nEDM — North American Efforts

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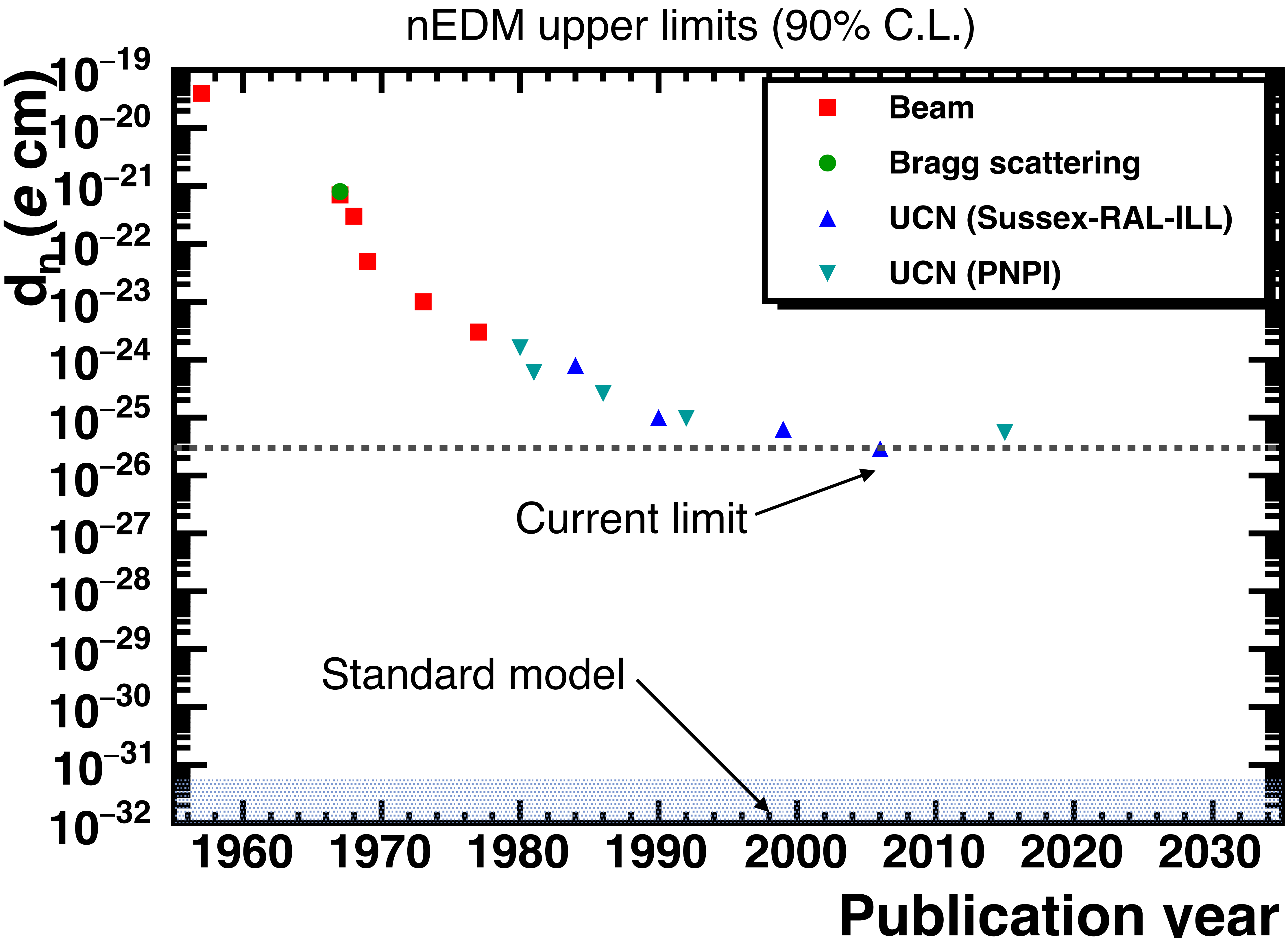
ACFI Workshop on “Theoretical Issues and Experimental Opportunities in Searches for Time Reversal Invariance Violation Using Neutrons”

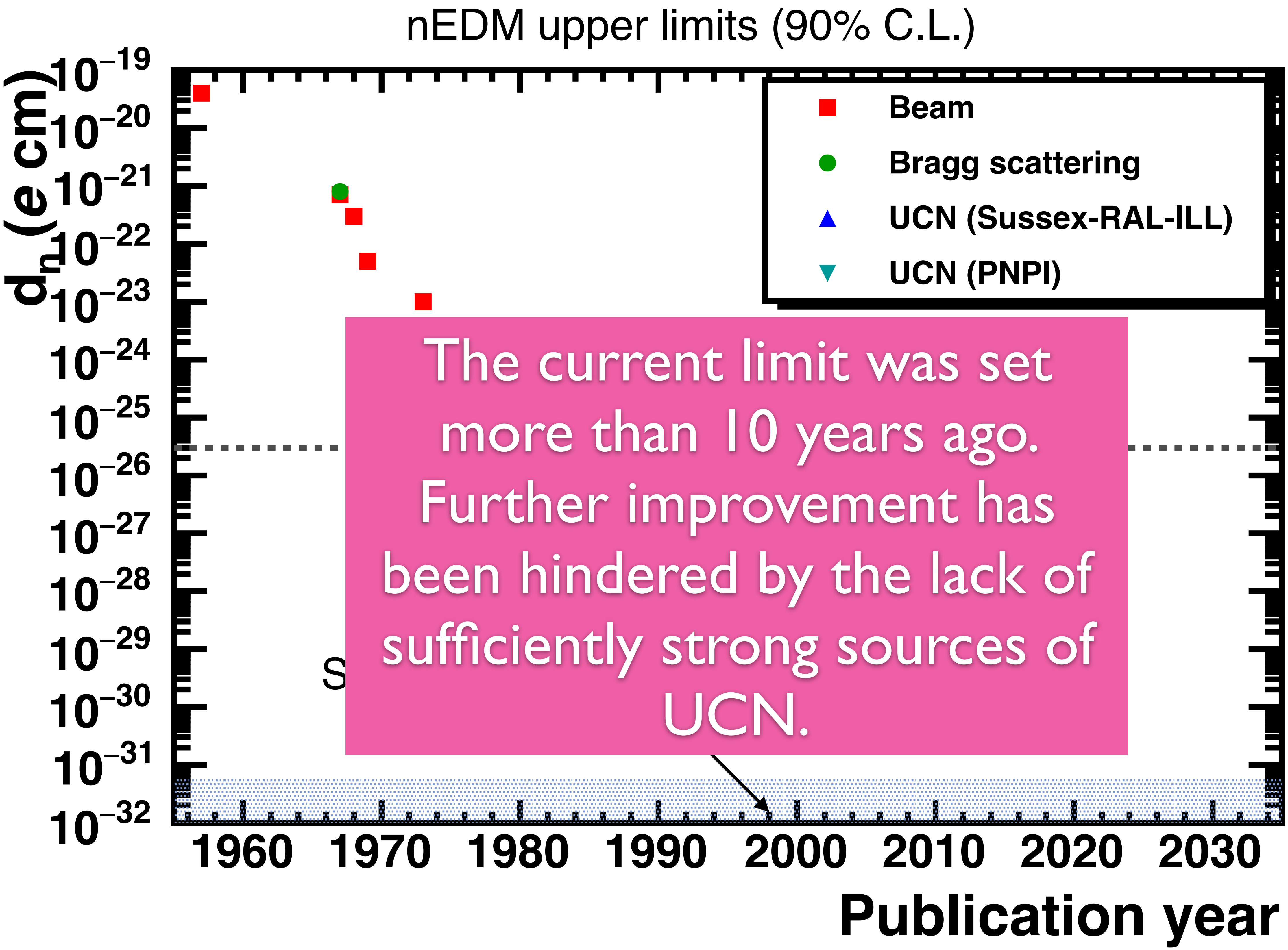
December 7, 2018

Thanks for slides to: S. Kawasaki (KEK), J. Martin (Winnipeg), W. Schreyer (TRIUMF), C. Swank (Caltech)

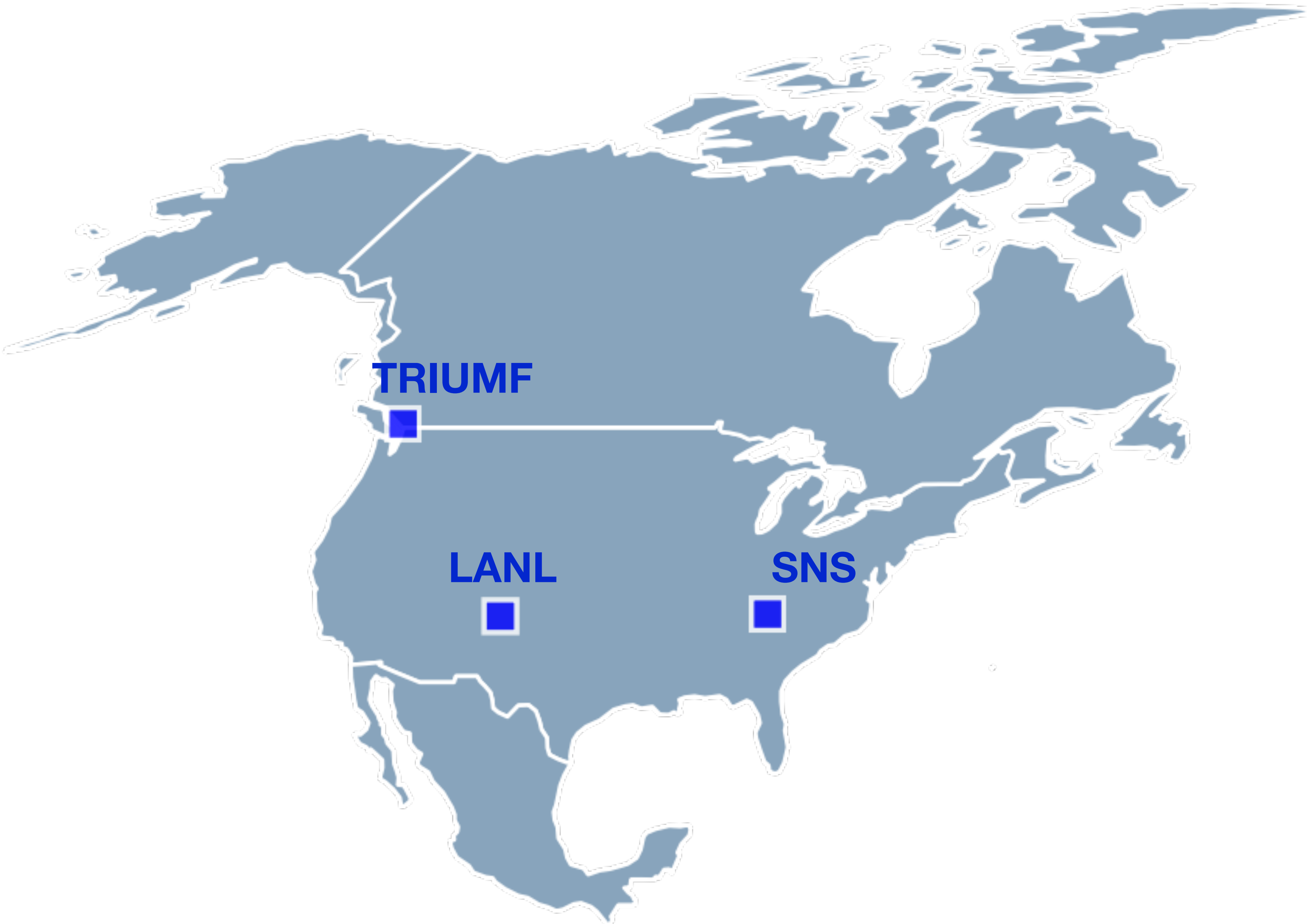
Evolution of nEDM experimental limits



Evolution of nEDM experimental limits



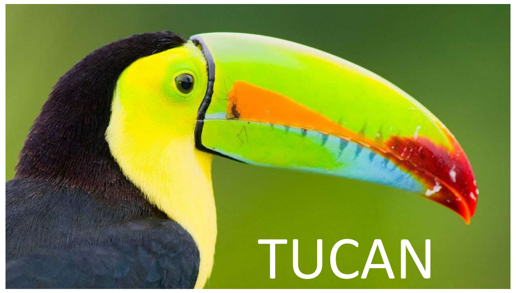
nEDM efforts in North America



nEDM efforts in North America

Experiment	UCN source	Method	Goal sensitivity
TUCANS at TRIUMF	Suerfluid LHe converter coupled to a spallation source	Ramsey method at room temperature with ^{199}Hg and ^{129}Xe comagnetometers	10^{-27} e-cm
nEDM@SNS	In-situ producing in superfluid LHe	Golub-Lamoreaux method in cryogenic apparatus	10^{-28} e-cm
LANL nEDM	SD2 converter coupled to a pulsed spallation source	Ramsey method at room temperature with ^{199}Hg comagnetometer	10^{-27} e-cm

TRIUMF Ultra-Cold Advanced Neutron



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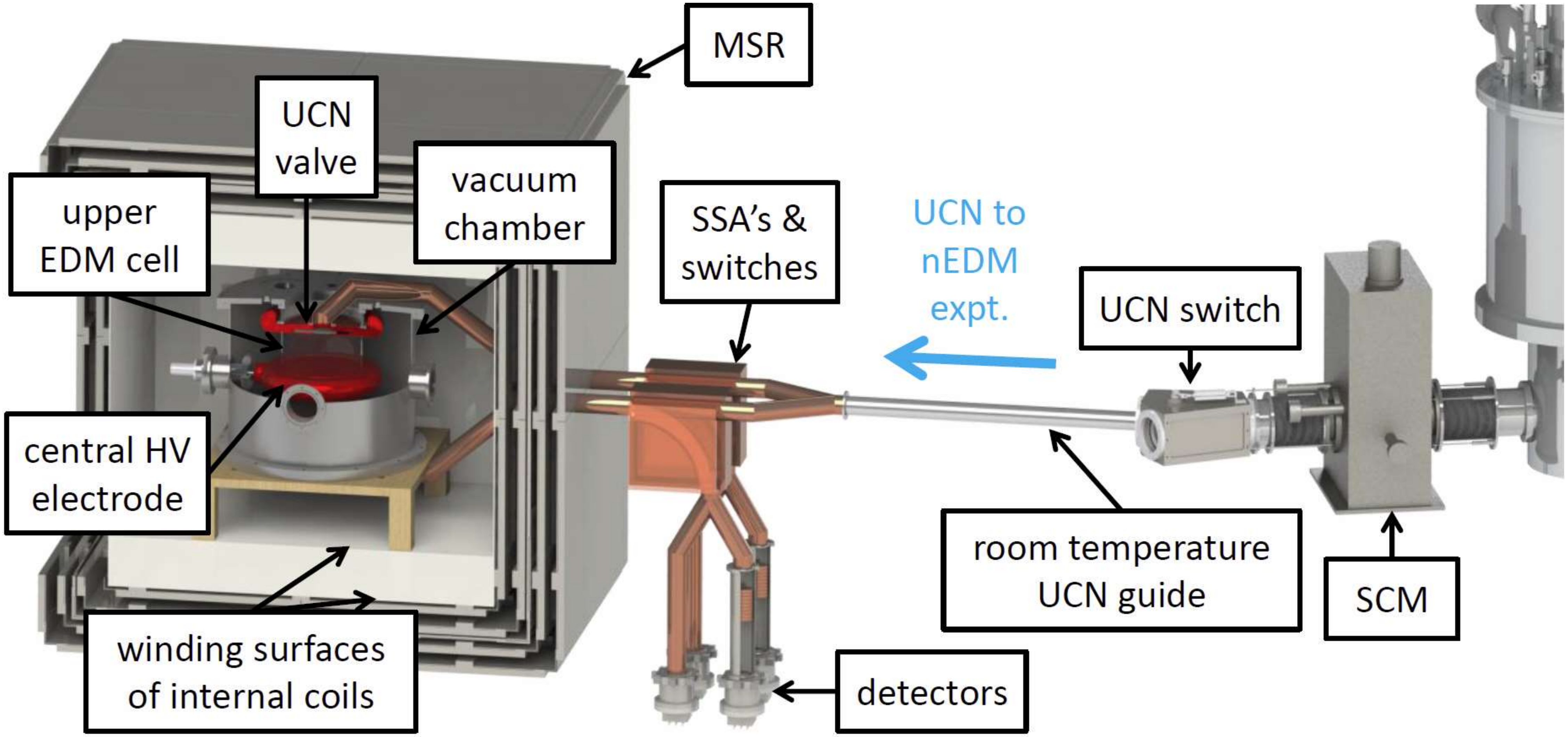
Goals

- **Measure the neutron Electric Dipole Moment (nEDM) at a precision of 10^{-27} *e*cm**
- **Develop world-leading intense Ultra Cold Neutron (UCN) source at TRIUMF**

Slide courtesy of S. Kawasaki

TUCAN nEDM apparatus

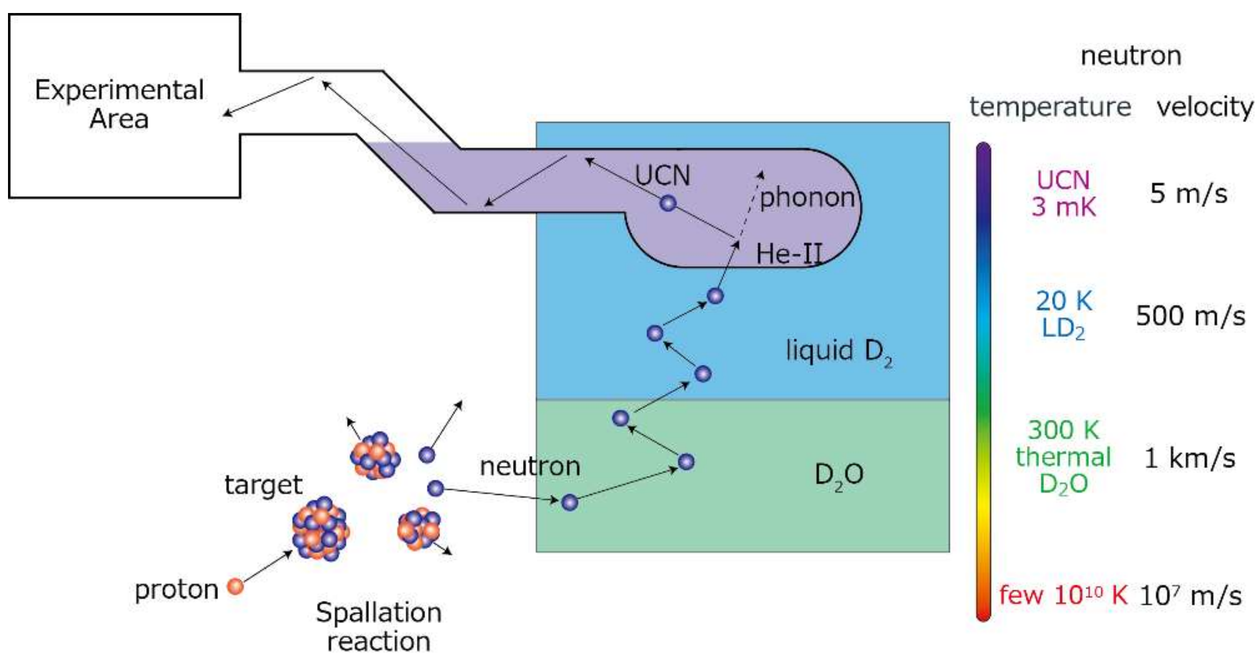


- Active compensation coil
- 4 layer magnetic shield room
- Magnetic field coil
- double cell
- Co-magnetometer (^{199}Hg, ^{129}Xe)

sensitivity: 10^{-27} ecm

Slide courtesy of S. Kawasaki

UCN production by super fluid Helium



UCN production

spallation neutron

↓ D_2O, LD2 Moderator (300K, 20K)

cold neutron ～meV

↓ Phonon scattering in He-II

Ultra cold neutron ～100neV

Feature of our source

・spallation neutron

High neutron flux

small distance between target and UCN production volume

・Super-fluid Helium (He-II) converter

long storage lifetime

important to accumulate UCN

Helium 4

- no neutron absorption cross section
- up-scattering by phonon

τ_s = 600 s at T_{HeII} = 0.8 K

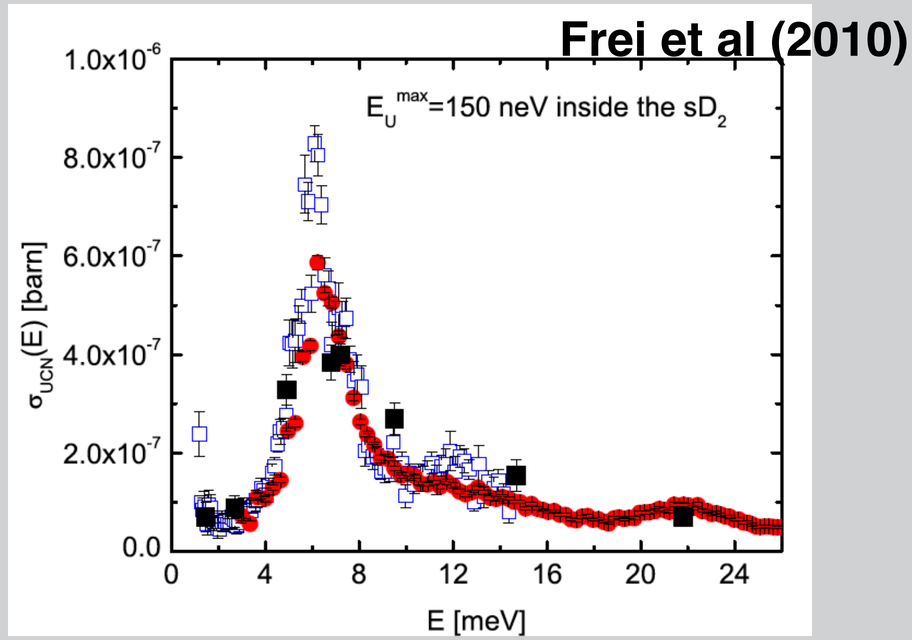
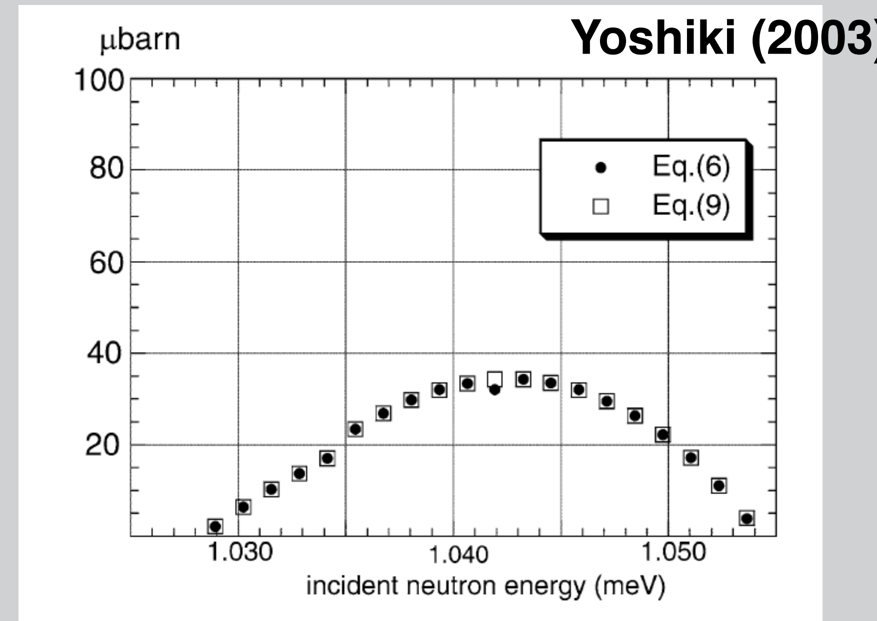
τ_s = 36 s at T_{HeII} = 1.2 K

$1/\tau_s \propto T^7$

It is important to keep He-II temperature around 1.0K with high radiation heat

Slide courtesy of S. Kawasaki

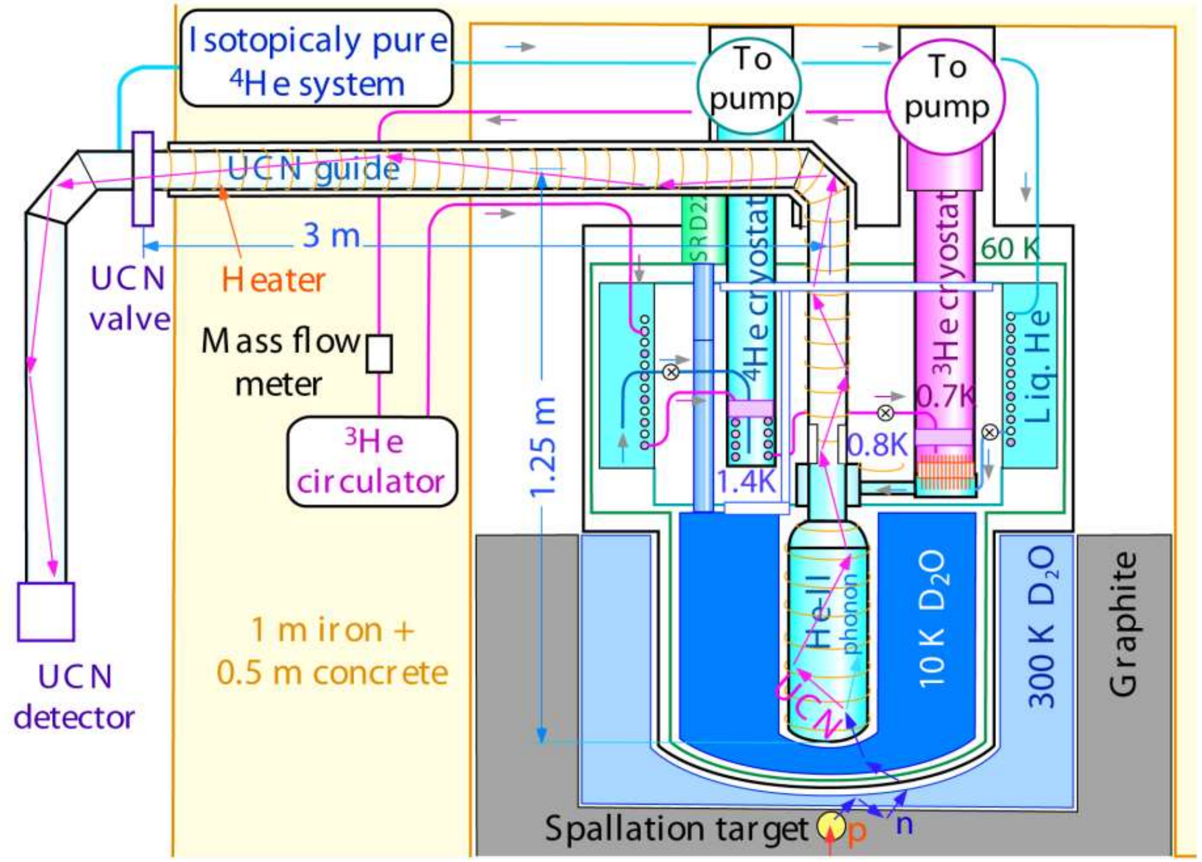
SD_2 vs LHe

<table>
<tr><th></th><th>SD_2</th><th>LHe</th></tr>
<tr><td rowspan="2">UCN production</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">$\int\sigma(SD_2)dE \sim 10 \times \int\sigma(LHe)dE$</td></tr>
<tr><td>Up scattering</td><td>$\tau_{abs} \sim$ 150 ms at 5 K</td><td>$\tau_{up} \sim T^7$, and ~1000 s at 0.7 K
(multiphonon process)</td></tr>
<tr><td>Nuclear absorption</td><td>$\tau_{abs} \sim$ 150 ms</td><td>0</td></tr>
<tr><td>Other losses</td><td>• Absorption by H contamination (τ_{abs}~150 ms at 0.2% HD)
• Up-scattering by para-D2 (τ_{up}~150 ms at 1.0% para)</td><td>Absorption by ^{3}He
(τ_{abs}~500 s at $X=10^{-10}$)</td></tr>
</table>

Prototype UCN source

- Prototype UCN source
  - developed at RCNP
    - $T_{He\text{-}II}$: 0.8 K
    - UCN life time: 81 sec
    - UCN density: 9 UCN/cm^3
      - 400 MeV × 1 μA = 0.4 kW

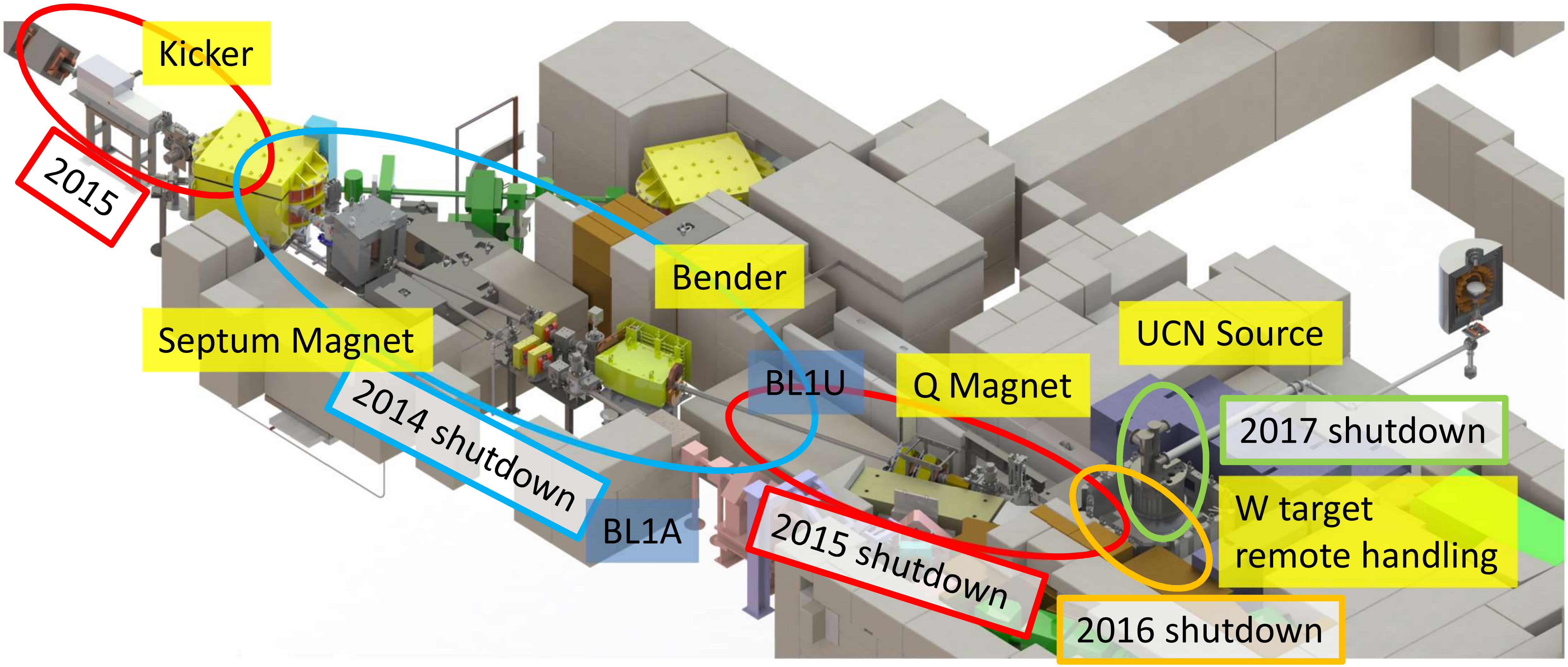
Y, Masuda et. al., Phys. Rev. Lett. 108, (2012), 134801



  - moved to TRIUMF
    - modification for safety requirement
  - 2017 Jan. – Apr. install at Meson hall
  - 2017 Nov. UCN production SUCCEEDED!!

Slide courtesy of S. Kawasaki

UCN Source @ TRIUMF



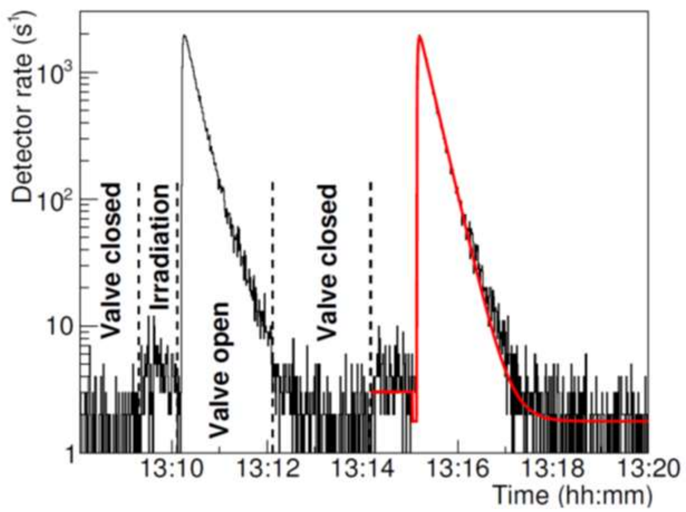
Major Milestone

✓ - 2016	proton beam line for UCN source(BL1U 500MeV, 40μA)
✓ 2016	commissioning proton beam line and cold neutron production
✓ 2017	UCN production by prototype the UCN source (~ 1μA)
- 2020	High intensity UCN source (40μA)

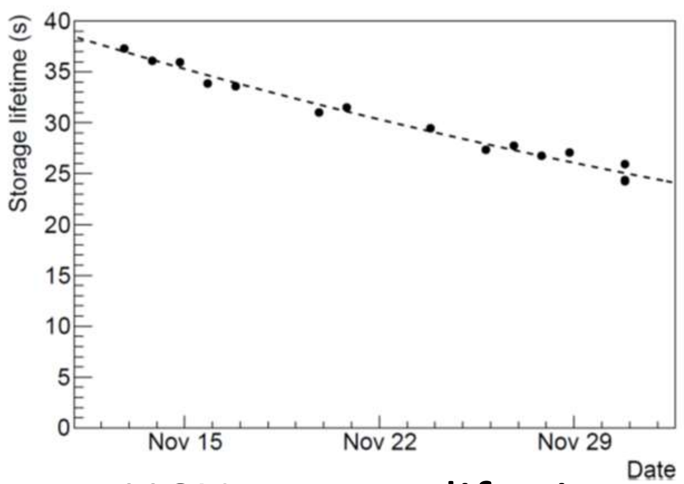
Slide courtesy of S. Kawasaki

First UCN production at TRIUMF

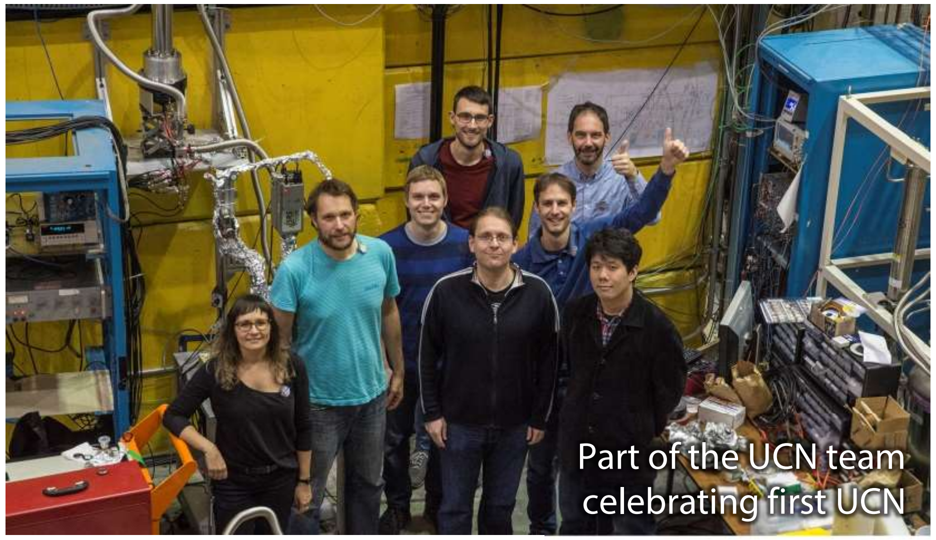
- 2014 - 2017: installation of beamline and source
- **Nov 13, 2017: first UCN produced at TRIUMF**
- Approx. 5×10^4 per shot at 1 μA and $> 3 \times 10^5$ at 10 μA
- experimental program: source and UCN hardware characterization
- UCN source works for 2 weeks
  - Initial storage time : 38 sec
  - Drop 2.1% per day



UCN counting



UCN storage life time



UCN will be used for R&D for Upgrading facility and EDM apparatus

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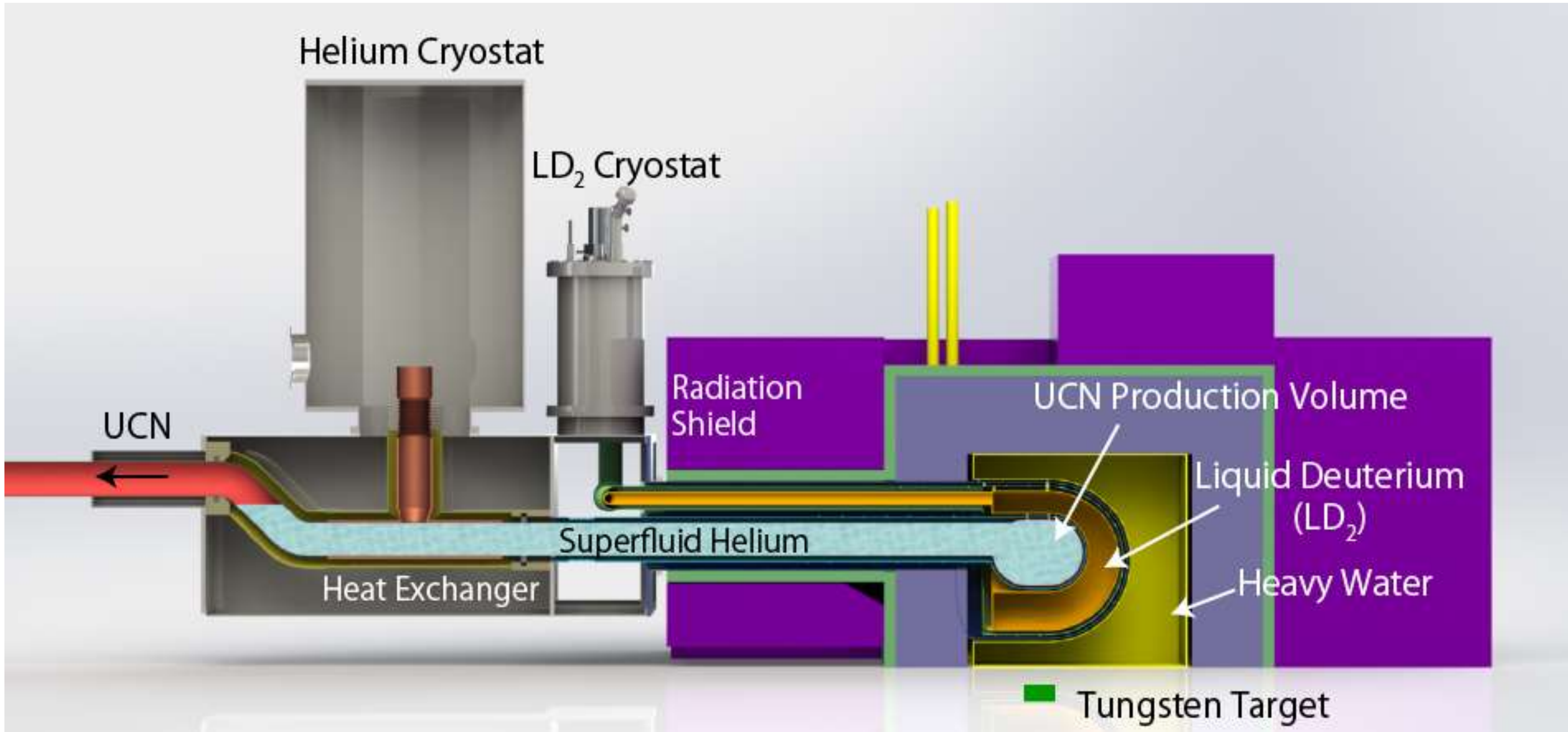
UCN source upgrade



- Liquid deuterium (LD_2)Moderator
  - To get colder neutron in order to produce UCN effectively
- High power helium cryostat
  - Remove high radiation heat
    - Cooling power of 10 W around 1.0 K
  - proton beam power
    - 0.4 kW at RCNP -> 20 kW at TRIUMF

Slide courtesy of S. Kawasaki

Expected statistics after UCN source upgrade

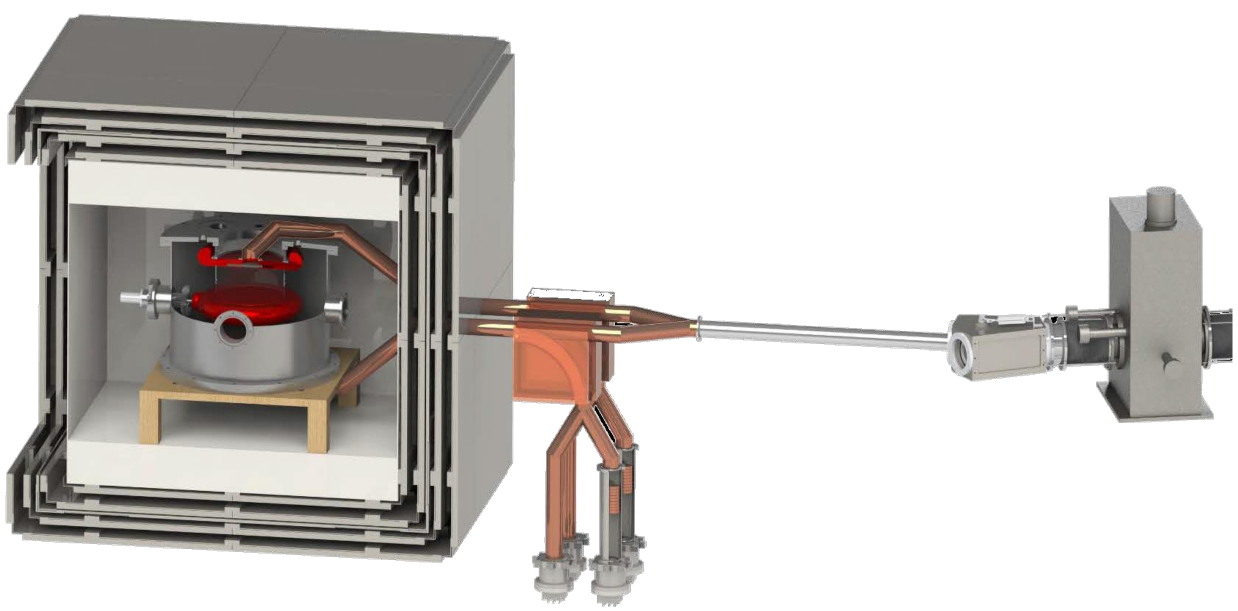
- New He cryostat will be made for 20 kW operation
- LD_2 moderator increase cold neutron flux

	Proto type	Up-grade
Moderator	sD_2O	LD_2
proton beam	0.4 kW	20 kW
production volume	8 L	34 L
Heat Load on He-II	200 mW	10 W
Working temperature	0.8 K	1.10 – 1.15 K
UCN production rate	**3.2×10^4 UCN/s**	**2.6×10^7 UCN/s**
UCN density in source	**26 UCN/cm^3**	**6,400 UCN/cm^3**

Slide courtesy of S. Kawasaki

TUCAN expected statistical sensitivity

Statistical sensitivity of 10^{-27} ecm reached after ~300 beam days



Many effects taken into account

- E = 12 kV/cm
- α_0 = 0.95, α_f = 0.6
- T_1 = 1000 s, T_2 = 500 s
- T = 120 s, τ = 130 s
- Guide transmission 90%/m
- N_0 = 300/cm^3, N_f = 200/cm^3
- V_{cell} = 16 L
- Measurement time per beam day: 16 h
- Beam days per year: 200

Slide courtesy of W. Schreyer

nEDM@SNS

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SNS nEDM experiment key features

Golub and Lamoreaux, Phys. Rep. 237, 1 (1994)

- Experiment performed in superfluid LHe
- In situ production of UCN from 8.9 Å cold neutron beam via superthermal process
- Higher electric field expected to be achievable in LHe
- Longer UCN storage time expected at cryogenic temperatures
- ^{3}He as comagnetometer and spin analyzer for UCN
- Two complementary approaches to look for the nEDM signal ($\boldsymbol{d} \cdot \boldsymbol{E}$)
  - Free precession method
  - Dressed spin method

SNS nEDM experiment key features

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- Experiment performed in superfluid LHe
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- Higher electric field expected to be achievable in LHe
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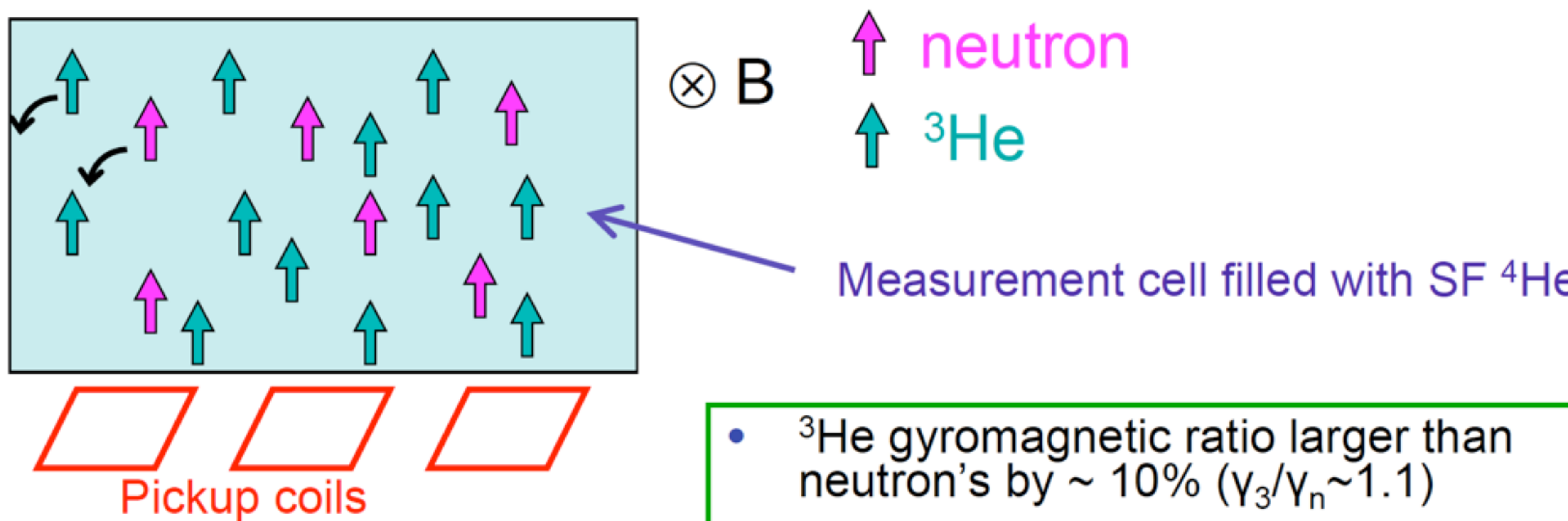
Statistical sensitivity increase due to the use of LHe

- ^{3}He as comagnetometer and spin analyzer for UCN
- Two complementary approaches to look for the nEDM signal ($\boldsymbol{d} \cdot \boldsymbol{E}$)
  - Free precession method
  - Dressed spin method

Two techniques provide critical crosscheck of the EDM results with different challenges and systematics.

Free precession method

A dilute admixture of polarized ^{3}He atoms is introduced to the bath of SF ^{4}He ($x = N_3/N_4 \sim 10^{-10}$ or $\rho_{3He} \sim 10^{12}$/cc)



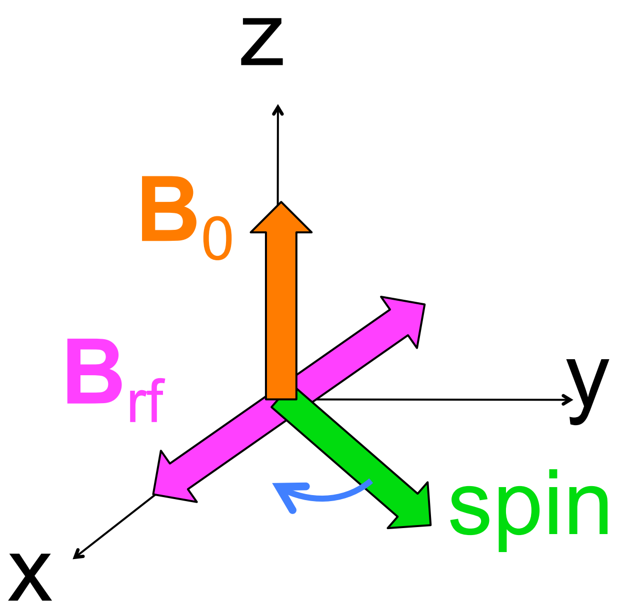
Change in magnetic field due to the rotating magnetization of ^{3}He detected by SQUID magnetometers

- ^{3}He gyromagnetic ratio larger than neutron's by ~ 10% ($\gamma_3/\gamma_n \sim 1.1$)
- Neutron absorption on ^{3}He highly spin dependent ($\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$)
- Reaction product of n+^{3}He→p+t generates UV (~80 nm) scintillation light in SF ^{4}He

Scintillation light from n-^{3}He capture reaction provides a measurement of $\omega_3-\omega_n$

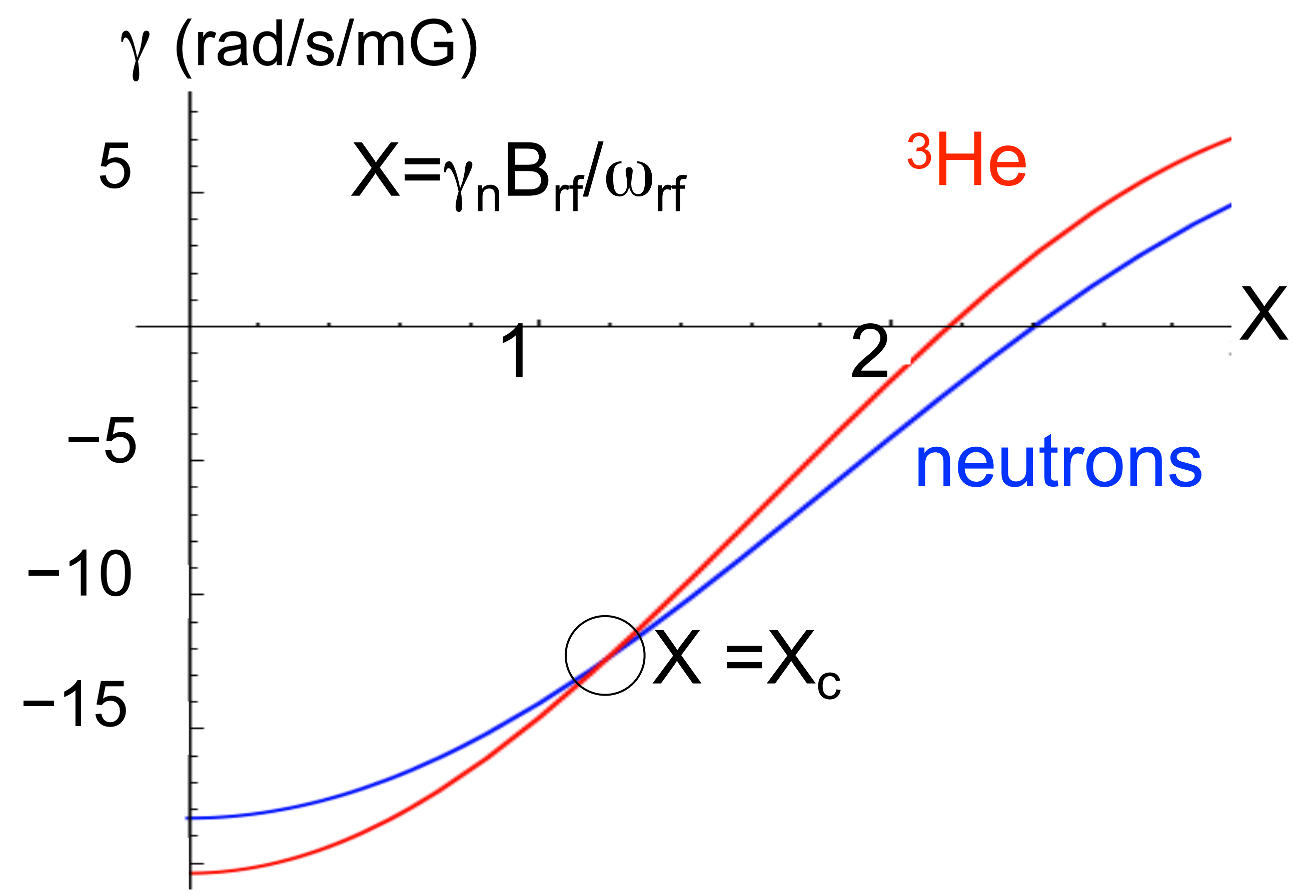
Signature of EDM appears as a shift in $\omega_3-\omega_n$ corresponding to the reversal of ***E*** with respect to ***B*** with no change in ω_3

Dressed spin method



A strong non-resonant RF field

$\mathbf{B_{rf}} \perp \mathbf{B_0}$, $B_{rf} >> B_0$, $\omega_{rf} >> \omega_0$

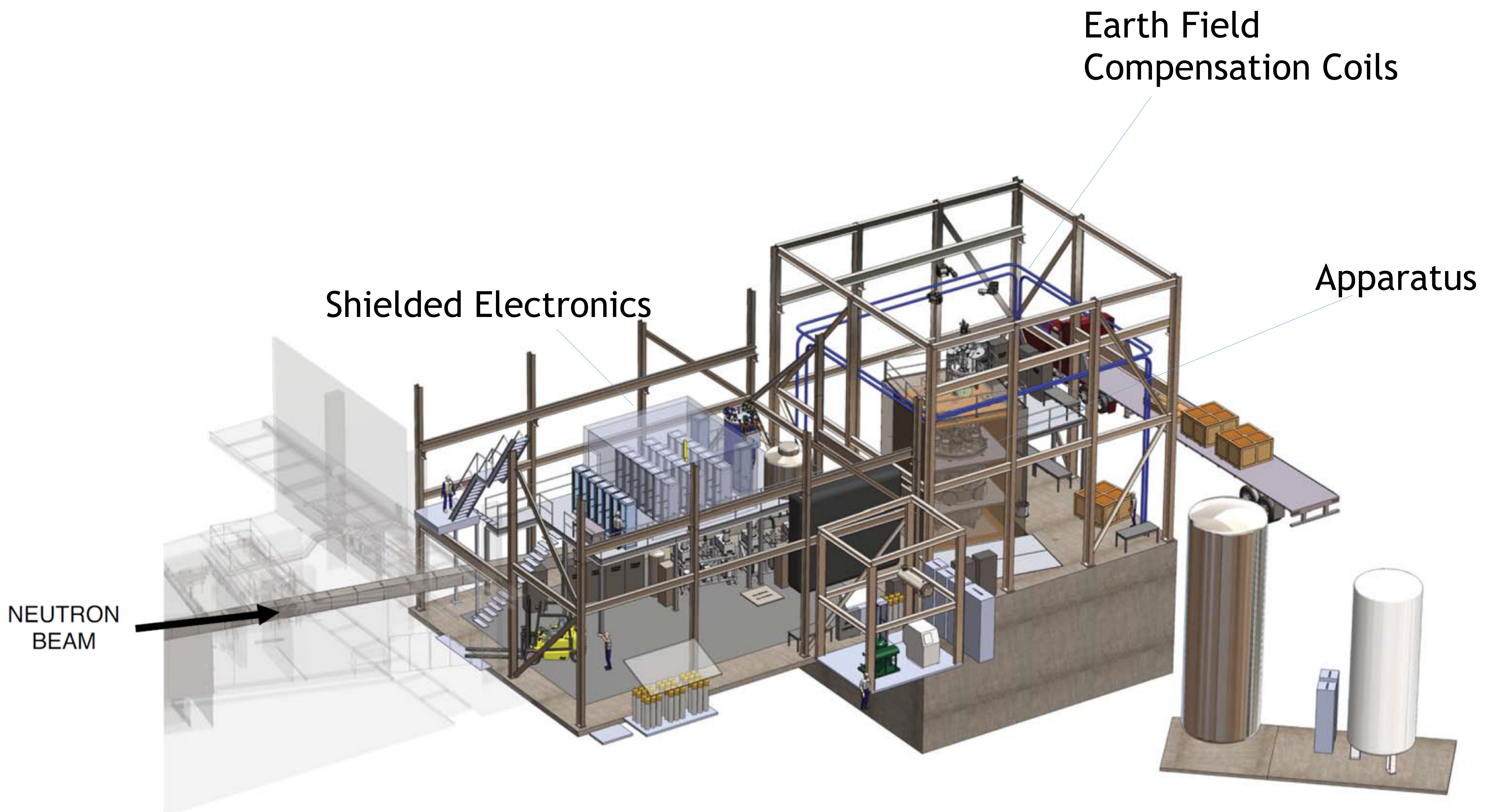


- By applying a strong non-resonant RF field, the gyromagnetic ratio can be modified or "dressed"

$$\gamma' = \gamma J_0\left(\gamma B_{rf}/\omega_{rf}\right) = \gamma J_0(X)$$

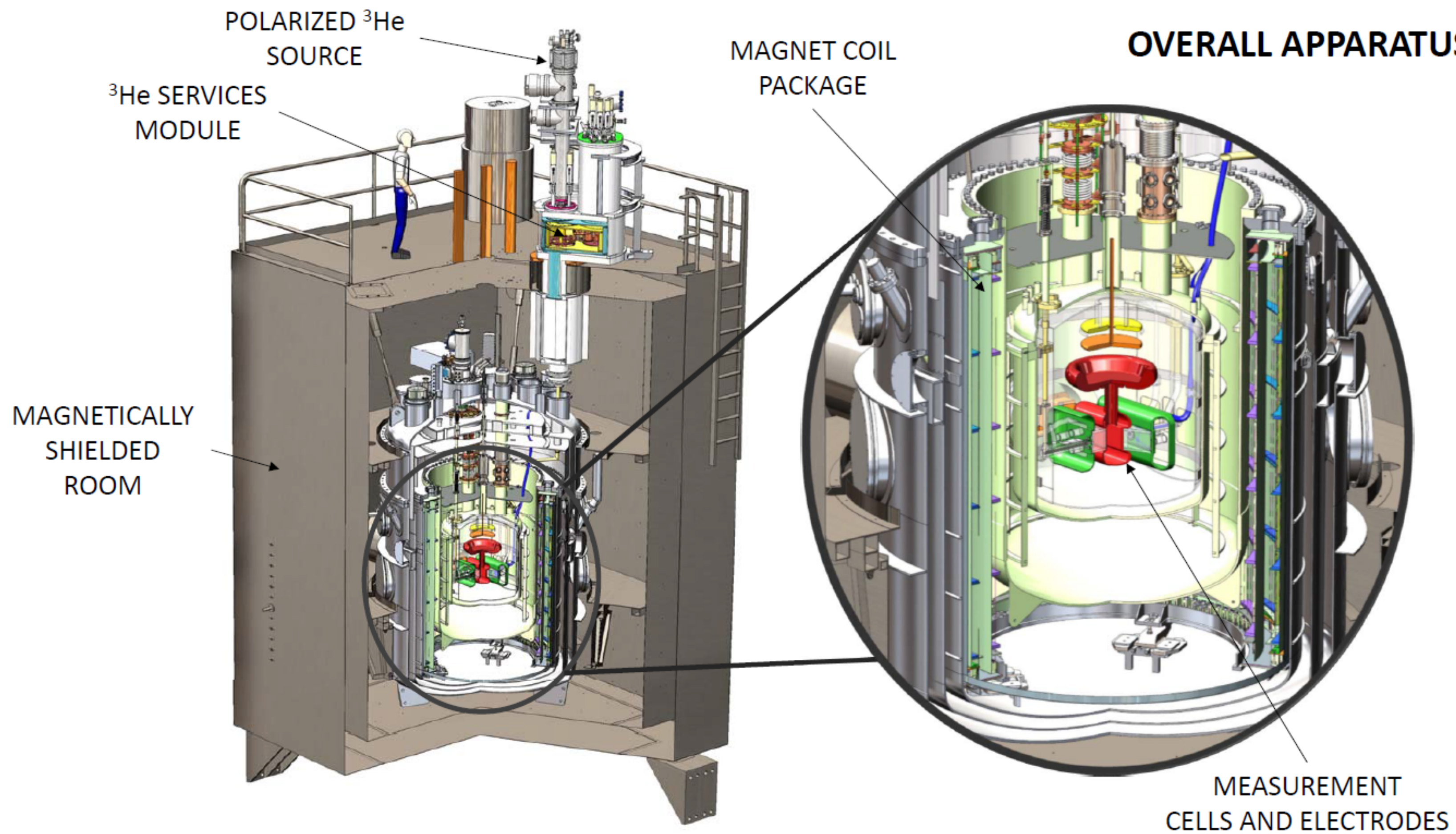
- Can tune the dressing parameter ($X = \gamma_n B_{rf}/\omega_{rf}$) until the relative precession between 3He and neutrons is zero ($X = X_c$).
- Look for X_c dependence on E field
- Provides access to EDM that is independent of variations of the ambient B-field

SNS Facility Floor plan

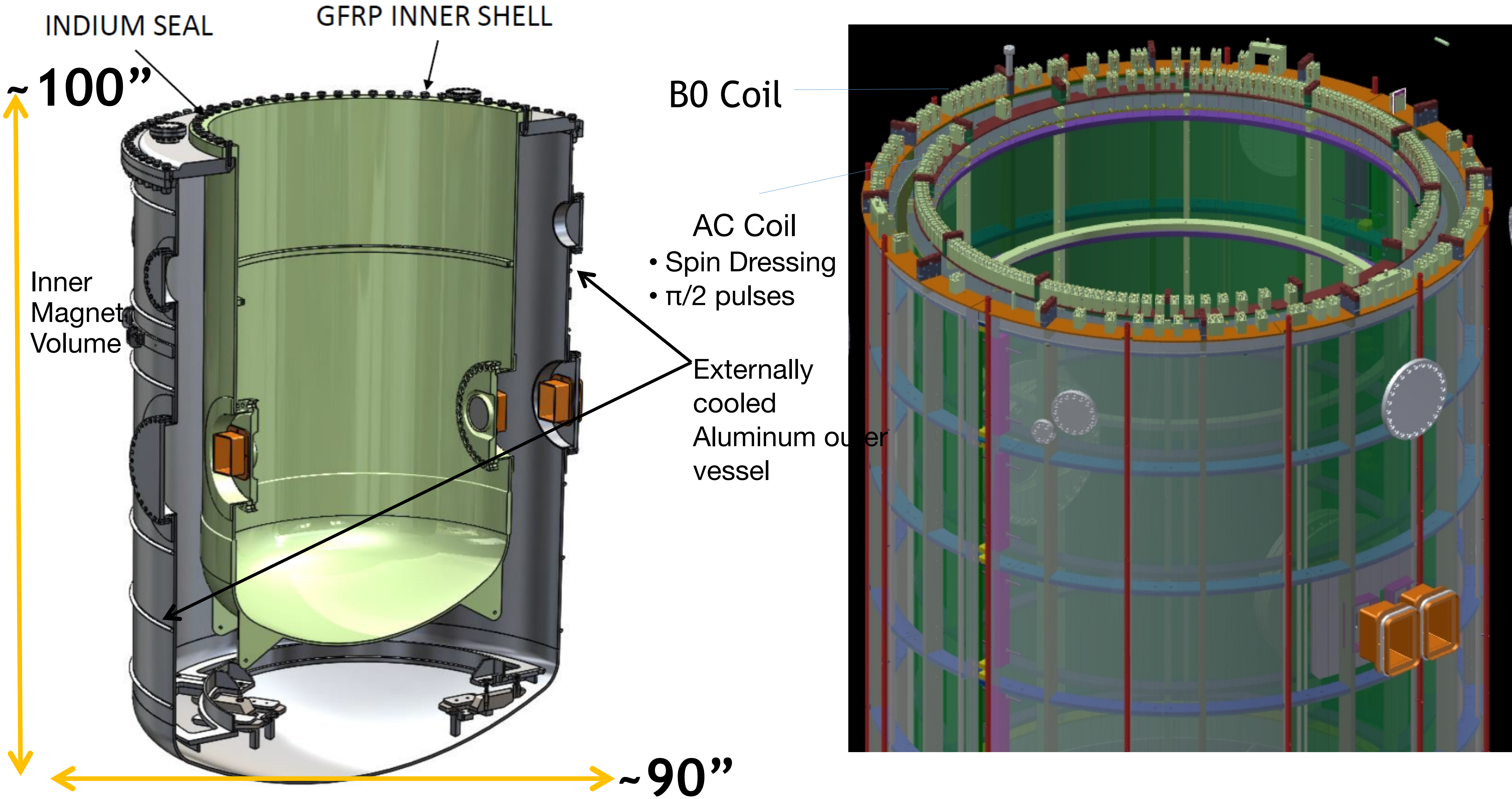


Apparatus Overview

- Magnetic fields
- Helium Transport
- Neutron Transport
- Central Detection
- PULSTAR Systematic Study apparatus



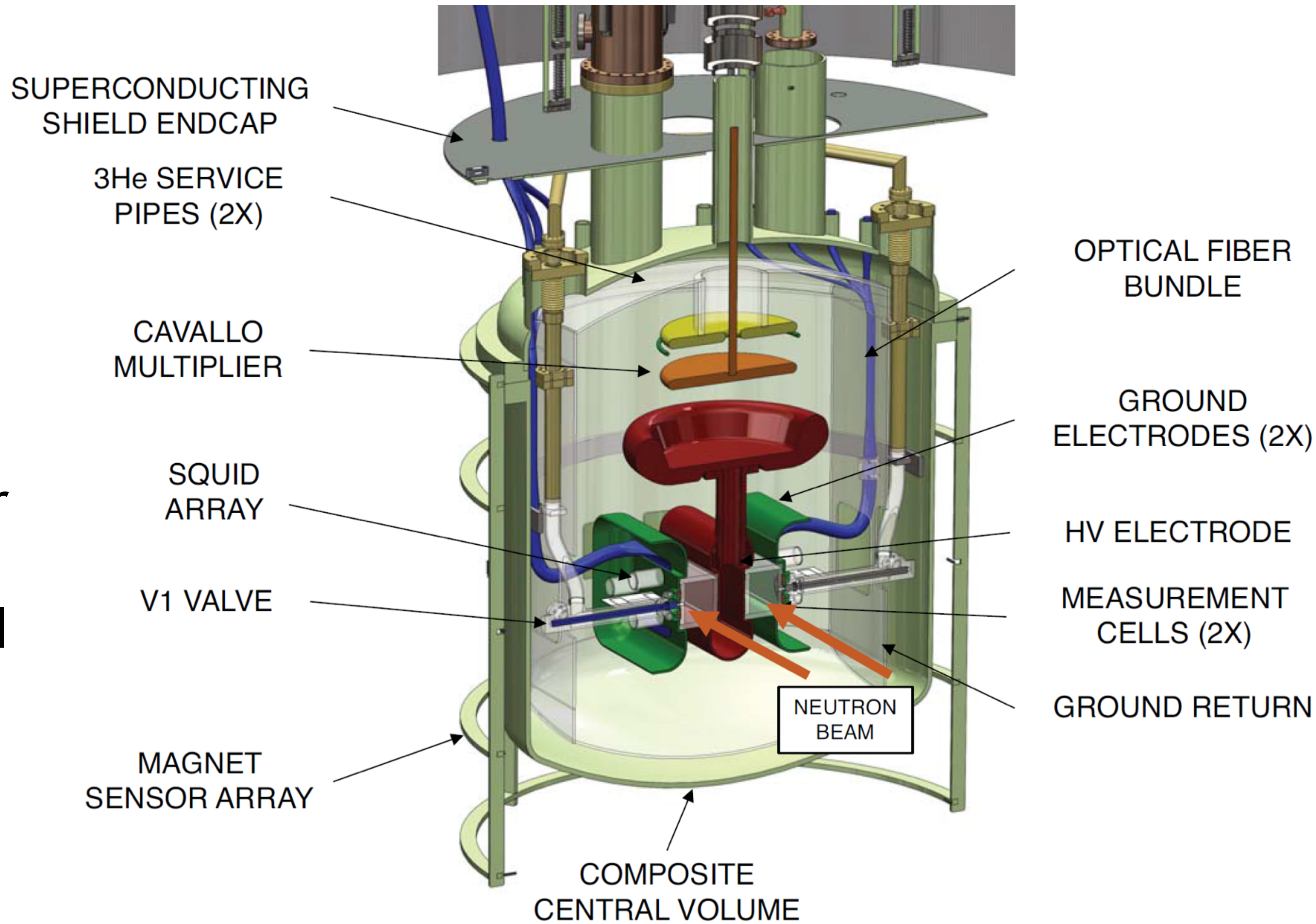
Magnetic Fields



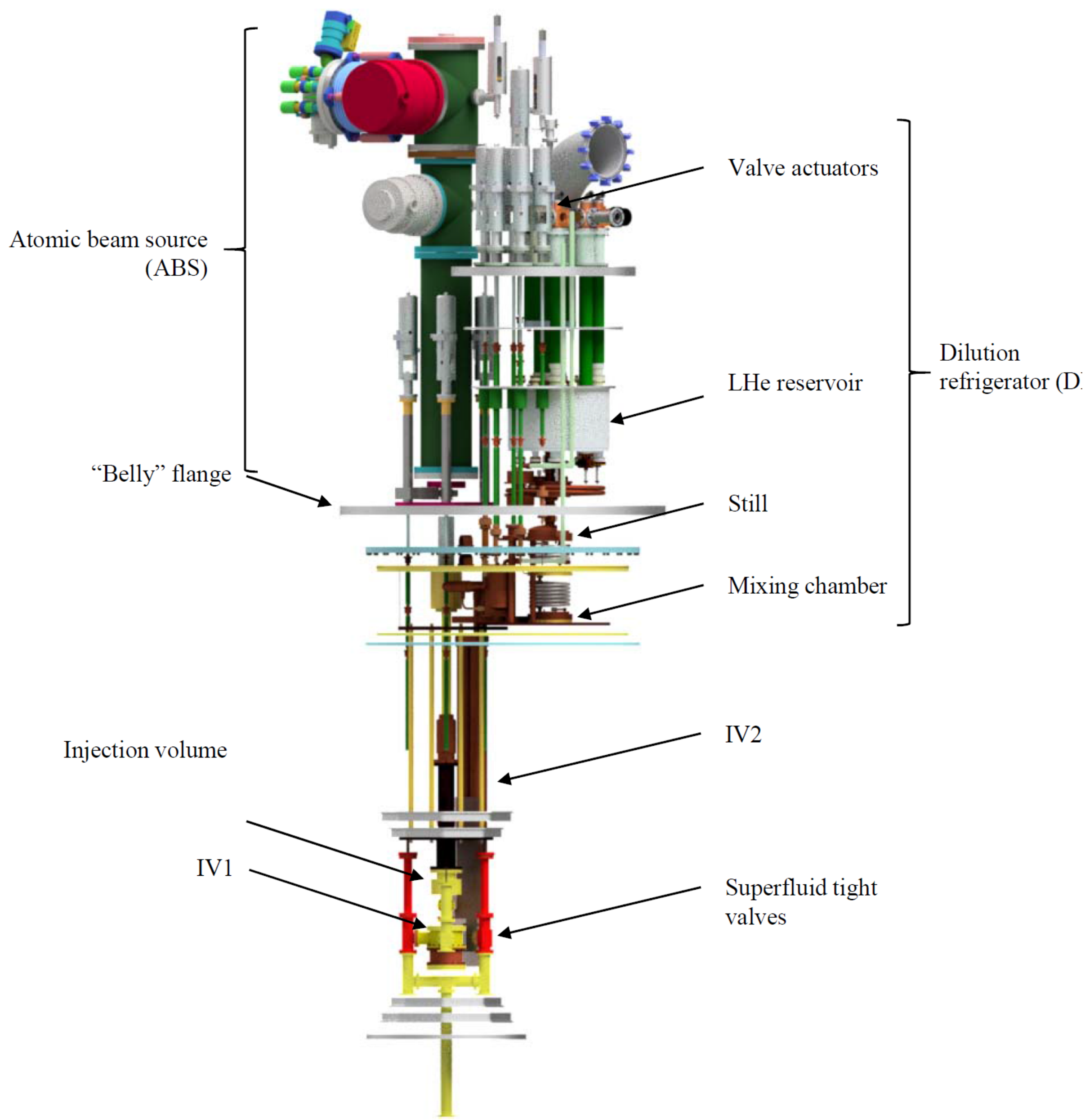
Central Detection System

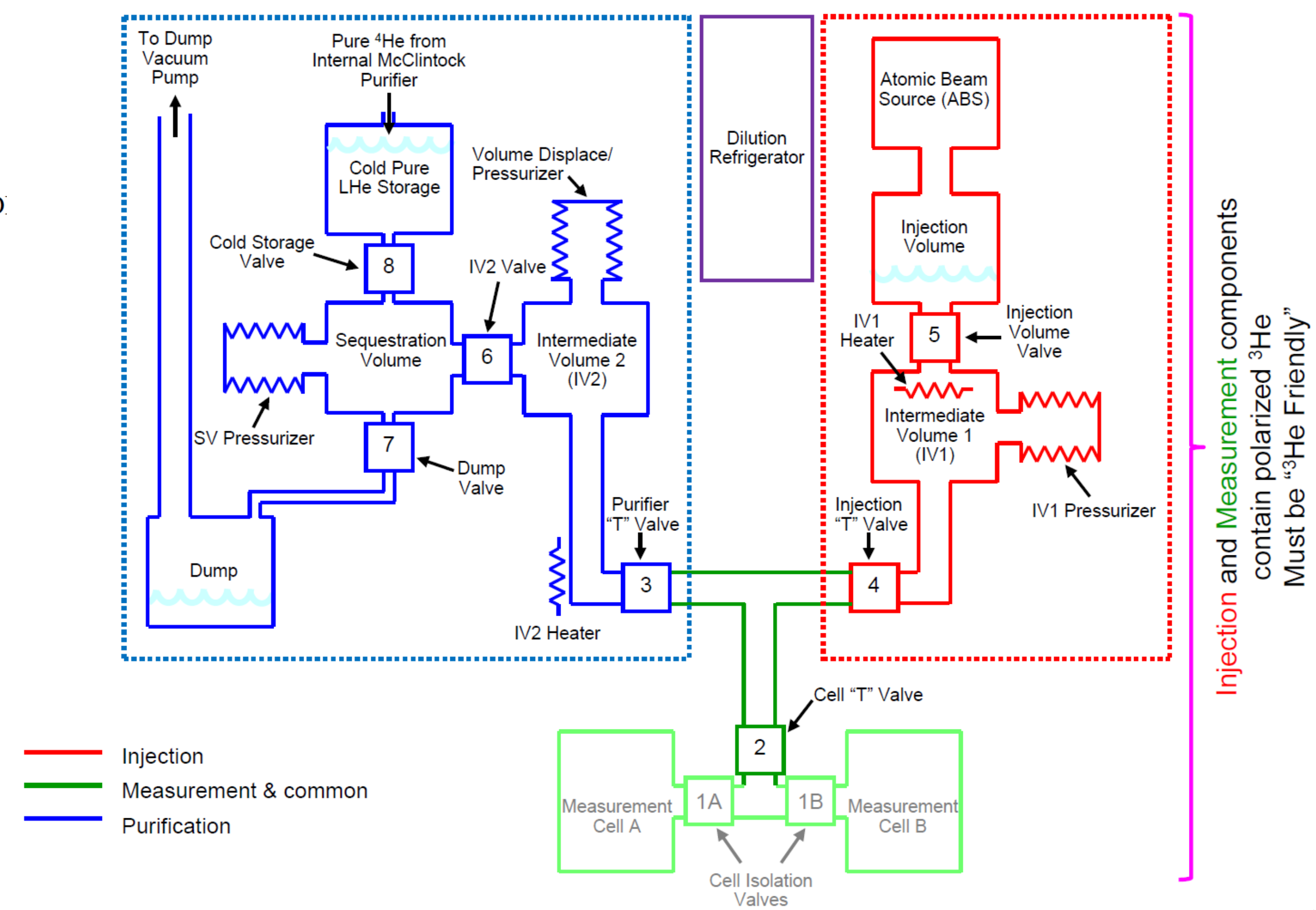
Main components

- Measurement cells with 75 kV/cm electric field inside
- Cavallo's Multiplier
- Squid Magnetometer
- 1600 L of super fluid helium
- Light collection



^{3}He Services



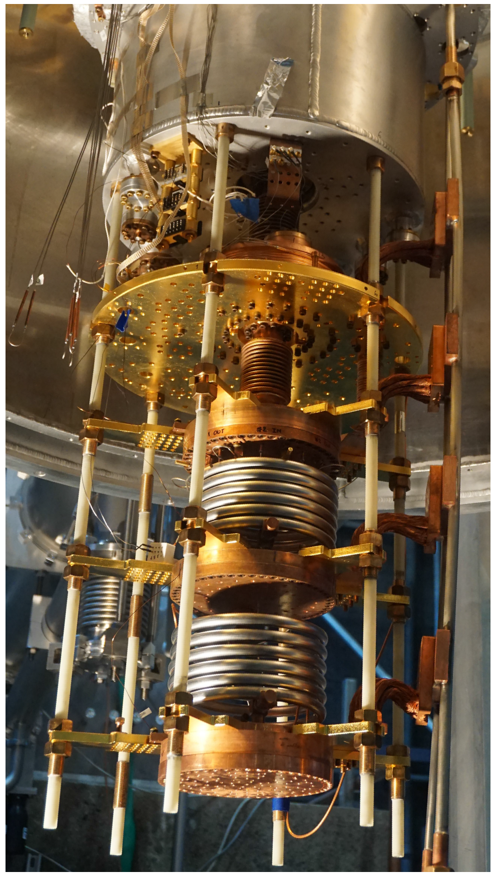


- Heat flush and diffusion methods is used to move ^{3}He
- ^{3}He flow is controlled by heaters, valves, and pressurizers.

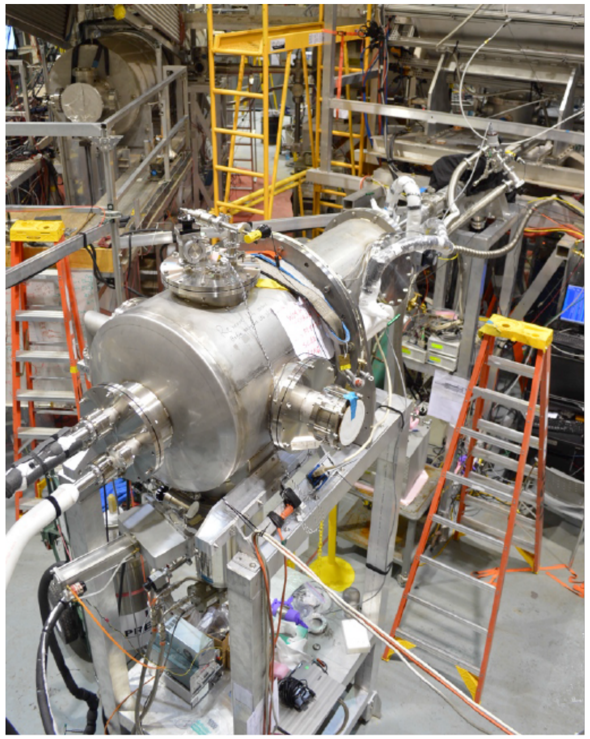
Status

	Status
Magnetic field subsystem	• Full scale lower cryostat being commissioned • Full scale coil package under construction • Magnetic shield room being designed
Central detector system	• > 75 kV/cm in 1/5 scale system demonstrated • Half scale HV test apparatus under construction • Cryogenic Cavallo multiplier prototype being designed • Tests of UCN storage under way using UCN from LANL UCN source • Advanced prototype of SQUID being tested • Non-magnetic, high-power dilution refrigerator being constructed • Final prototype of the light collection readout electronics being
3He services	• Non-magnetic, high-power dilution refrigerator being commissioned • Atomic beam source being re-commissioned • Helium purification system components under construction
Systematic study apparatus	• Cryostat and various components under construction

Status



Dilution refrigerator



UCN storage test

Half scale HV test apparatus

Cryovessel

LANL nEDM Collaboration

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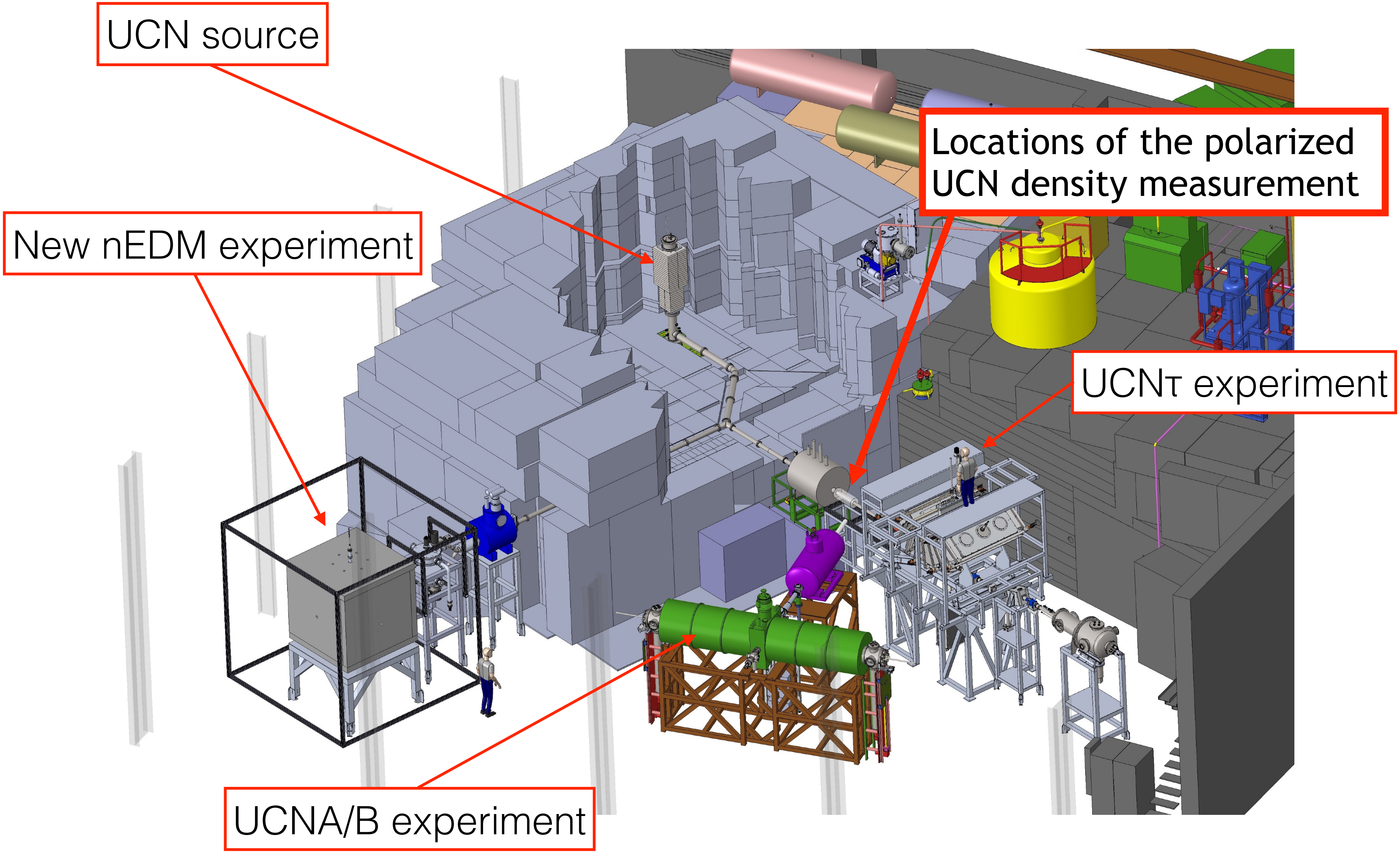
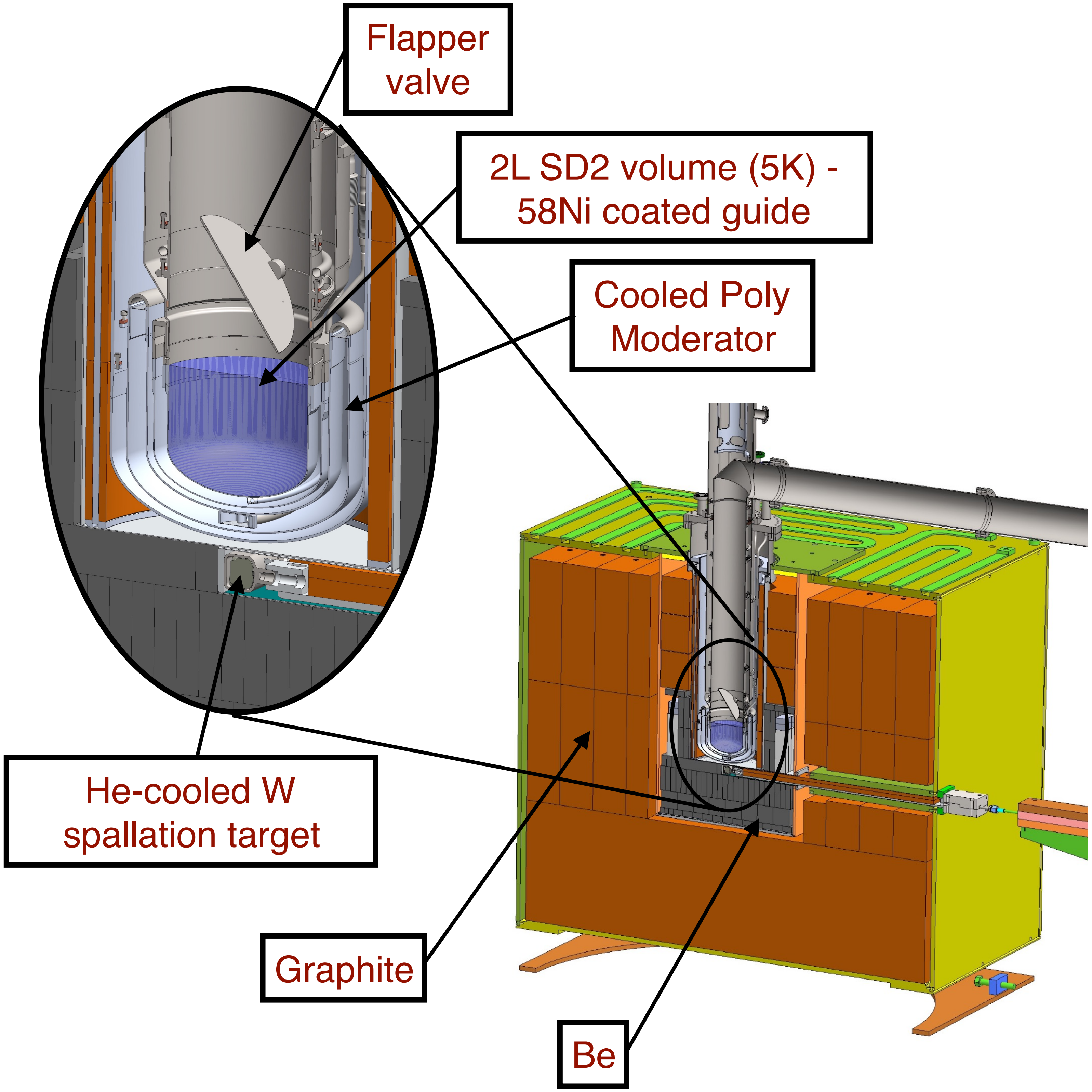
Concept for nEDM experiment at LANL

- A neutron EDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm based on already proven room temperature Ramsey's separated oscillatory field method could take advantage of the existing LANL SD_2 UCN source
  - nEDM measurement technology for $\delta d_n \sim O(10^{-27})$ e-cm exists. What is holding up the progress is the lack of UCN density.
  - The successfully upgraded LANL UCN source has shown to provide the UCN density required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ e-cm
- Such an experiment could provide a venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.

LANL UCN Facility



LANL UCN Source



Spallation neutrons from W target ~ 2 MeV

Thermal neutrons in Be and graphite moderator ~ 25 meV

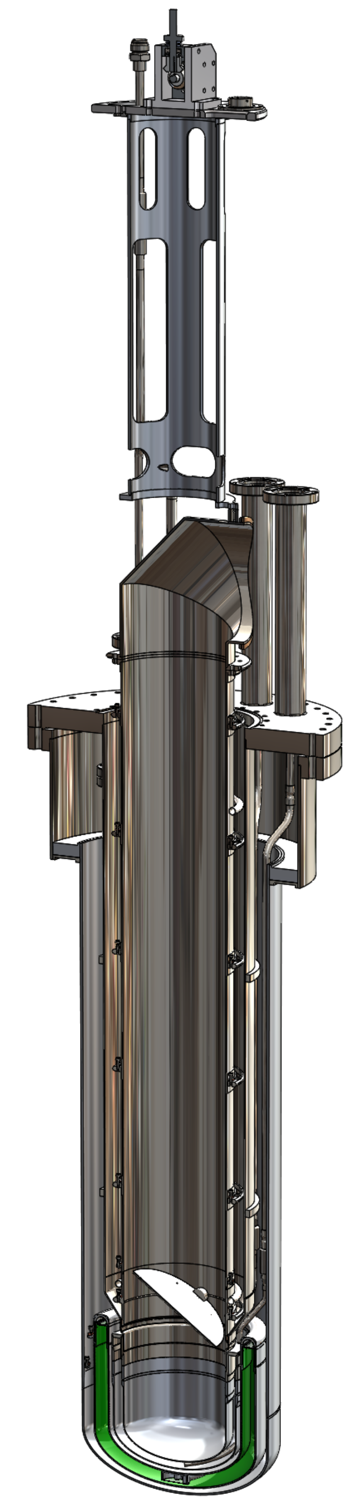
Cold neutrons in polyethylene cold moderator ~ 6 meV

Ultracold neutrons in SD2 converter ~ 100 neV

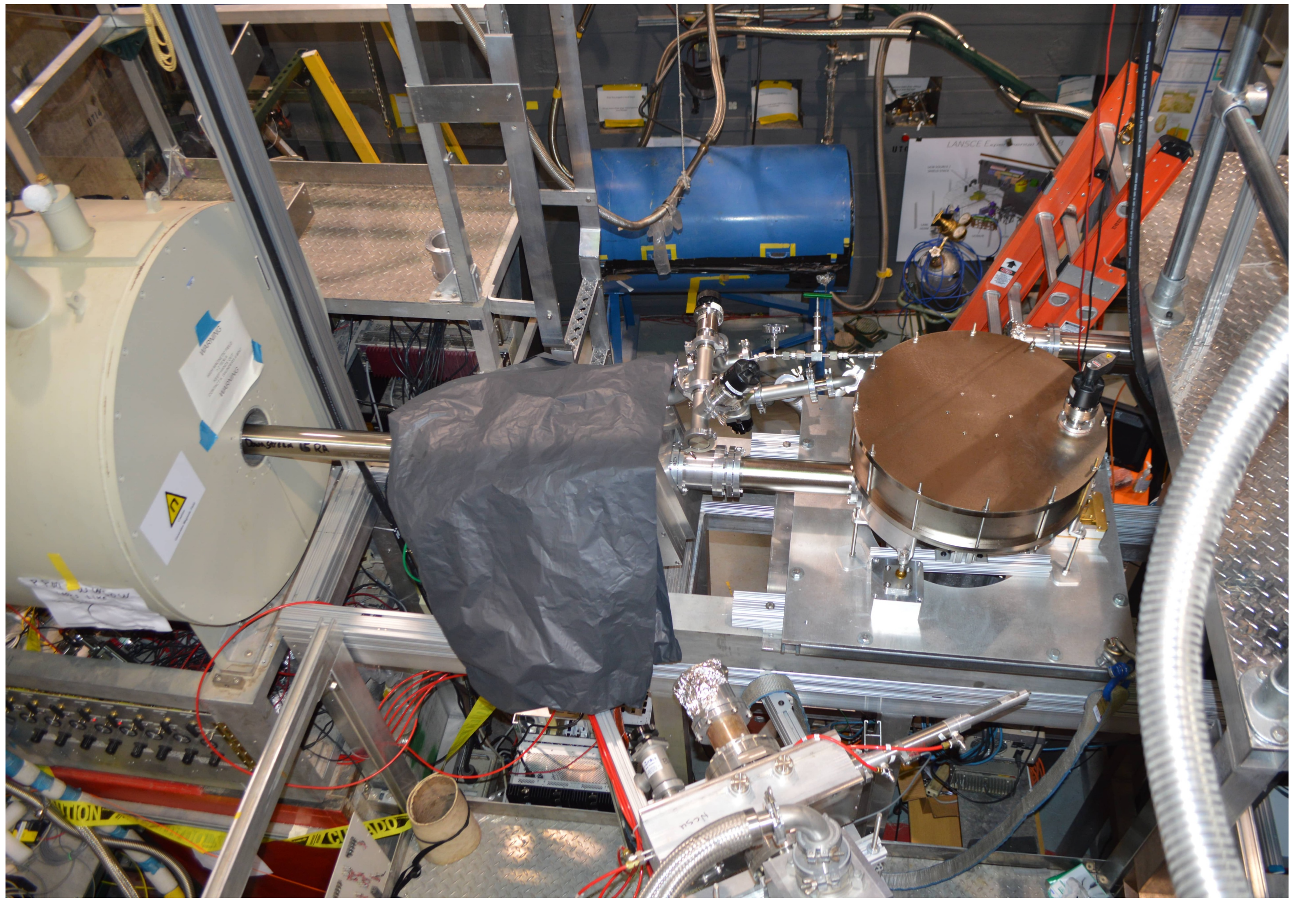
UCN source upgrade

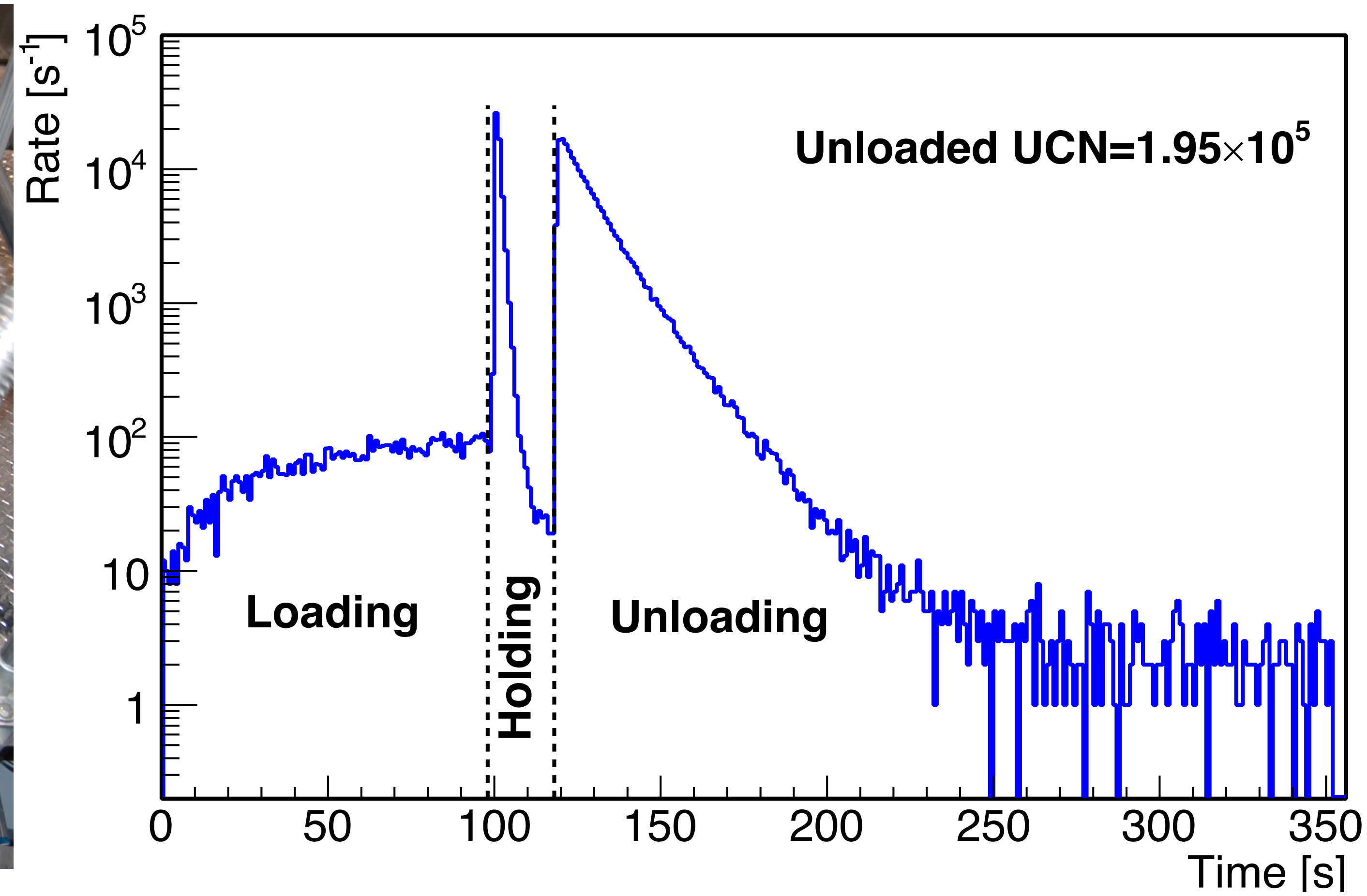
- New source cryostat
  - New design based on previous UCN source cryostat, which had been successfully operating since 2004
  - Dramatic, yet adiabatic changes
  - Optimize source cryostat and moderator geometry to improve UCN output (based on simulation that is benchmarked against the current source)
  - Replaceable moderator

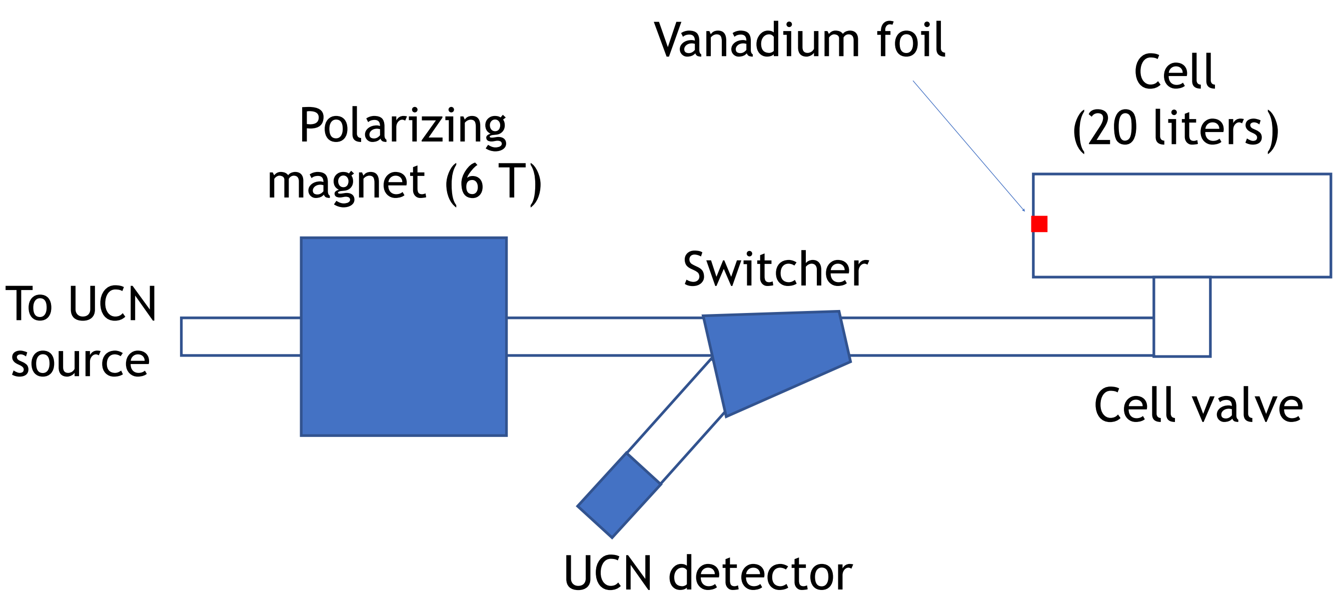
- New flapper valve design based on current successful model
  - Most recent model has surpassed 1M cycles cold with UCN friendly materials
  - Tightly integrated with source cryostat design
  - Flapper drive components moved outside the UCN volume
  - Modify UCN tee geometry for improved UCN flow and reduced loss



Polarized UCN density in a dummy nEDM cell





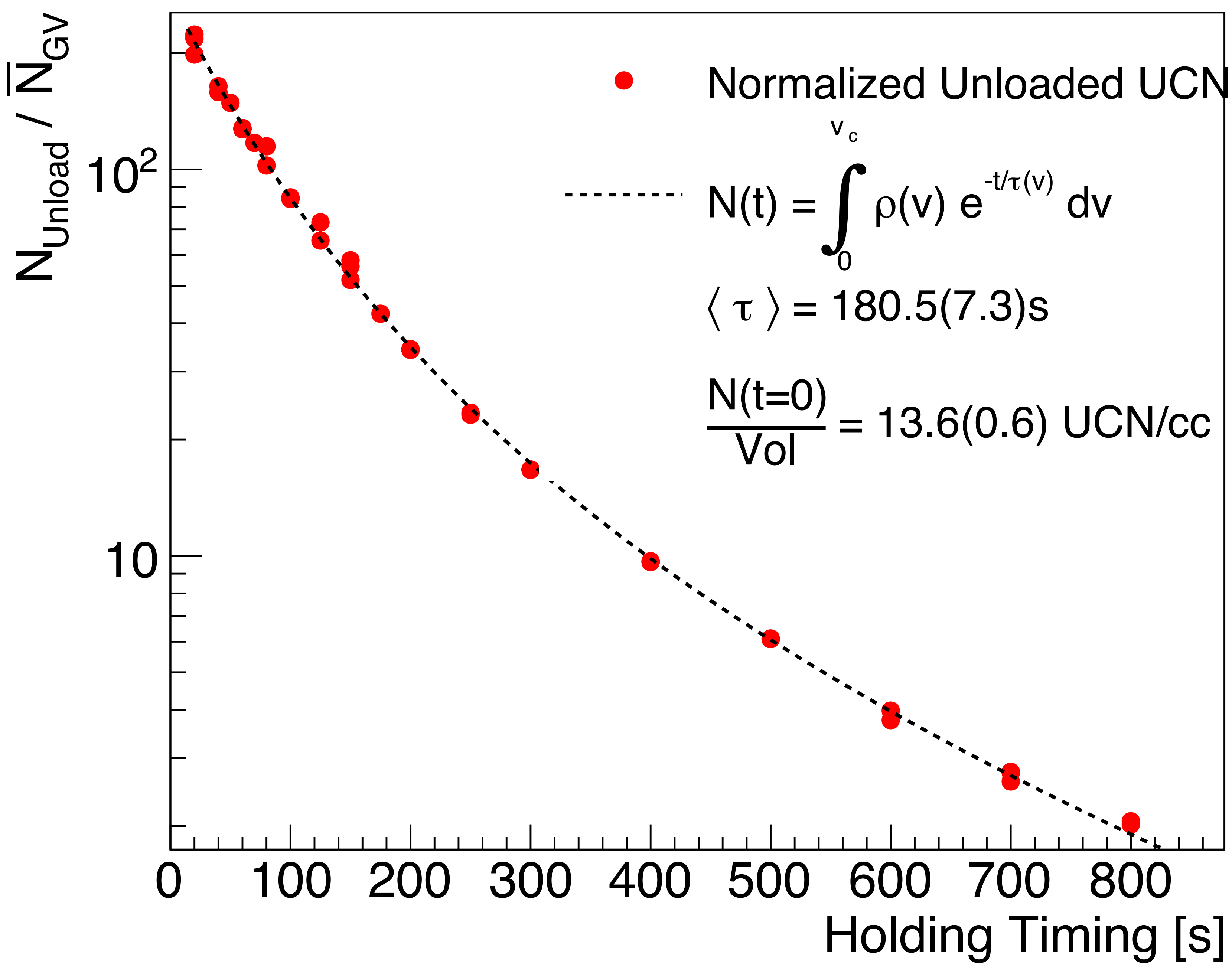


Polarized UCN density (E < 170 neV) at t=0

- 13.6(6) UCN/cc from the fill and dump measurement (was 2.5 UCN/cc before the source upgrade)
- 39(7) UCN/cc from vanadium foil activation measurement

The difference can be attributed to loss in the switcher (~0.5) and the finite detection efficiency (~0.7).

Storage time curve



Holding time	# of counted UCN
20	~200,000
150	~45,000

Estimated statistical sensitivity of an nEDM experiment

$$\delta d_n = \frac{\hbar}{2\alpha T E \sqrt{N}}$$

Parameters	Values
E(kV/cm)	12.0
N(per cell)	39,100
T_{free} (s)	180
T_{duty} (s)	300
α	0.8
σ/day/cell (10^{-26} e-cm)	5.7
σ/day (10^{-26} e-cm) (for double cell)	4.0
σ/year (10^{-27} e-cm) (for double cell)	2.1
90% C.L./year (10^{-27} e-cm) (for double cell)	3.4

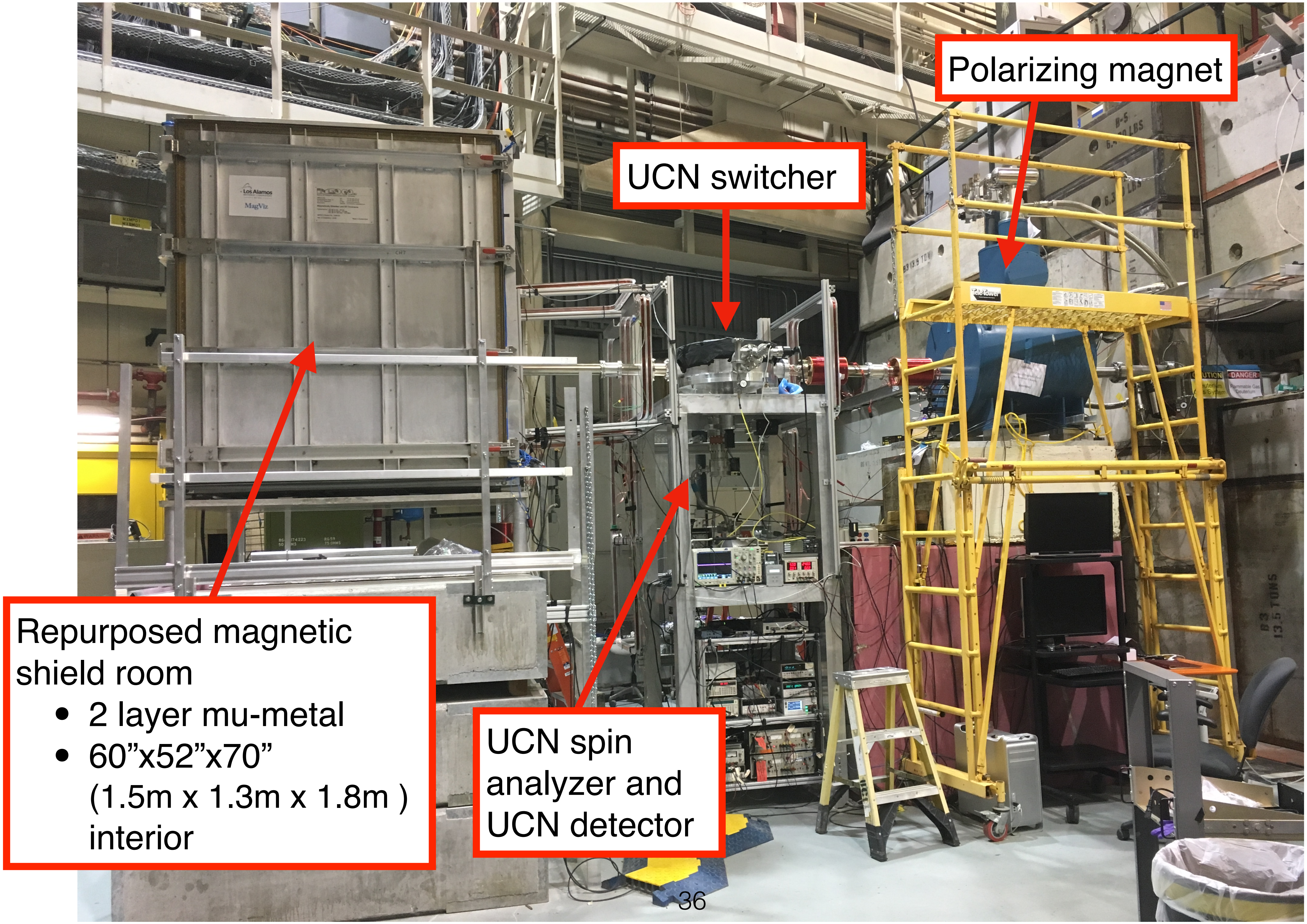
This estimate is based on the following:

- 50 cm diameter cell
- The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.
- The estimate for N is based on the actual detected number of UCN from our fill and dump measurement at a holding time of 180 s. Further improvements are expected (new switcher and new detector).

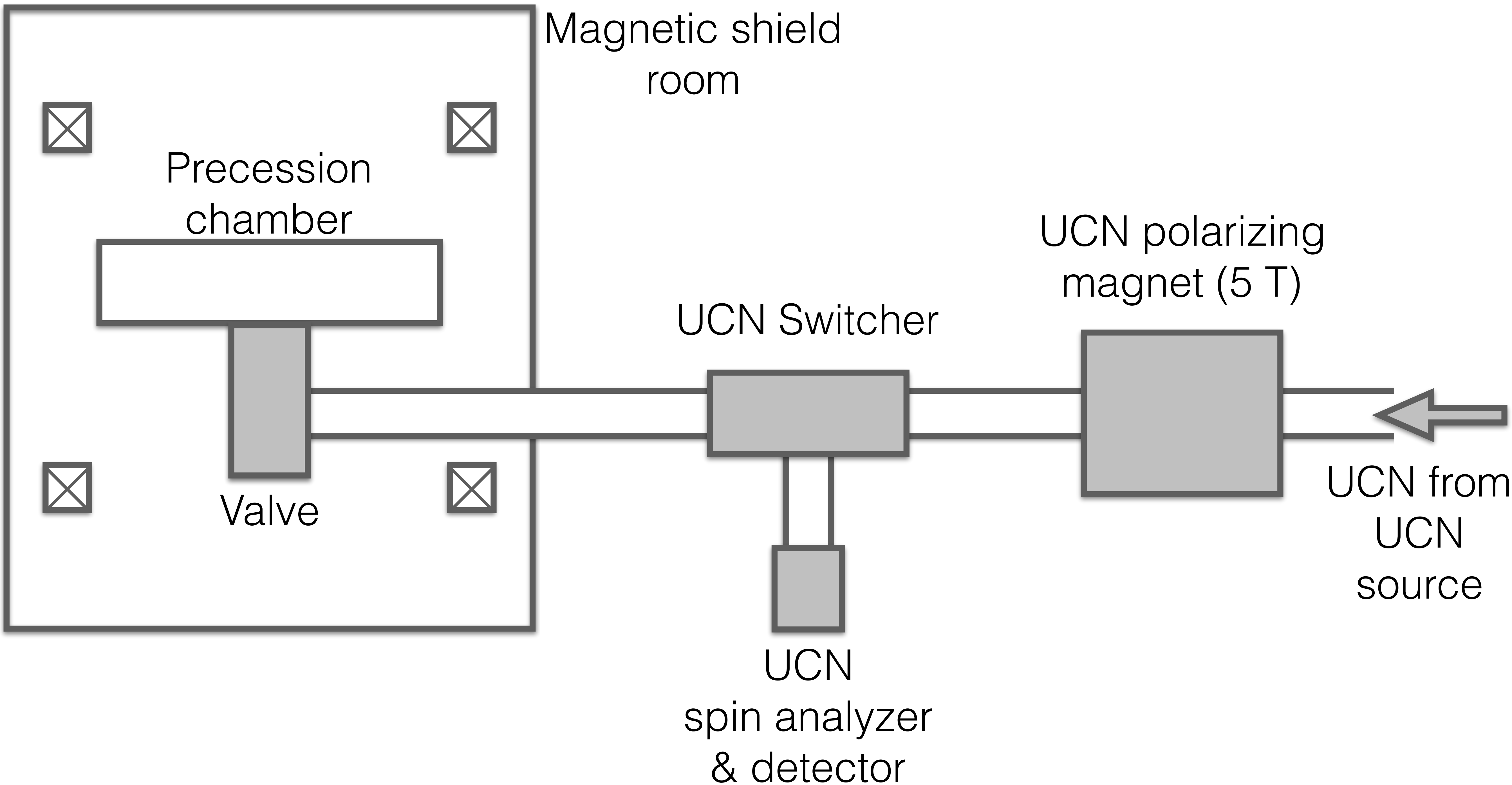
*** "year" = 365 live days. In practice, it will take 5 calendar years to achieve this with 50% data taking efficiency and nominal LANSCE accelerator operation schedule**

Ramsey demonstration apparatus

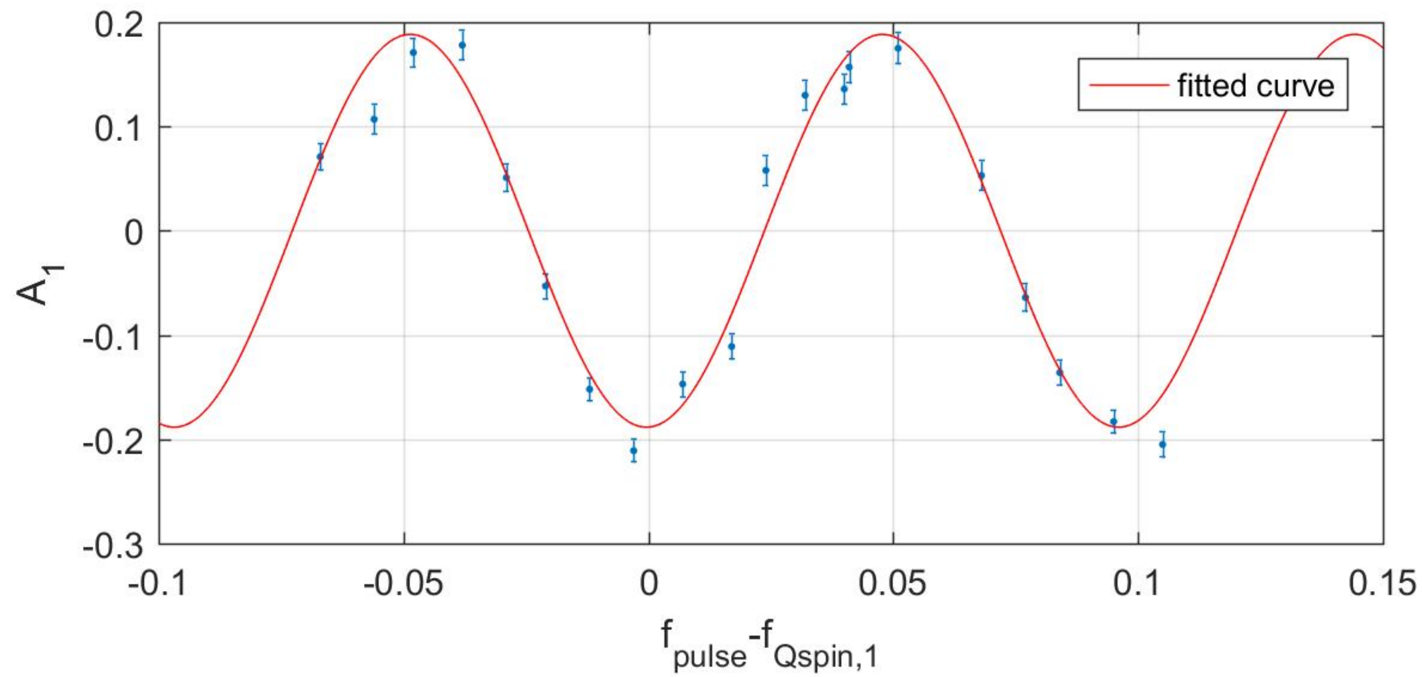
First step towards building an nEDM experiment

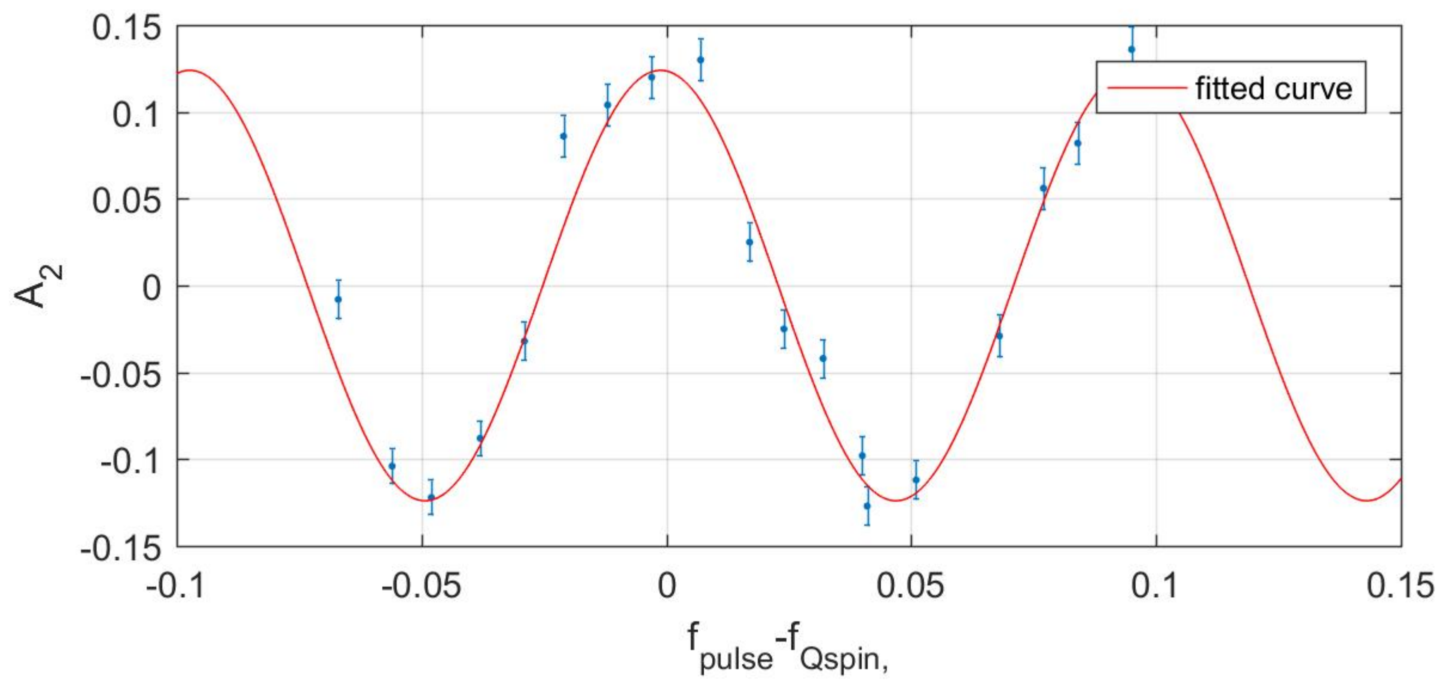


Schematic diagram of Ramsey demonstration apparatus



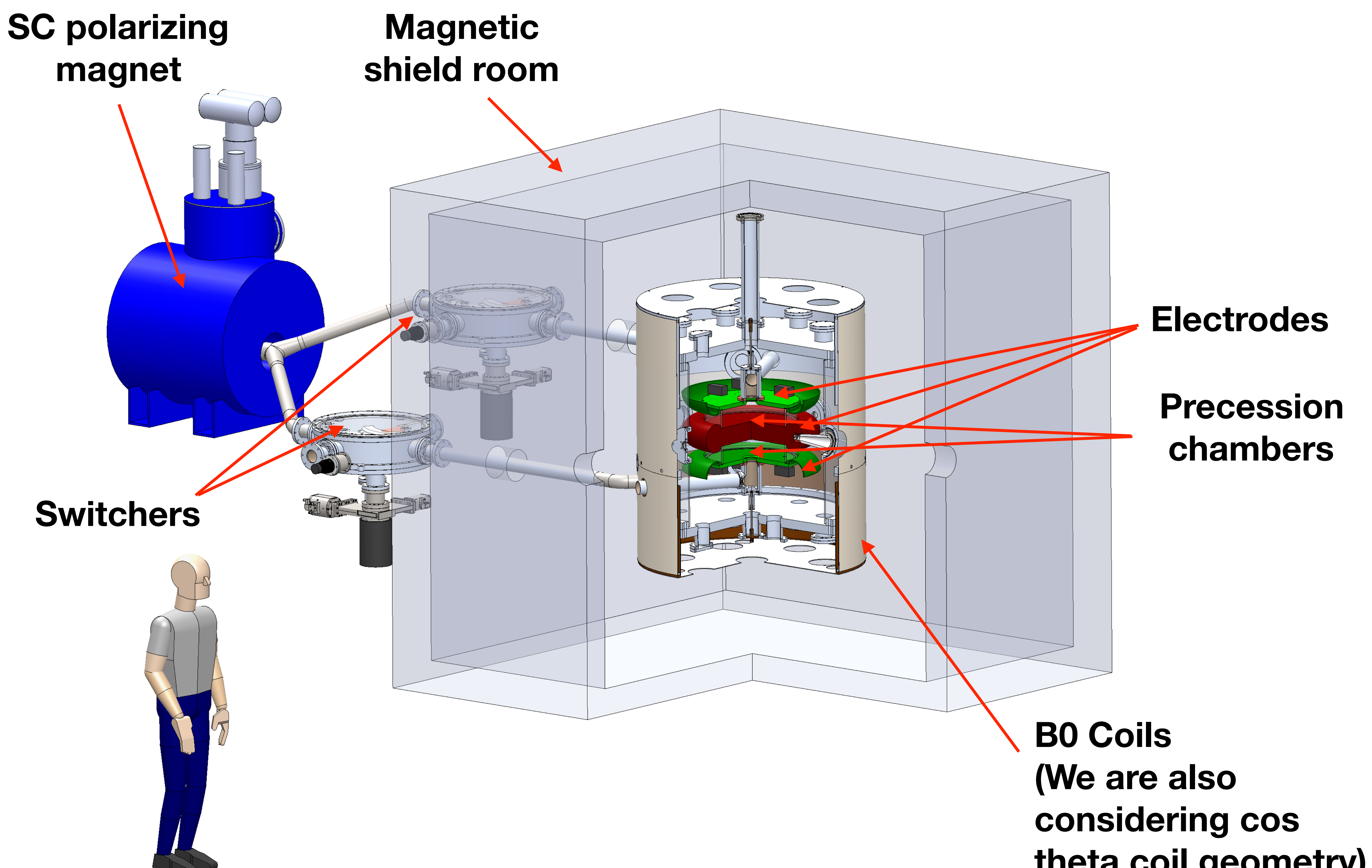
Ramsey curve with a 10 s free precession time





T2 ~ 20 s

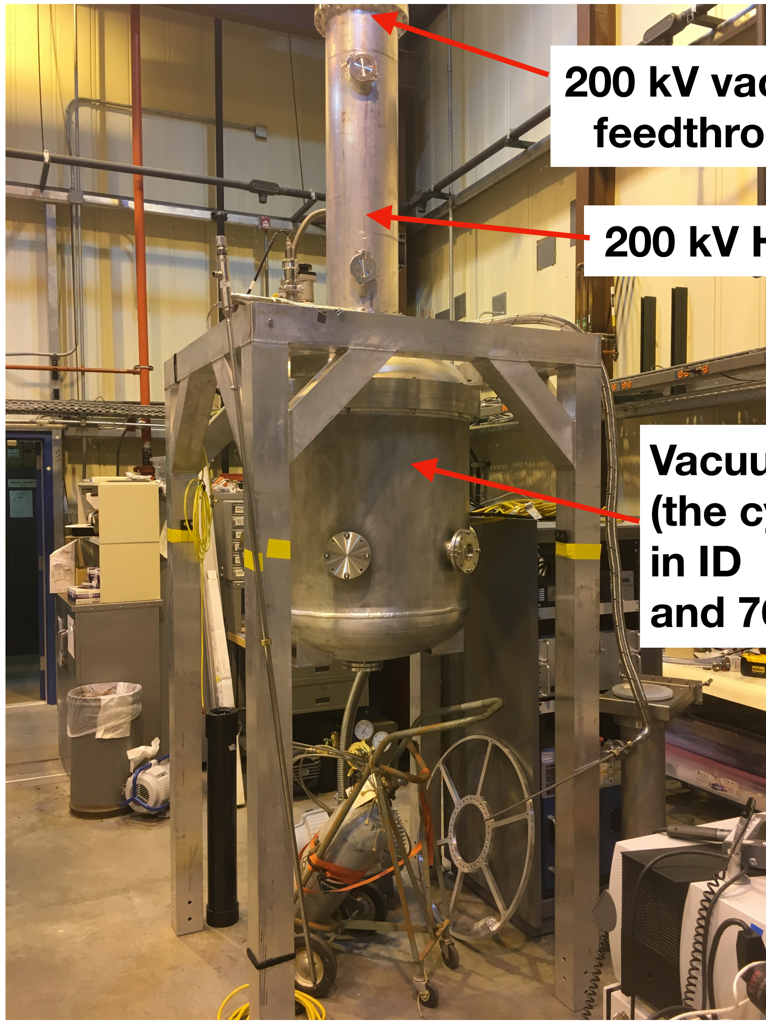
Proposed LANL nEDM experiment (conceptual)

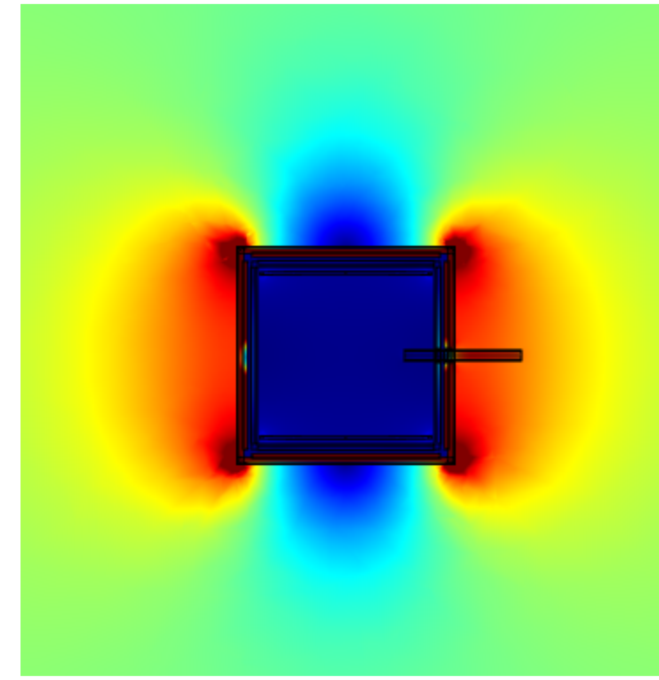


Status

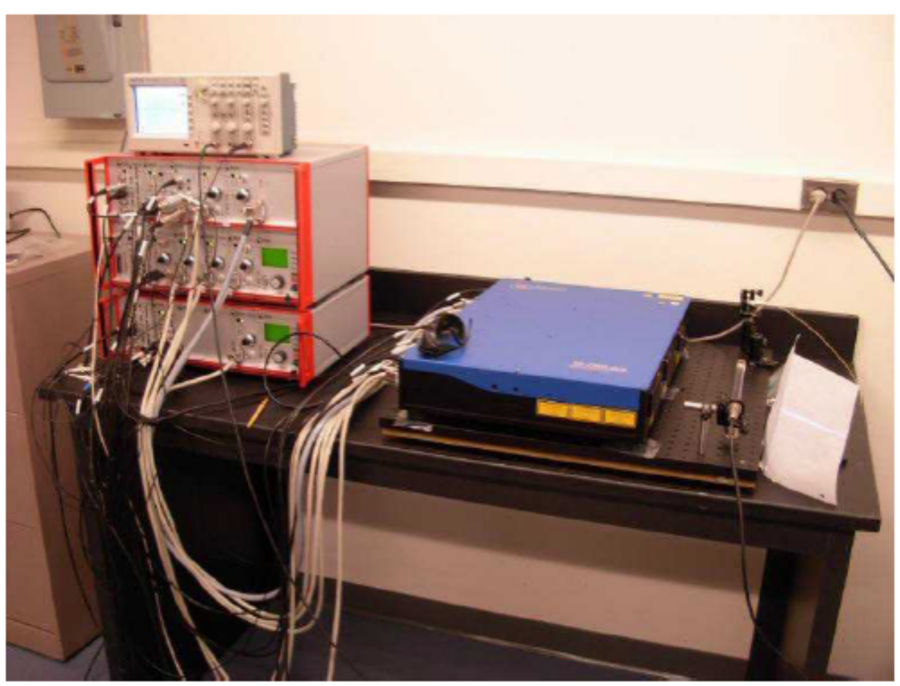
- Continued R&D using the prototype apparatus
  - Test bed for: spin transport, magnetic field, material selection, DAQ system, etc.
- The experimental apparatus being designed
  - Current focus is on the design of the MSR, longest lead-time component

Status

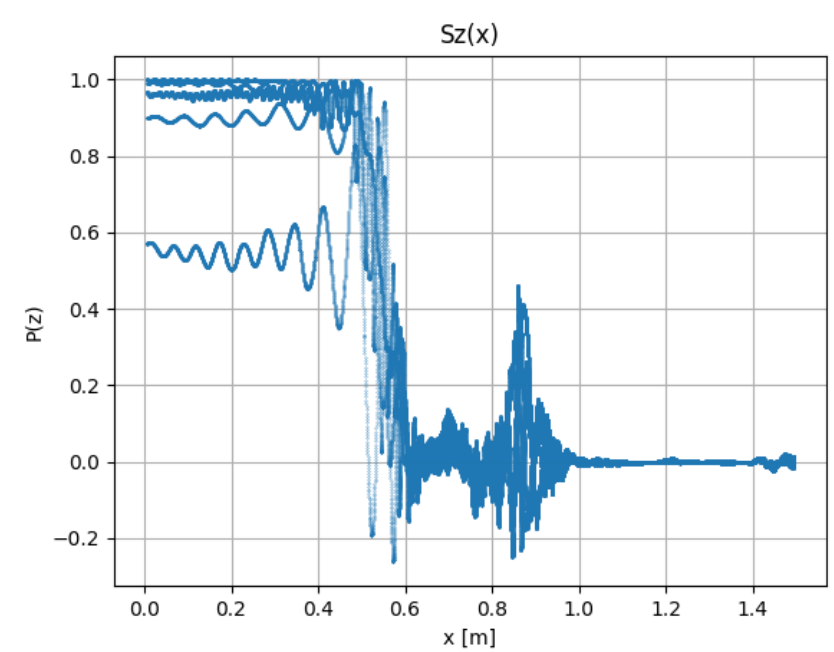




MSR simulation using COMSOL (Helmholz coil in mumetal box)



Topica quadrupled system



Spin transport simulation

nEDM efforts in North America

Experiment	UCN source	Method	Goal sensitivity
TUCANS at TRIUMF	Suerfluid LHe converter coupled to a spallation source	Ramsey method at room temperature with ^{199}Hg and ^{129}Xe comagnetometers	10^{-27} e-cm
nEDM@SNS	In-situ producing in superfluid LHe	Golub-Lamoreaux method in cryogenic apparatus	10^{-28} e-cm
LANL nEDM	SD2 converter coupled to a pulsed spallation source	Ramsey method at room temperature with ^{199}Hg comagnetometer	10^{-27} e-cm