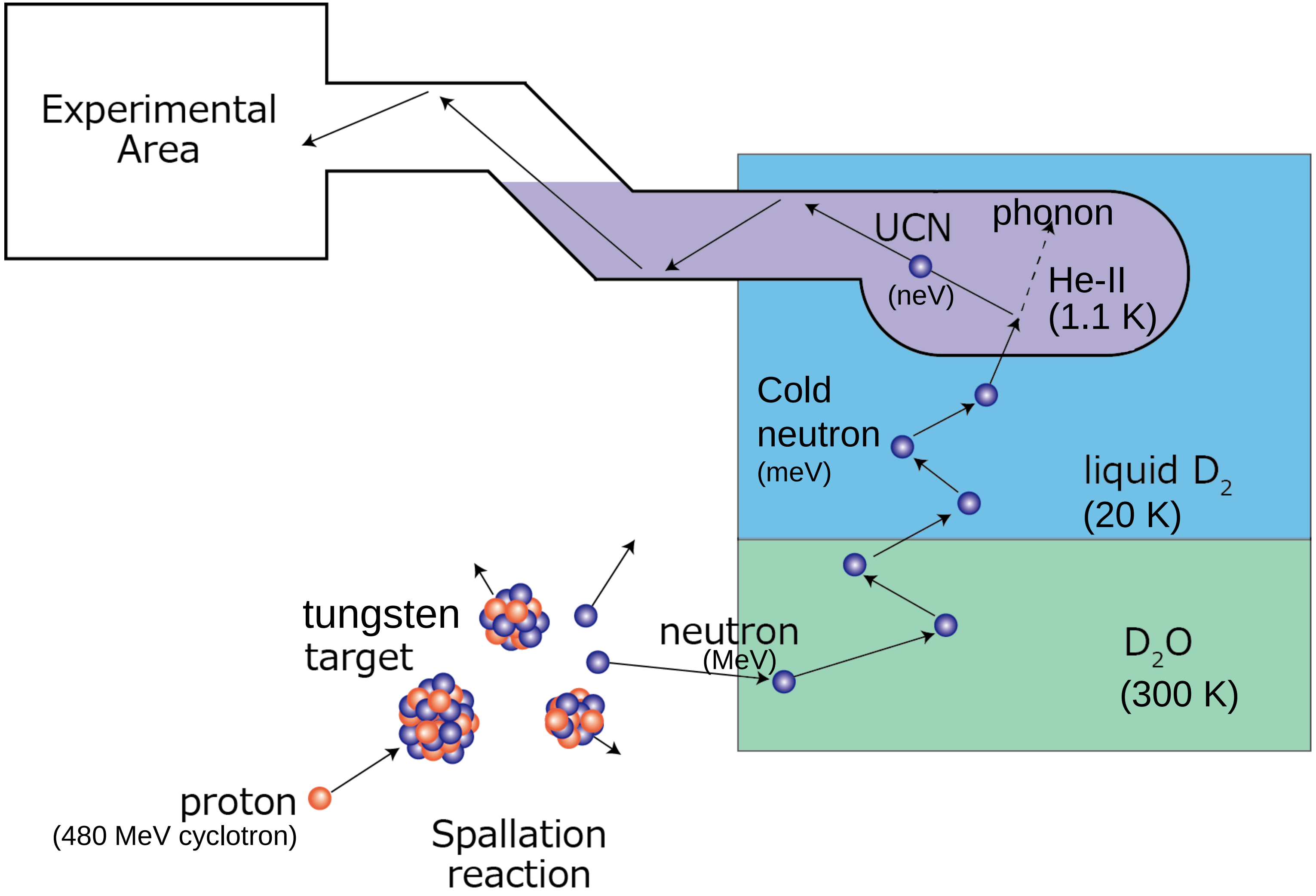
- Existing
- New
- Planned

- **H^- ions** are accelerated by TRIUMF's main cyclotron (up to 520 MeV).
- Foils strip electrons and **p^+ can be extracted** at selectable radii (and energies).
- **Three beamlines** can be fed with up to 120 μ A simultaneously.

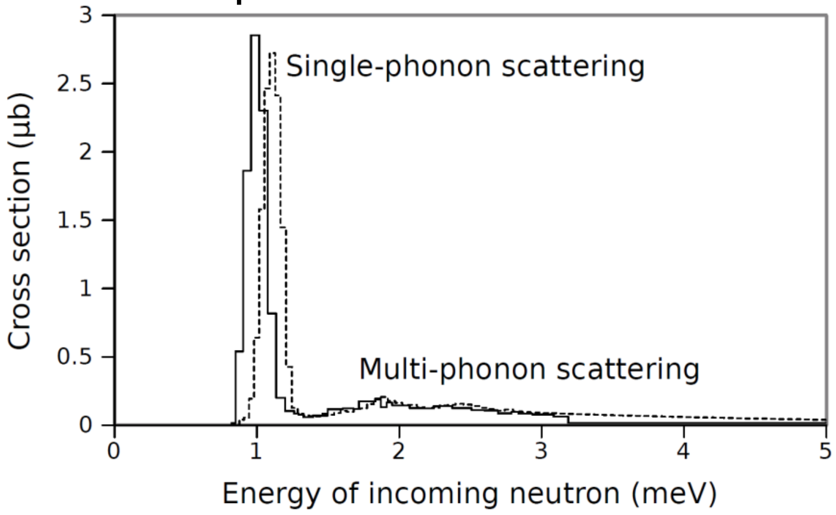
- Simultaneous operation of different facilities
  - Nuclear Physics, Particle Physics, Life Sciences, Material and Molecular Science, Material Irradiation with Protons and Neutrons
- **UCN shares the beam with CMMS**
  (Center for Material and Molecular Science)

Inside the TRIUMF cyclotron

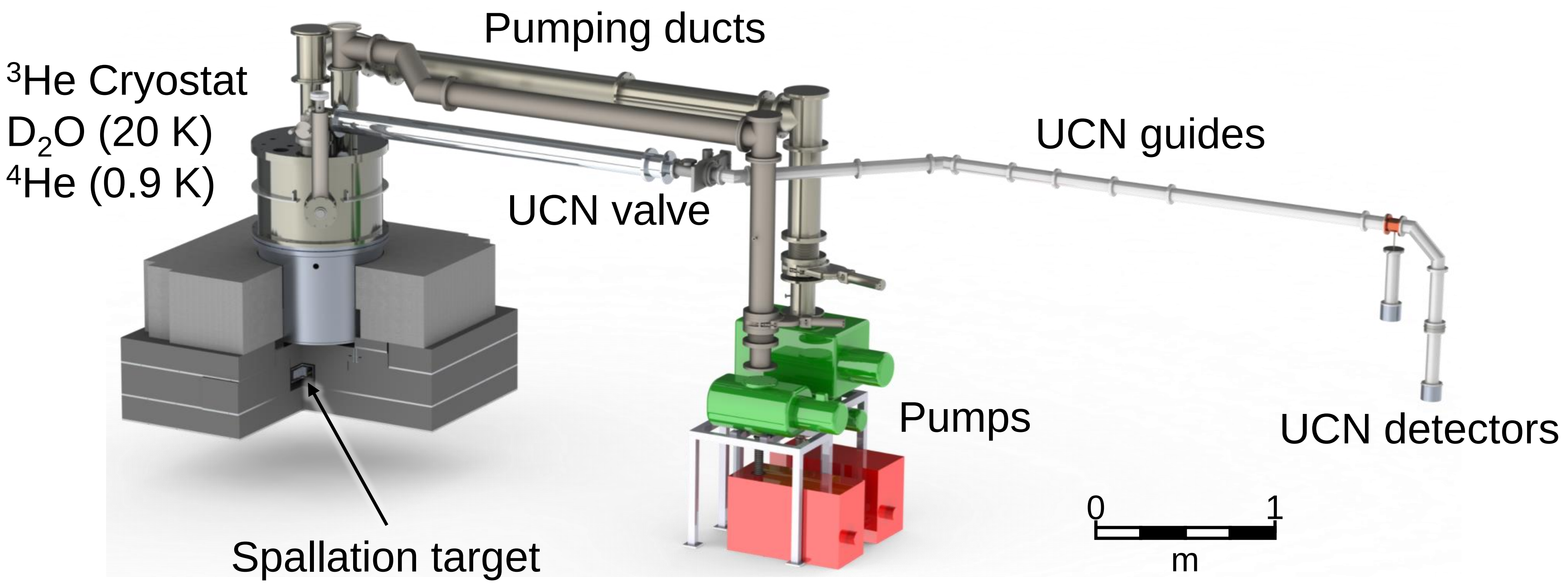
A unique spallation-driven UCN source using superfluid helium



UCN-production cross section in superfluid helium



Prototype source (decommissioned 2020)

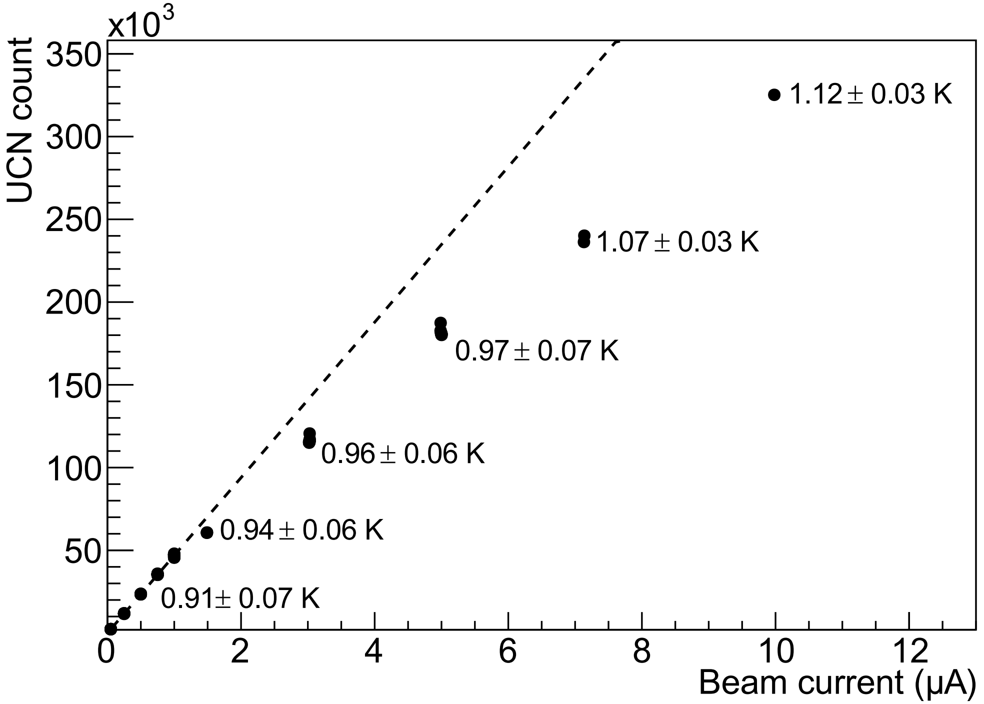


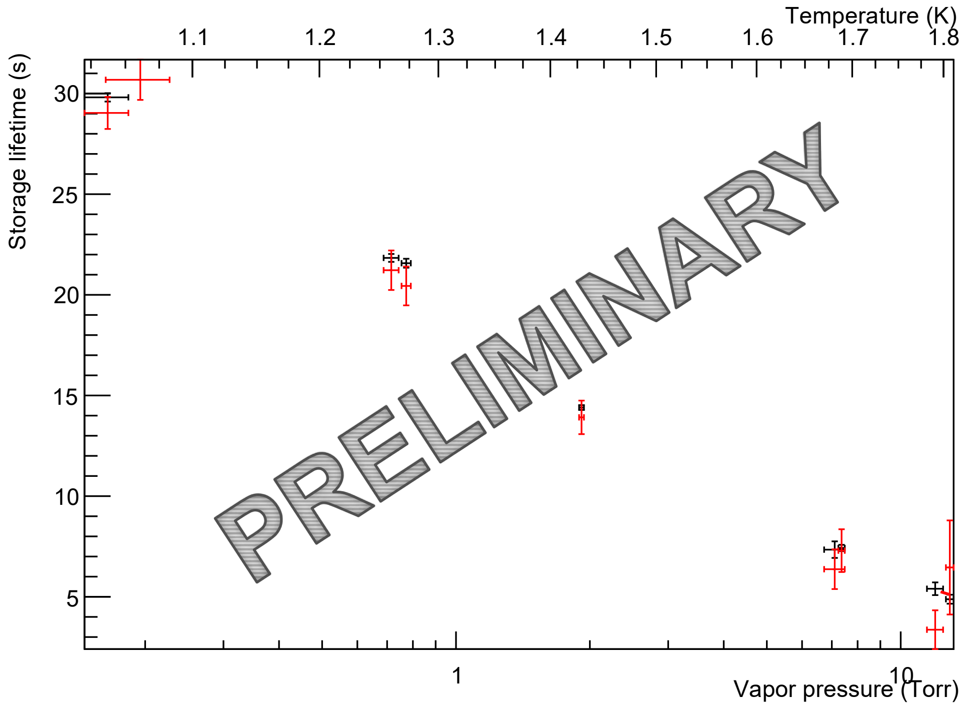
Helped us learn a lot during three runs (2017 – 2019):

- Potential performance bottlenecks, clogging issues
- Tested UCN guides (polishing, NiP coatings), valves, polarizers & detectors

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

Performance of prototype source



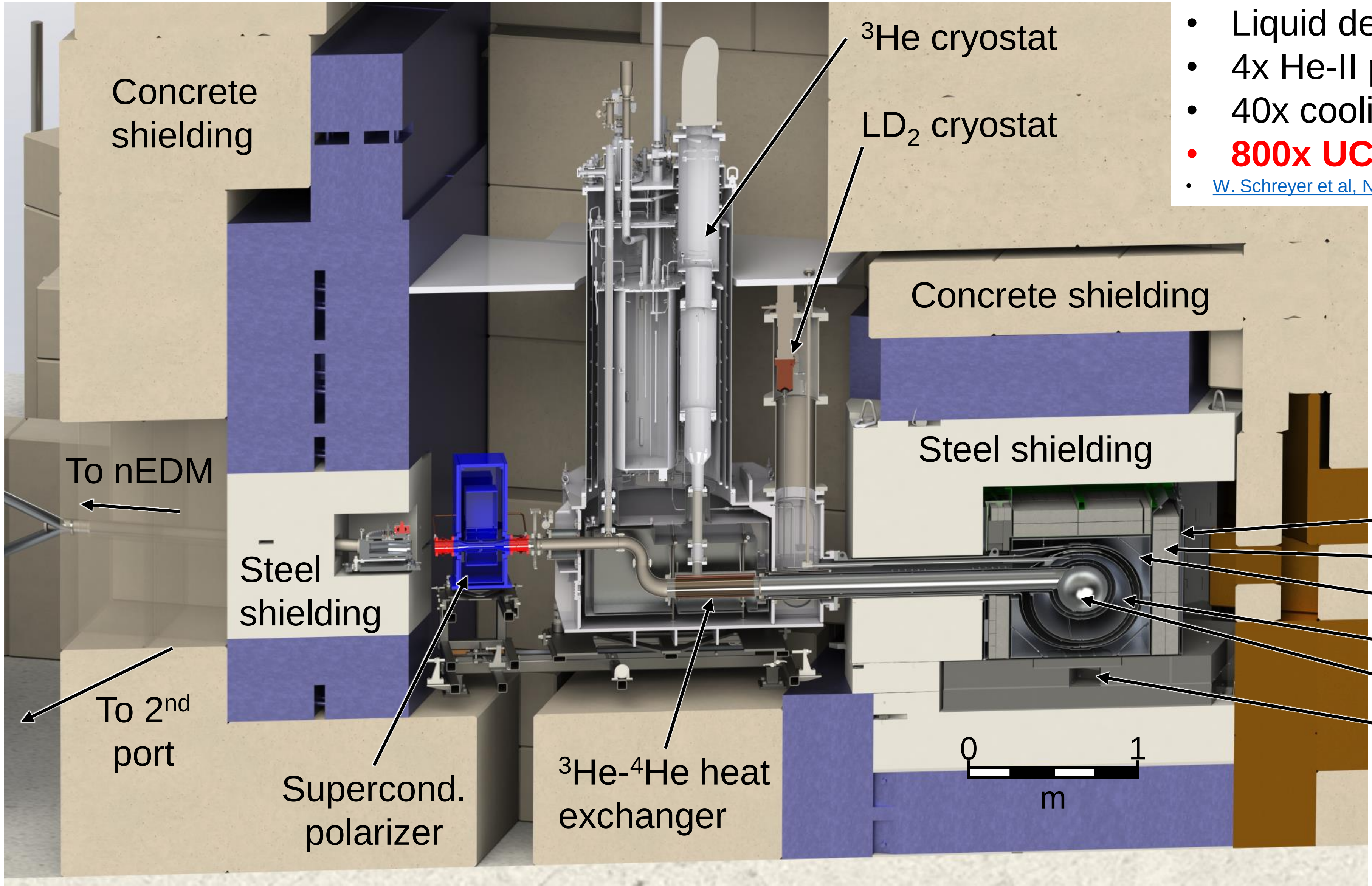


UCN lifetime in He-II strongly dependent on temperature ➔ need low temperature, high cooling power

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

TUCAN source

- 40x proton-beam current
- Optimized moderator geometry
- Liquid deuterium moderator
- 4x He-II production volume
- 40x cooling power (10 W @ 1.1 K)
- **800x UCN-production rate (1.5x10^7)**
- W. Schreyer et al, Nucl. Instrum. Meth. Phys. Res. A 927, 101-108 (2019)

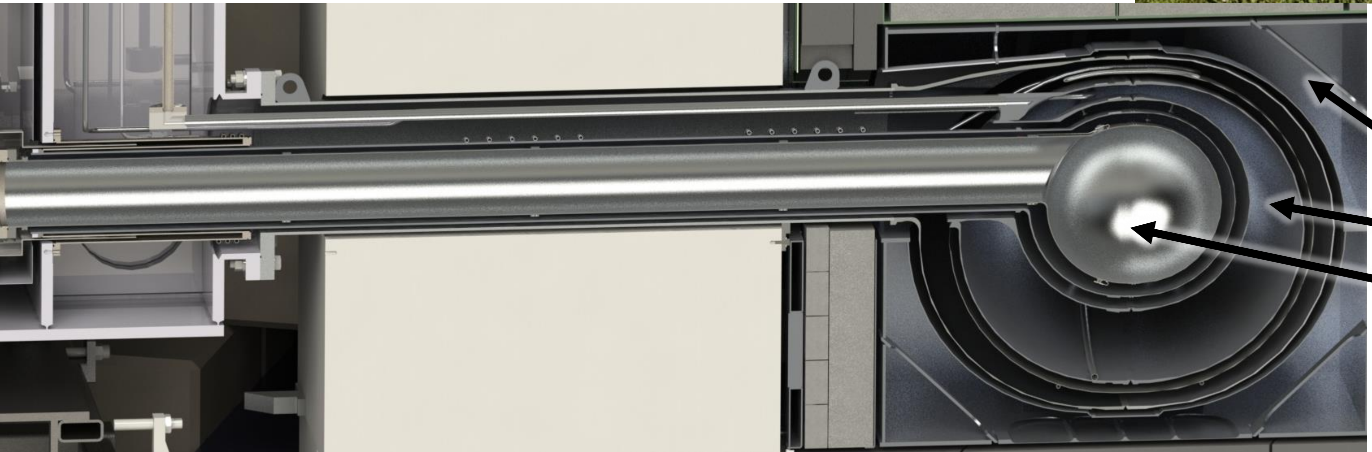


Superfluid-helium converter vessel

- Machined, thin-walled Al domes to minimize neutron absorption and heat load
- UCN-reflective NiP coating: Measured UCN storage lifetime at LANL in 2021
  ➔ higher loss rate than expected, but acceptable
- Superfluid-tight: Undergoing extensive leak checking

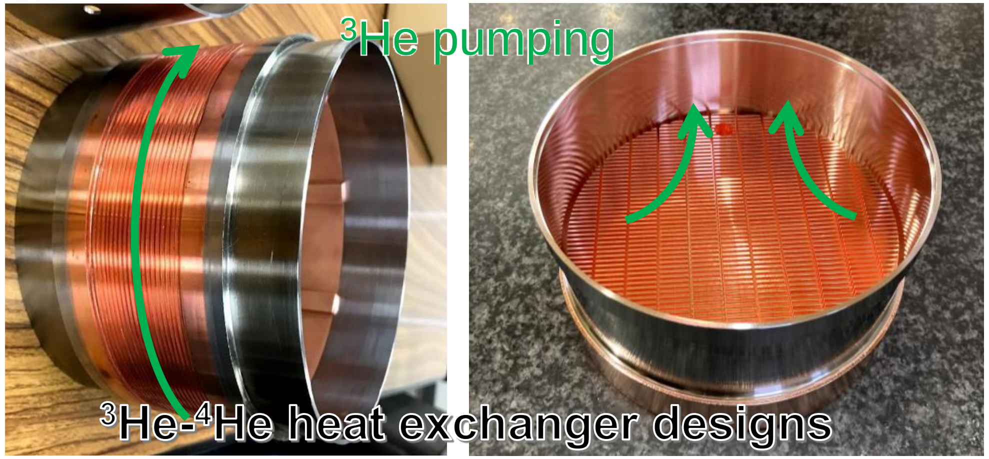
Moderator vessels

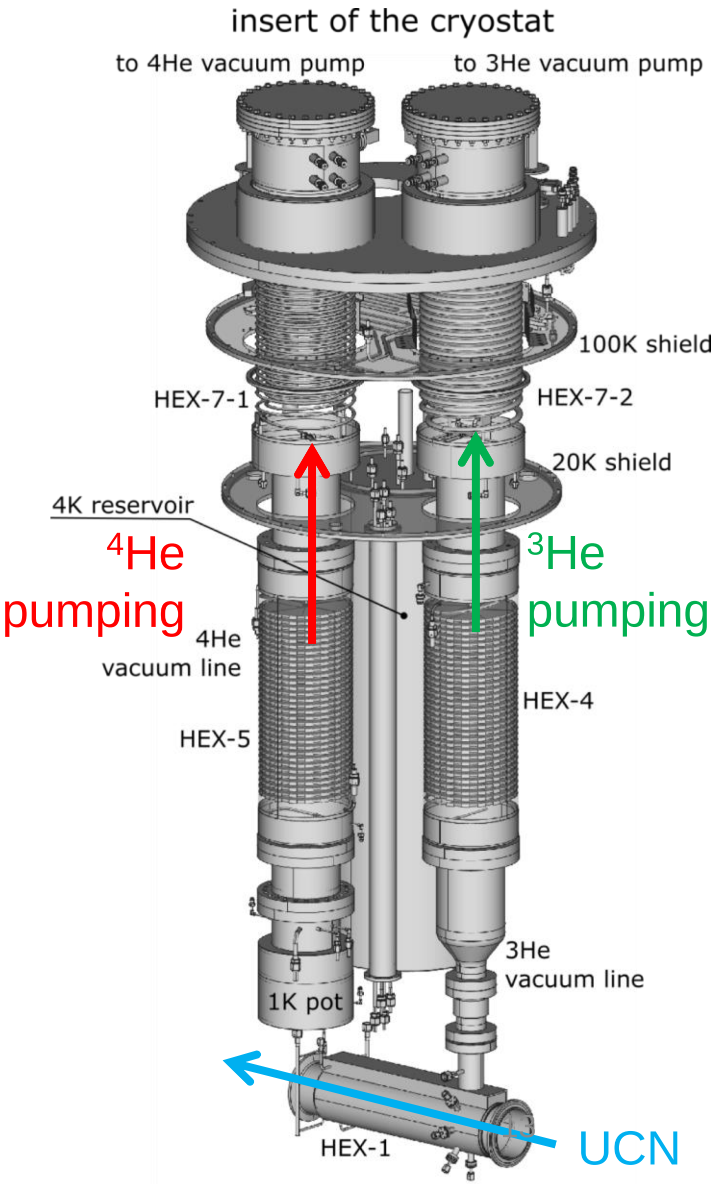
- Machined, thin-walled Al domes to minimize neutron absorption
- Withstand potential D_2 explosion pressures
- Machining finished, preparing to start complicated assembly



Cooling power: 10 W at 1K

- 3He fridge built & tested in Japan, shipped to TRIUMF in 2021
- Pumps arrived 2021
- Undergoing acceptance tests





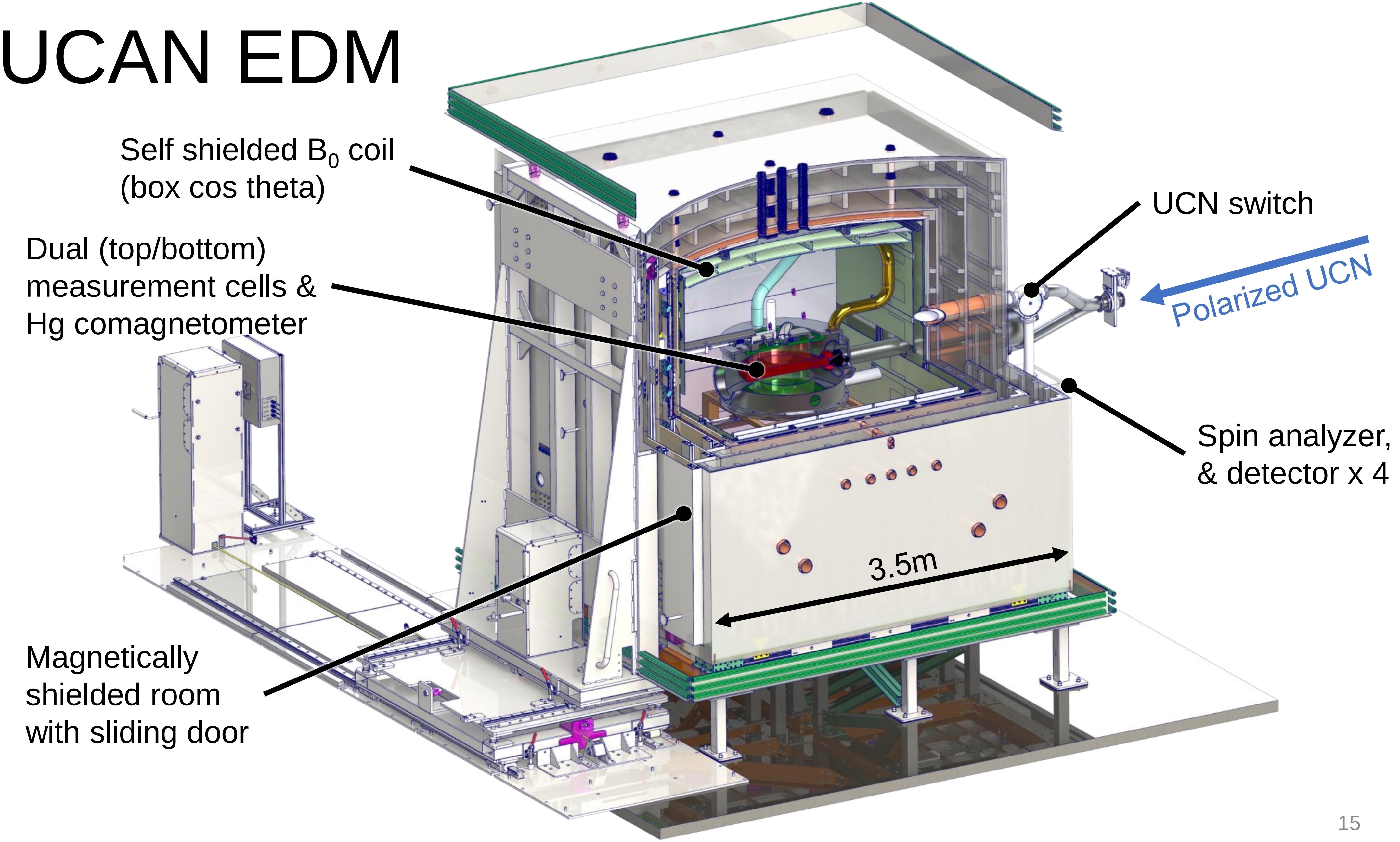
Lots of infrastructure installed this year.

33 m-long liquid-helium transfer line

Large pumps to cool cryostat

- Power
- Cooling water
- PLC
- Pumping ducts
- Piping for four different gas systems

TUCAN EDM


Self shielded B_0 coil
(box cos theta)
Dual (top/bottom)
measurement cells &
Hg comagnetometer
UCN switch
Polarized UCN
Spin analyzer,
& detector x 4
3.5m
Magnetically
shielded room
with sliding door

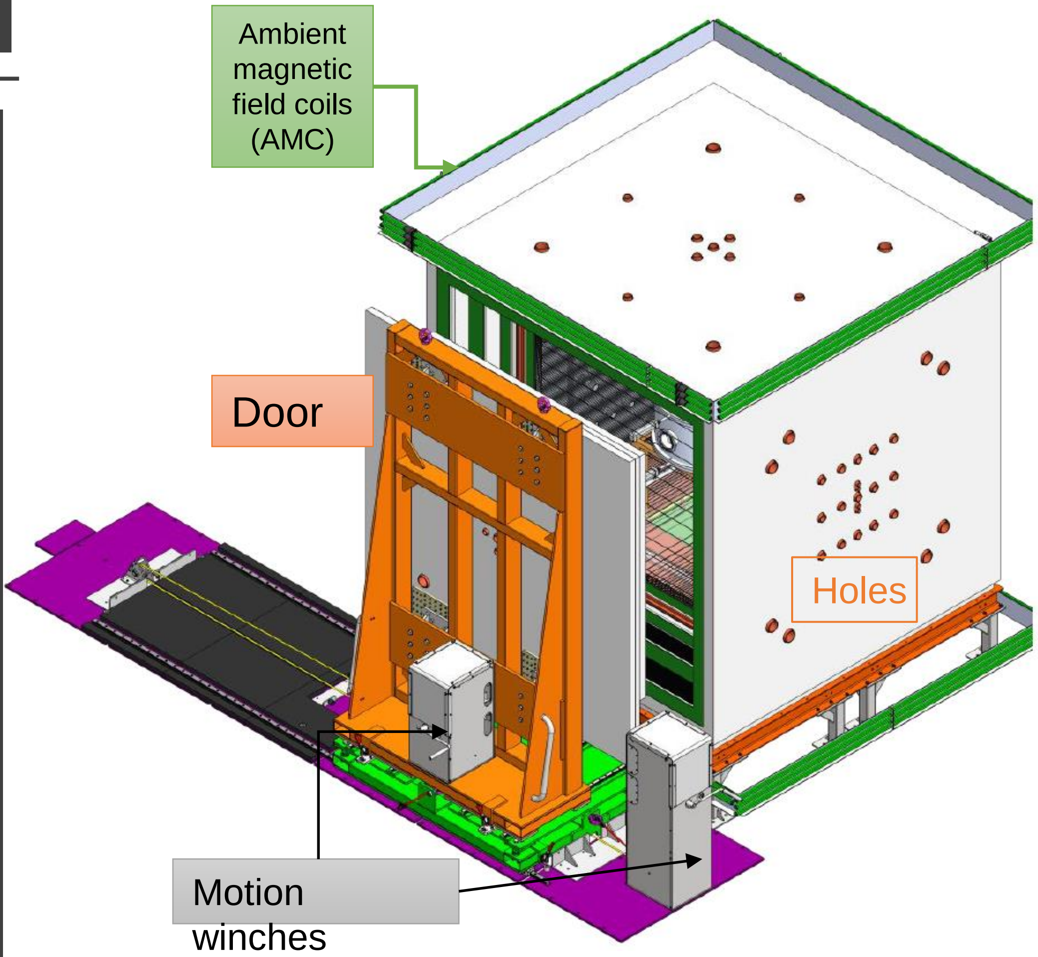
Magnetically shielded room (MSR)

TUCAN MSR

A Magnetically Shielded Room (MSR) is a multi-layer room built with high permeability material, such as mumetal, and high conductivity sheet materials, such as copper.

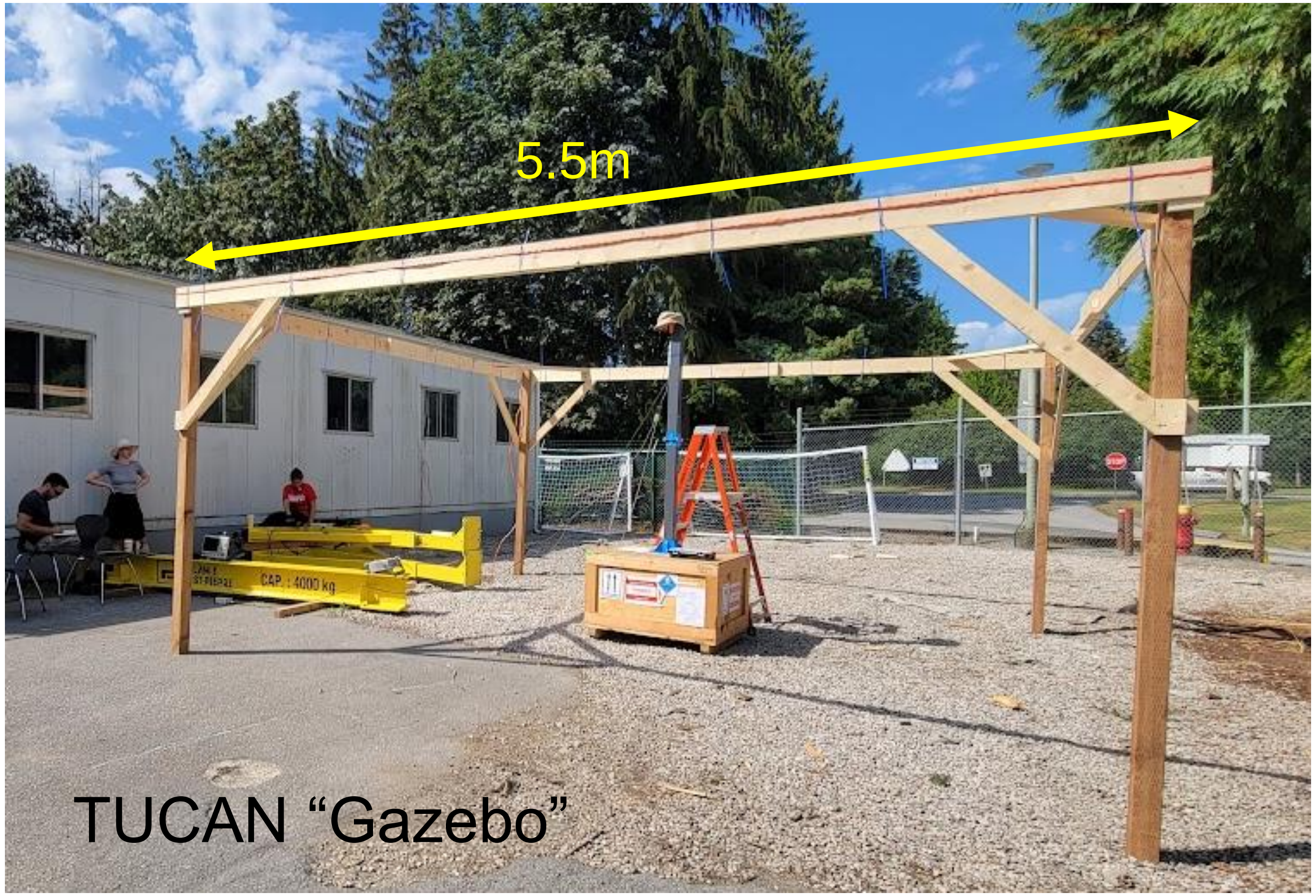
DC Shielding factor: 100,000

Size:
- inner: 2.4 m^3
- outer: 3.5 m^3



- Contract awarded to Magnetic Shields Limited (UK)
- Design largely complete
- Installation began July 2022, will be completed in June 2023
- Degaussing system in preparation

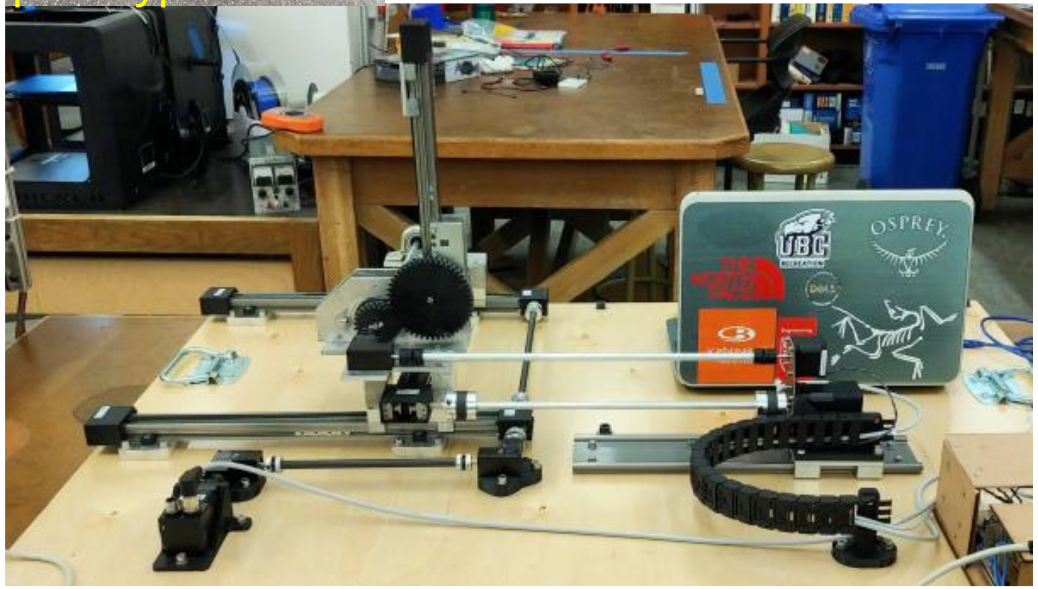
Recent Prep for MSR



Perturbation coil commissioning
used to access Shielding Factor

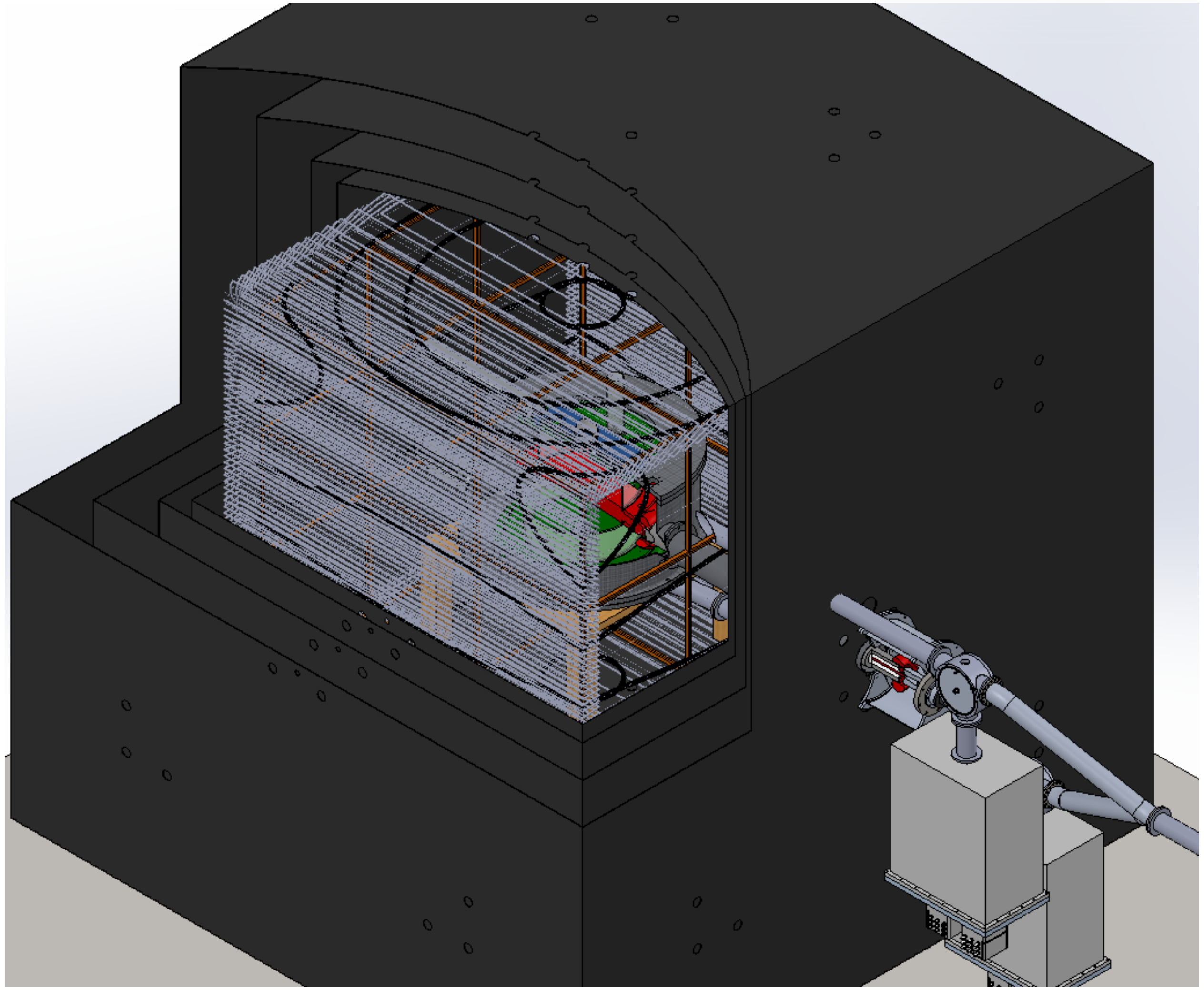
Will use:

- high precision fluxgates
- Qspin optically pumped magnetometers



"Inside" Mapper prototype

Internal Coils Intro



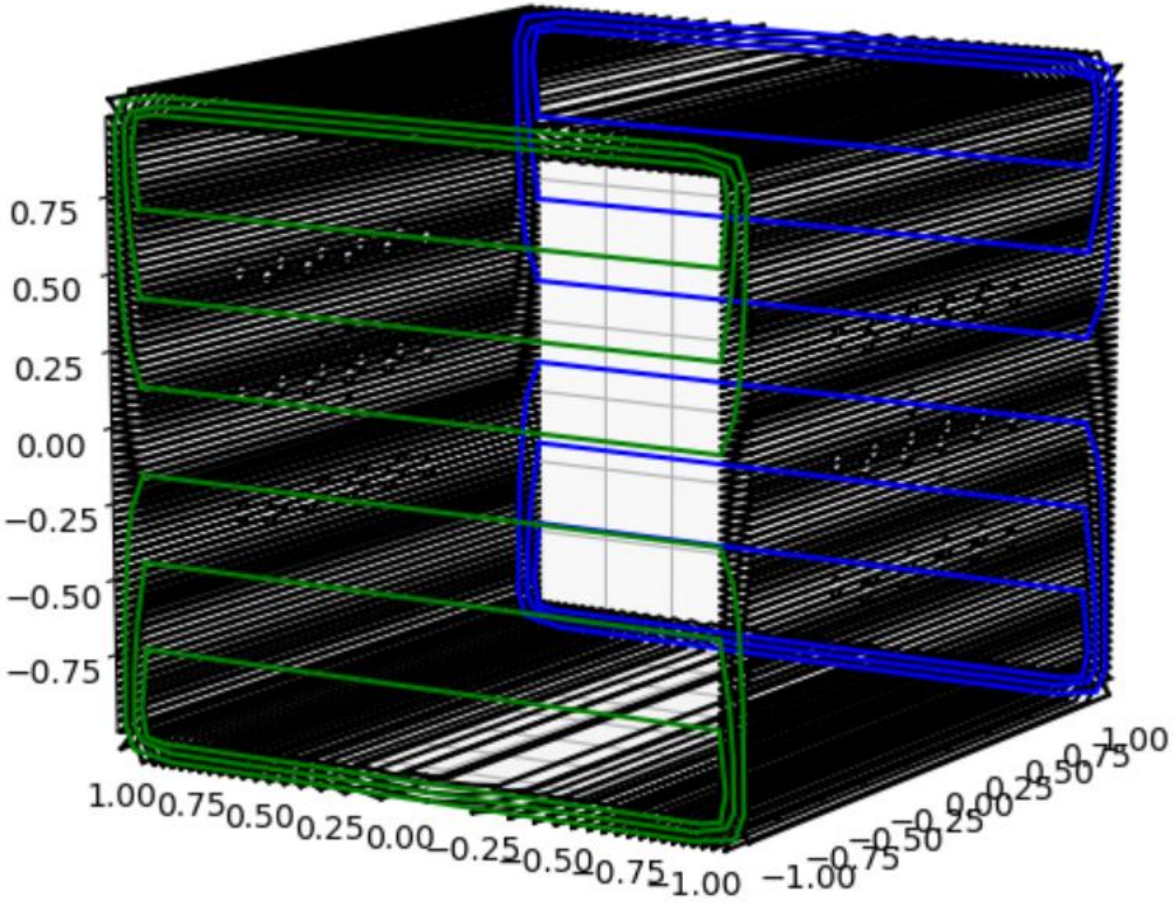
3 Different electromagnet sets will be used to produce the static neutron precession
field:

- B_0 Holding Field Coil (grey)
  - Self Shielded
- n × n Coil Array
  - Shim shield coupled
- $G_{\ell,0}$ Systematic Coils (black)

Work of M. McCrea and J. Martin

Holding Field Self Shielded Coil

Square Cosine Theta Coil



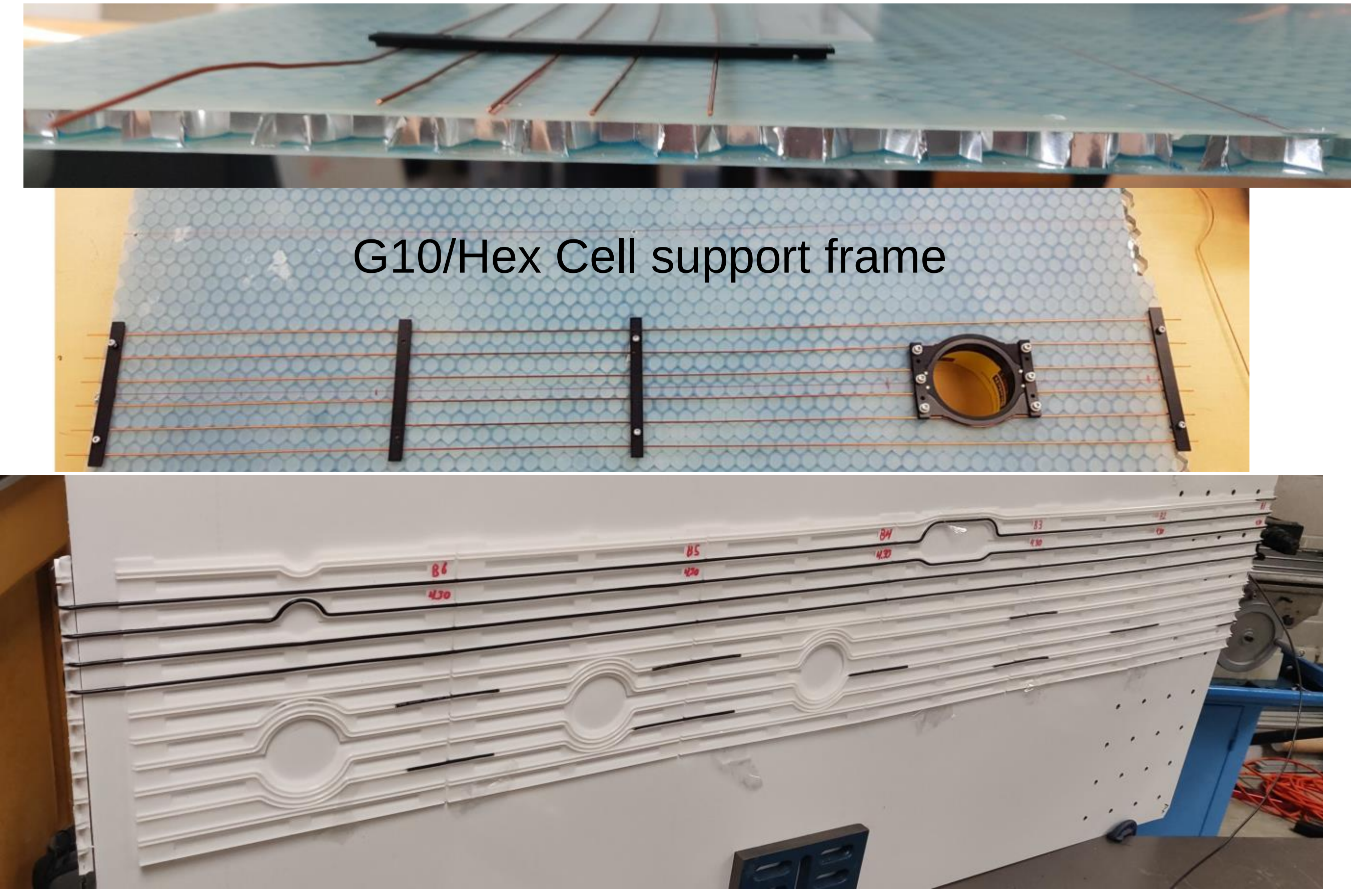
Use “Scalar Potential Method” and COMSOL FEA to tell were currents should be placed (learned from C. Crawford at UKentucky)

- Simulations of the field using Biot-Savart wires show they must be placed to an accuracy of 1 mm to meet uniformity requirements:

$\Delta B_z = |\max(B_z) - \min(B_z)| < 140$ pT = 0.000140 μT
$\sigma(B_z) < 40$ pT = 0.000040 μT

Work of M. McCrea and N. Massacret

B0 Coil Manufacturing R&D

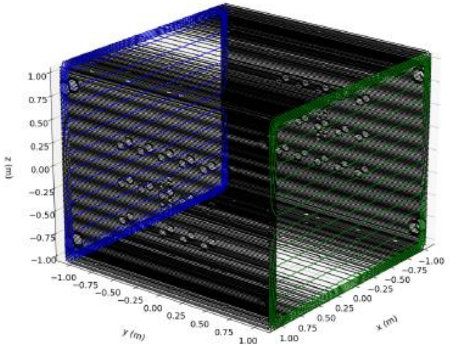


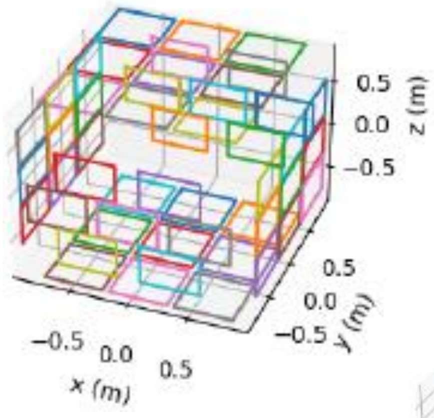
G10/Hex Cell support frame

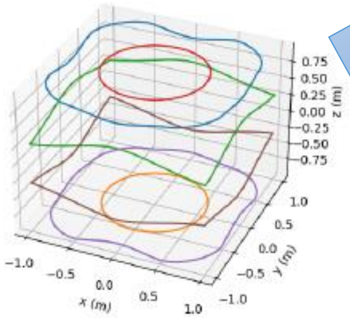
3D printed wire guides

(b) B0 Full Assembly

Shim/Trim Coils







self-shielded B_0(1uT)

Shim (<5 nT)

G_{l0}

(b) B0 Full Assembly

NxN Box coils

Place set of square coils on cubic surface around cells.

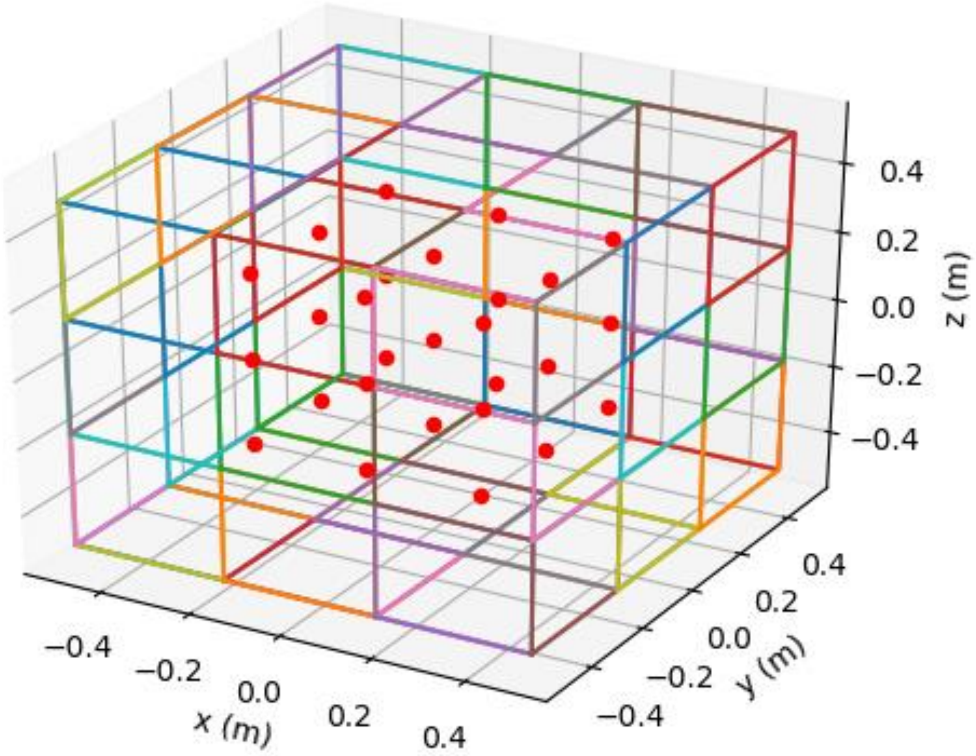
At each of the sensor positions
or $B = MI$ where M is a matrix

We can determine the currents to set on each coil to generate a target field using

Problem: M is not a square matrix; use SVD:
$M = USV^T \rightarrow M^{-1} = VS^{-1}U^T$ where S is diagonal and same dimension as M.

- Matrix problems: ill conditioning, bad modes, truncation
- Experimental problems: sensor positioning, sensor orientation, location of coils, magnetic mapping of coils, …

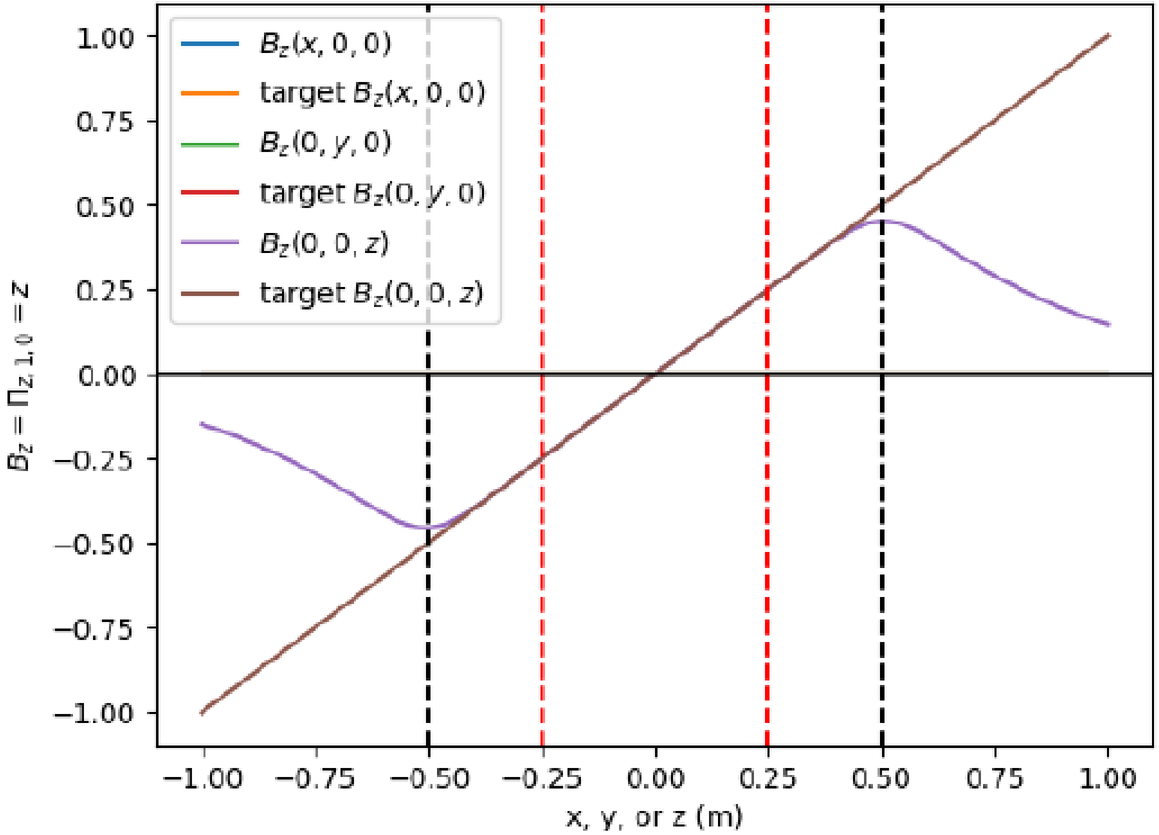
M. Rea et. al.,NeuroImage, Volume 241, 2021, 118401



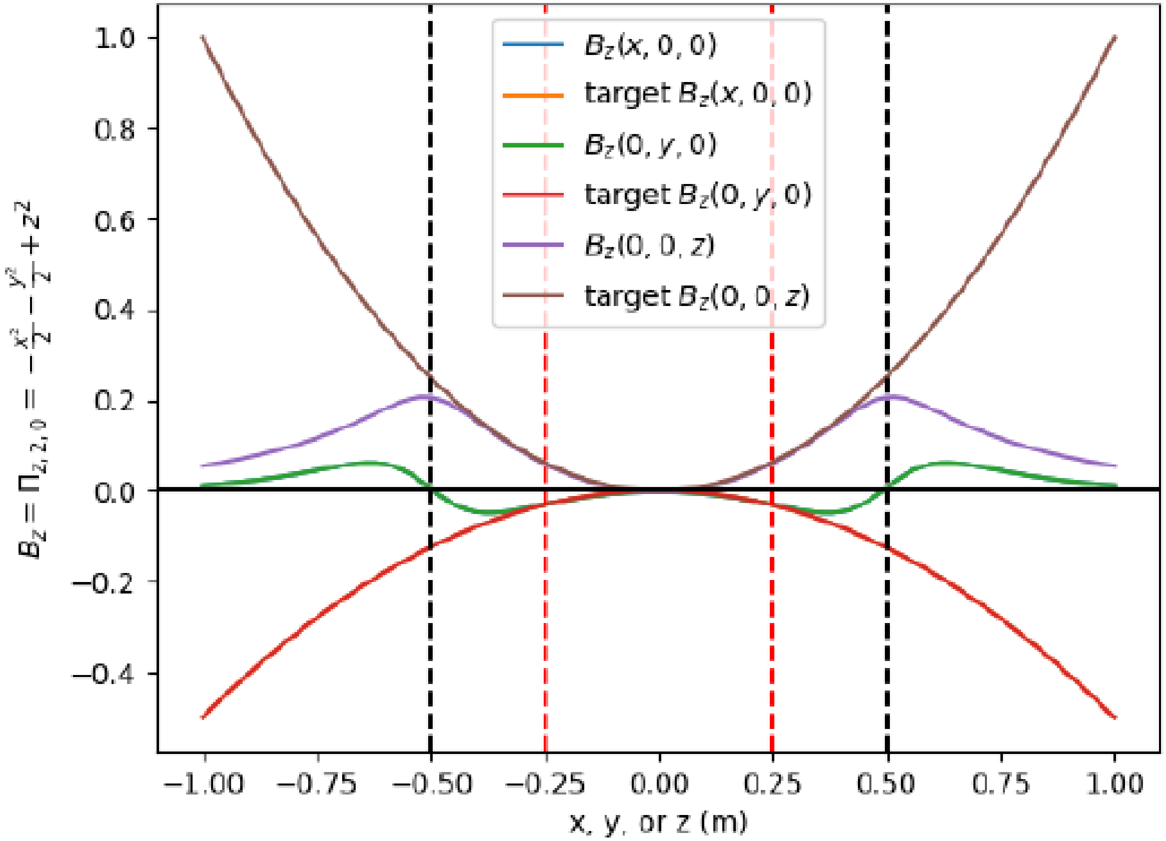
Example: 9 square coils on each of 6 faces of a cube = 54 coils

27 sensor positions x 3 axes = 81 sensor axes

Sample results of 9x6 coils



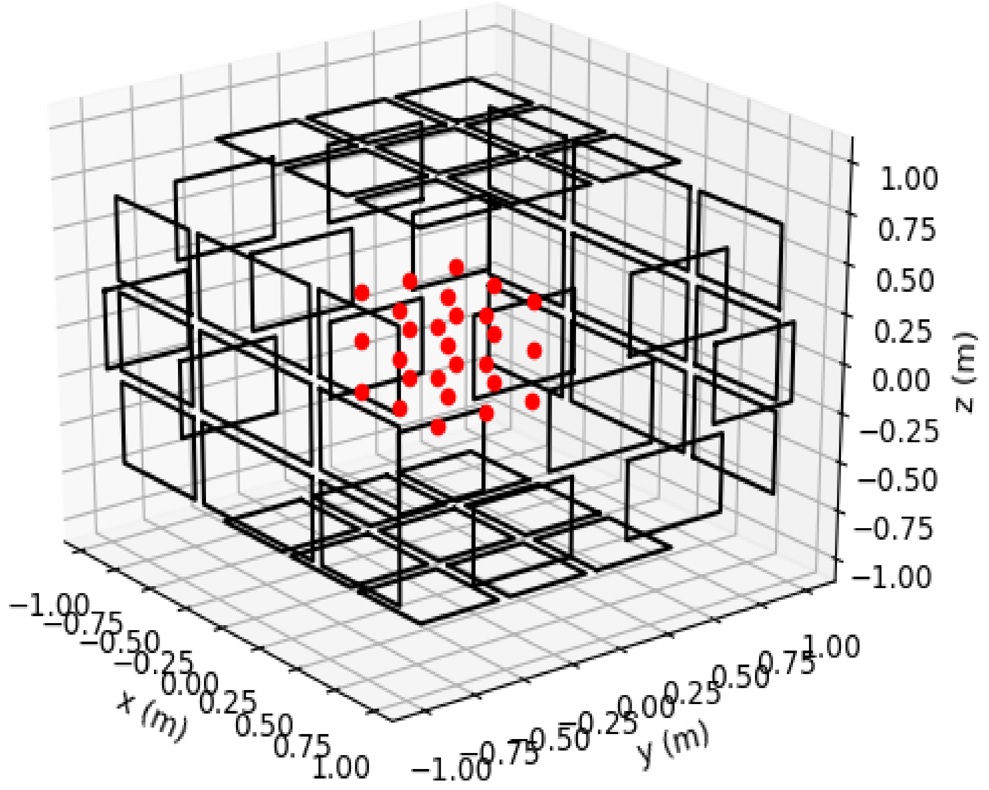
Perfectly linear gradient



Quadratic gradient

Results and conclusion

- When quantitatively measuring over the UCN cells, the coil system meets the requirements for TUCAN ($\Delta B_z < 140$ pT, $\sigma(B_z) < 40$ pT).
- Now moving into engineering of coil system:
  - Interface/mounting to B_0 coil (M. McCrea, N. Massacret at TRIUMF)
  - Development of multichannel stable current source (S. Ahmed, A. Jaison)
- Incredibly flexible design with simple geometry capable of generating arbitrary fields.



More realistic concept for TUCAN:

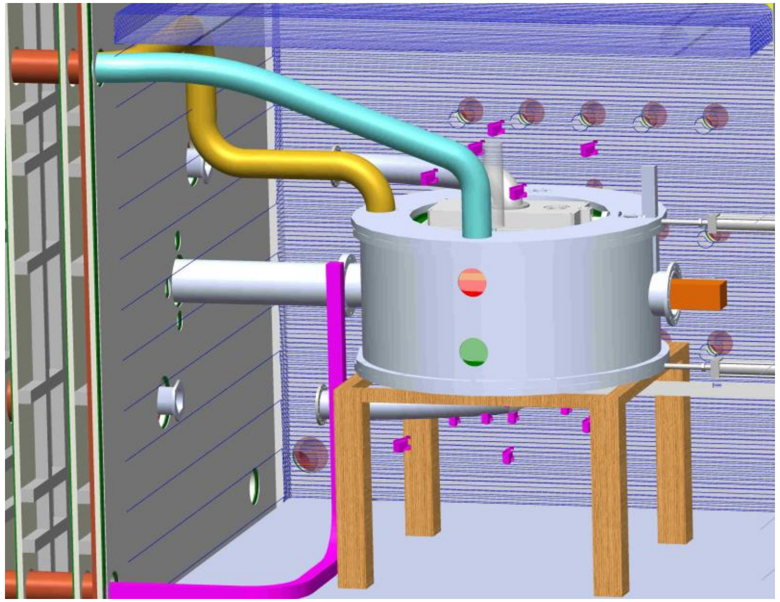
- Inner surface of B_0 coil used for mounting
- Coils adjusted to avoid conflicts with all feedthroughs to the experiment (UCN guides, high-voltage).

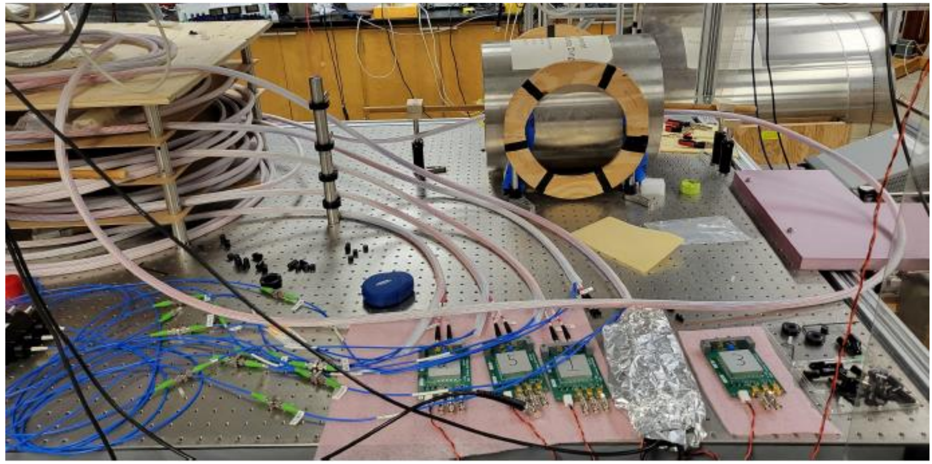
Works even better than original concept!

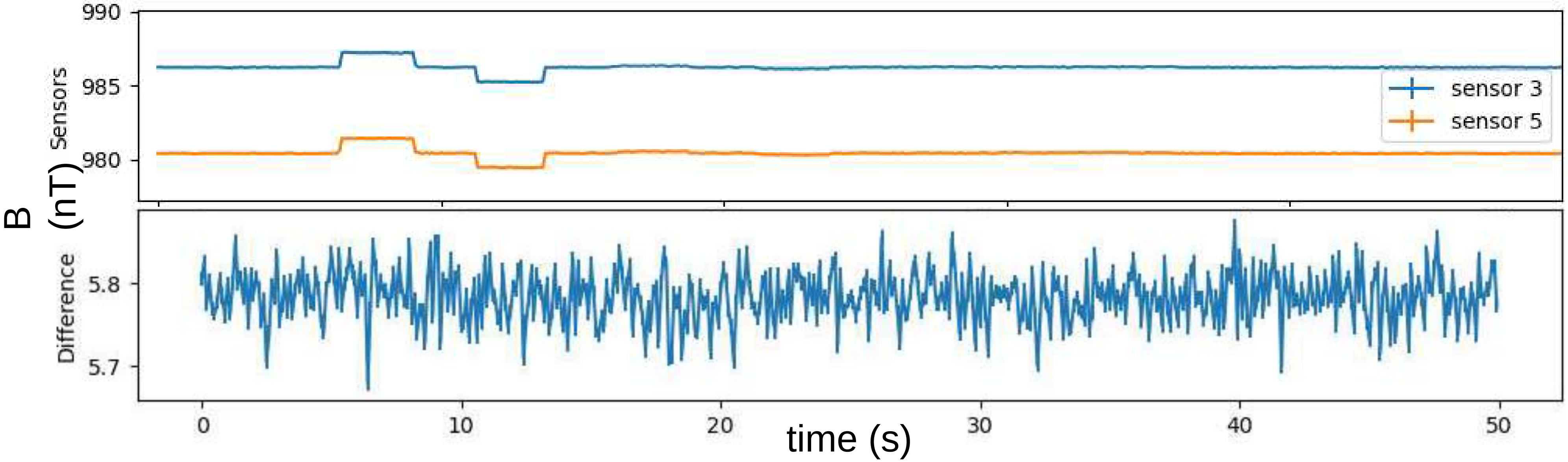
Cs NMOR sensors

https://mspace.lib.umanitoba.ca/handle/1993/34596?show=full

Contract with Southwest Sciences to build 20 sensors.
Fully non-magnetic Cs sensors with no electric parts.
Precise to ~ pT/rtHz
Key requirement of < pT frequency shifts difficult to measure (need MSR)
System now moving from Winnipeg to TRIUMF





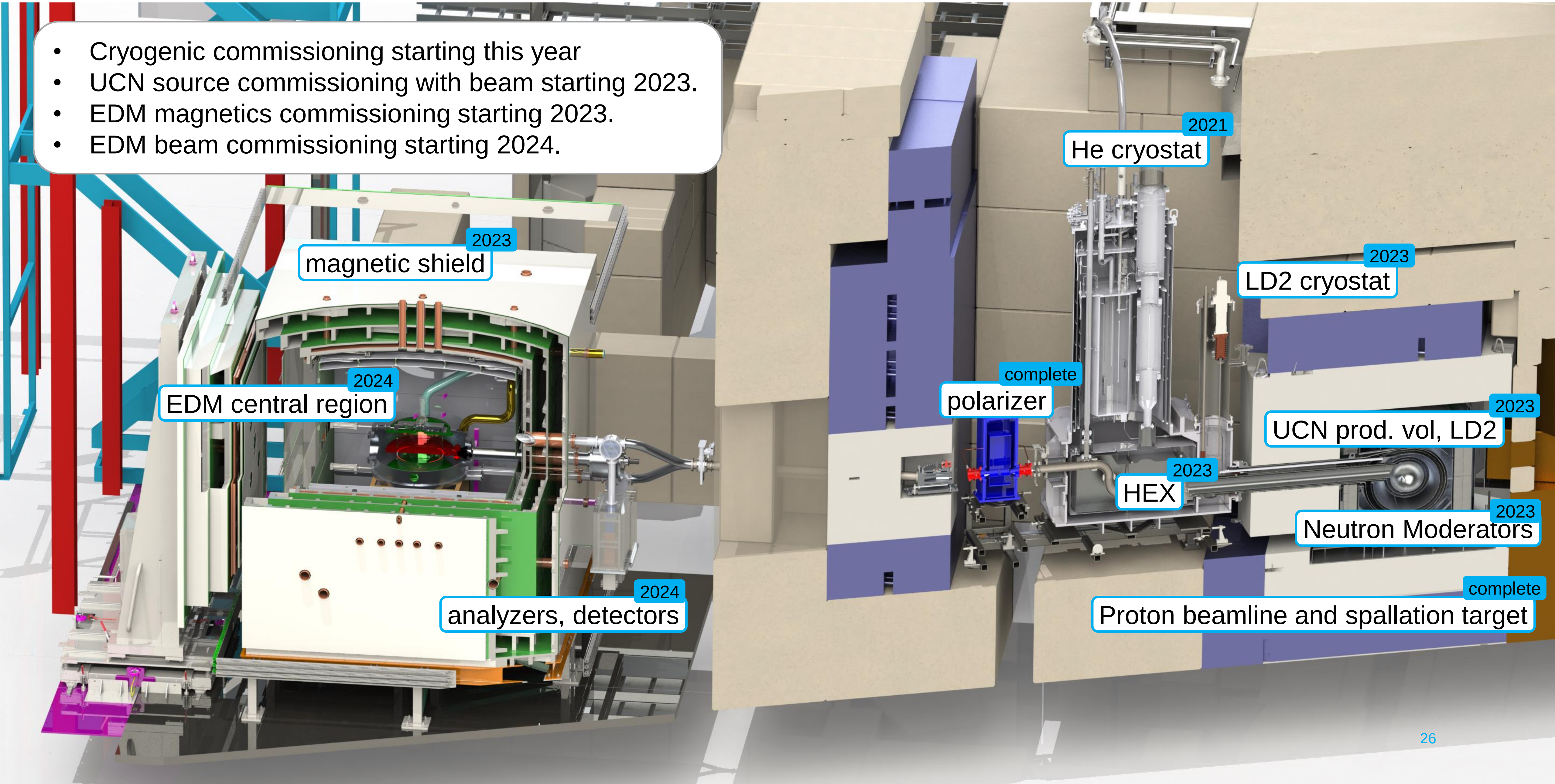


Can now operate eight sensors at once.

(But can only fit two in our small magnetic shield – looking forward to MSR!!!)

Main ingredients and status

- Cryogenic commissioning starting this year
- UCN source commissioning with beam starting 2023.
- EDM magnetics commissioning starting 2023.
- EDM beam commissioning starting 2024.



Thanks

Recommended Resources:

T. Chupp, P. Fierlinger, M.J. Ramsey-Musolf, and J.T. Singh RevModPhys.91.015001

Best nEDM limit paper: C. Abel, et al. PhysRevLett.124.081803

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