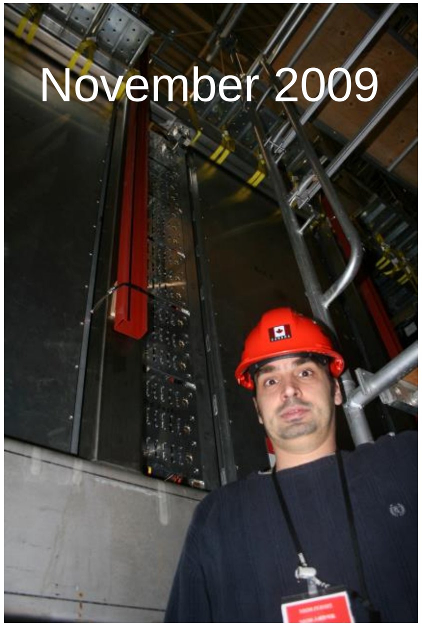
Searches for the Neutron Electric Dipole Moment



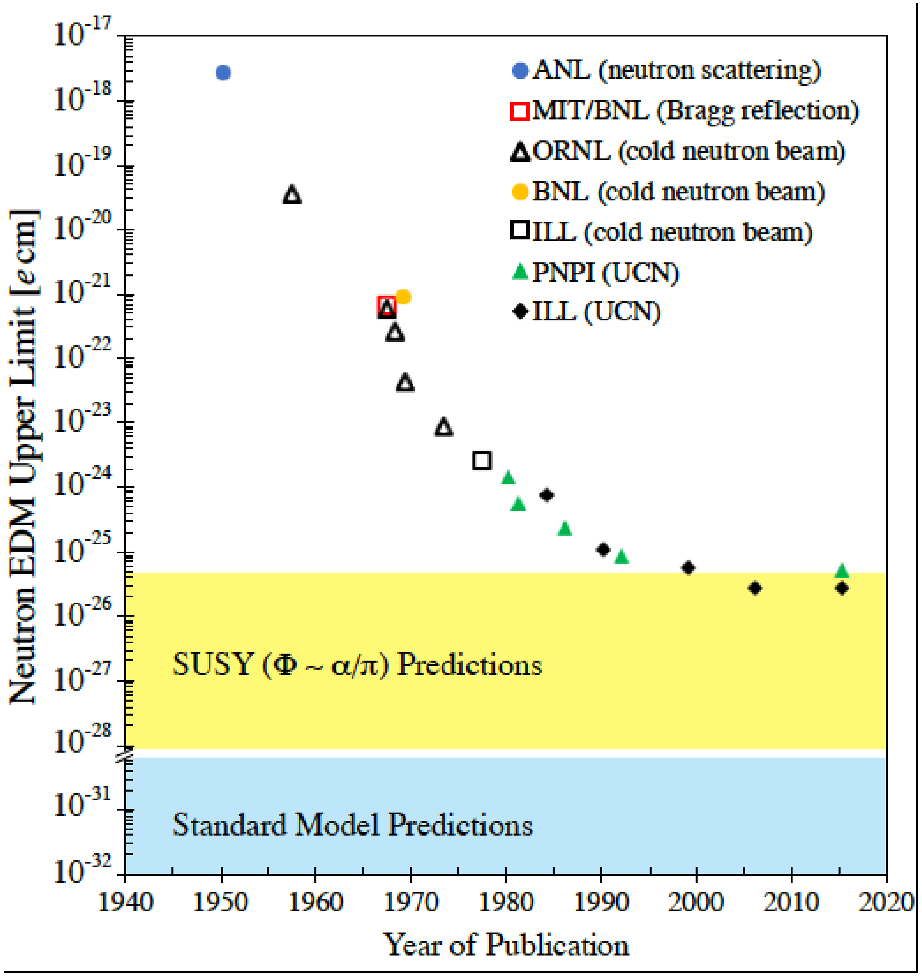
T. Lindner

TRIUMF & University of Winnipeg

Searching for nEDM with Ultracold Neutrons

Neutron Electric Dipole Moments

- Sensitive probe of CP violation.
  - CP violation in Standard Model not large enough to explain observed baryon asymmetry of universe
- Can constrain beyond Standard Model physics.
- Current limit: $d_n < 3.0 \times 10^{-26}$ e-cm (90% CL)
  - (ILL-Sussex-RAL; Pendlebury et al., Phys. Rev. D 92, 092003, 2015)



nEDM measurements from neutrons
From R. Matsumiya

nEDM Experiments Around World

- nEDM@PSI
  - Spallation + sD2 moderator
  - Data taking finished in 2016
  - $\sigma_{\text{raw}} = 0.944 \times 10^{-26} e\text{cm}$
  - Results expected soon
- n2EDM Setup
  - Double UCN chamber, Hg co-magnetometer
  - 100+ Cs magnetometers
  - MSR installed
  - Statistical sensitivity $\sigma \leq 1.1 \times 10^{-27} e\text{cm}$ (in 500 days)

Courtesy of P. Schmidt-Wellenburg

大強度陽子加速器施設
J-PARC

Crystal nEDM at J-PARC

Content adapted from S. Itoh

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

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]	$\sim 10^{8}$	$\sim 10^{4}$	$\sim 10^{2}$
sensitivity $\sigma(d_n)$	$\sim 10^{-25}/\sqrt{\text{Day}}$	$\sim 10^{-25}/\sqrt{\text{Day}}$	$\sim 10^{-25}/\sqrt{\text{Day}}$

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

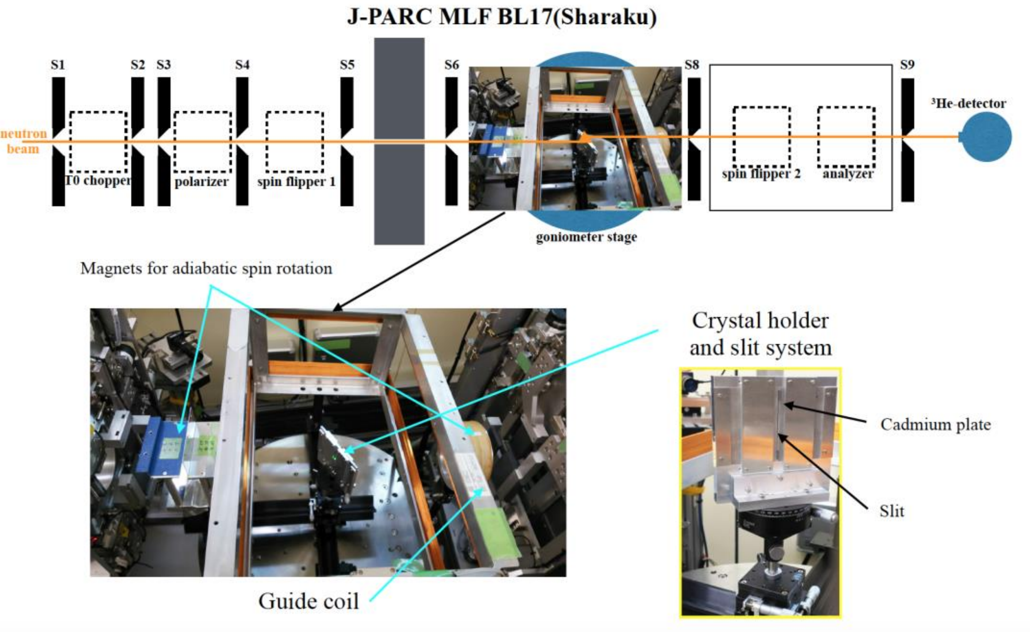
Crystal EDM vs UCN EDM
- Higher electric field
- Shorter interaction time

Search for the electric dipole moment of neutrons by the diffraction of a single crystal

伊藤茂康，福村省三，菱田真由，北口雅暁，清水裕彦
Shigeyasu Itoh, Seiso Fukumura, Mayu Hishida, Masaaki Kitaguchi, Hirohiko M. Shimizu

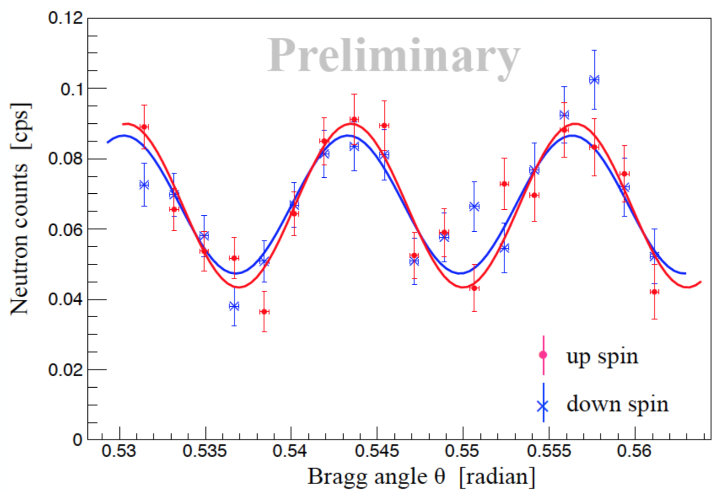
大強度陽子加速器施設

Crystal EDM at J-PARC: Status



Experiment setup at J-PARC MLF

2019/04:
successfully observed Pendellösung fringes with SiO2 by using polarized pulsed neutrons.



The pendellösung Fringes with SiO2(110) by using polarized pulsed neutron beam with up spin and down spin state. The effective flectric field inside a crystal was obtained by the phase shift.

under the analysis

TUCAN Collaboration

(TRIUMF Ultra-Cold Advanced Neutron)

- 10 institutions:
  - 4 Japanese
  - 6 Canadian
- 45 members

Goals of TUCAN collaboration:

- *Most intense UCN source*
- *Most sensitive nEDM experiment*

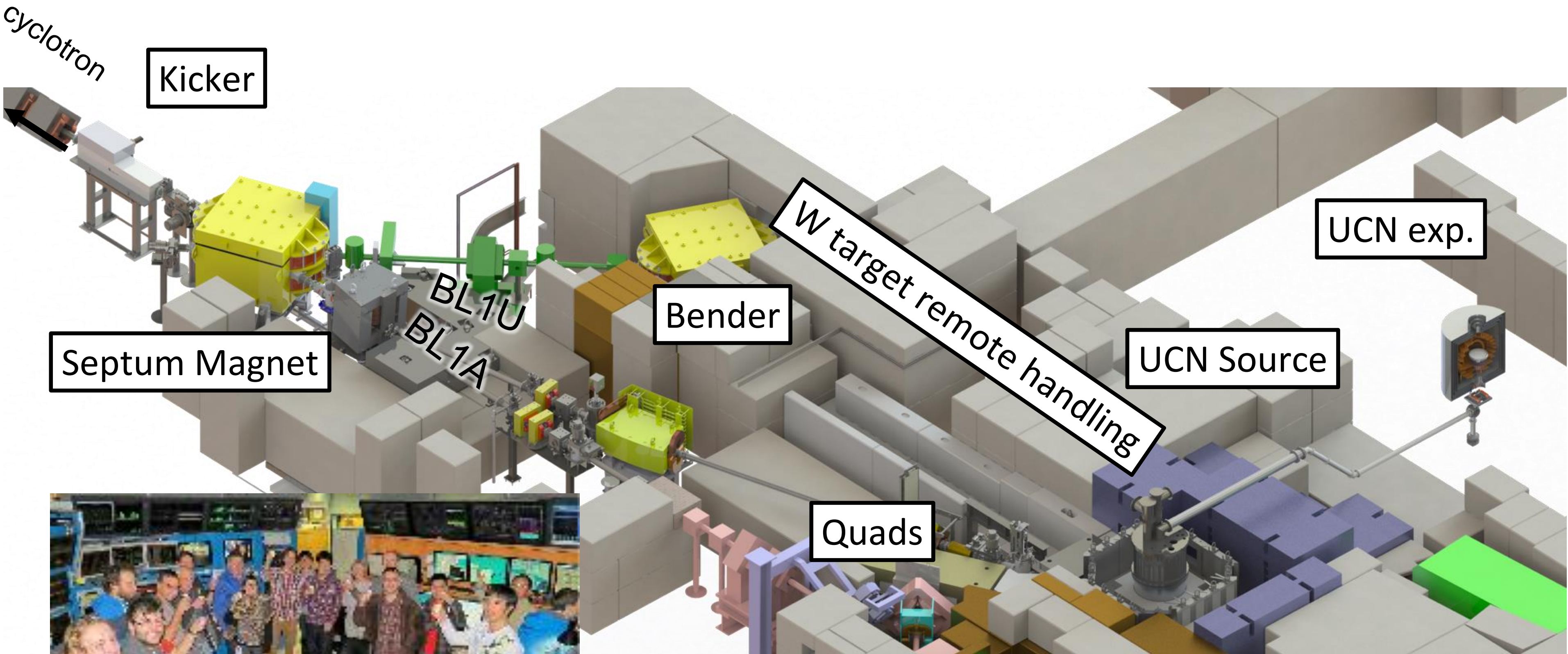
TRIUMF KEK RCNP The University of Winnipeg

The University of British Columbia University of Manitoba SFU Simon Fraser University Engaging the World Nagoya University

UNBC University of Northern British Columbia

TRIUMF

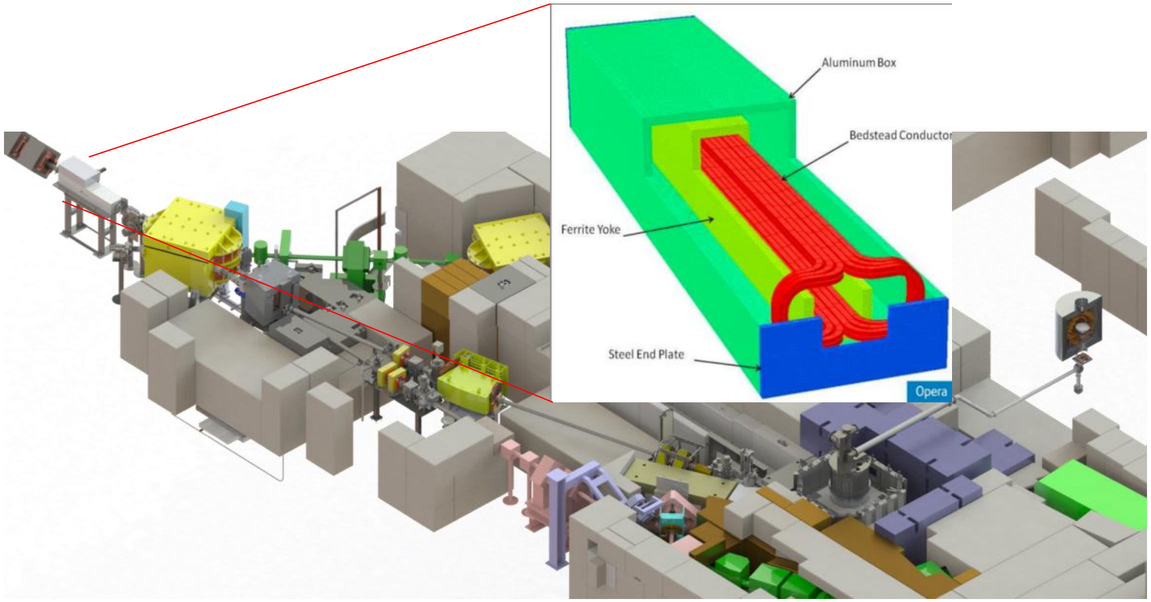
New beamline at TRIUMF for the UCN source

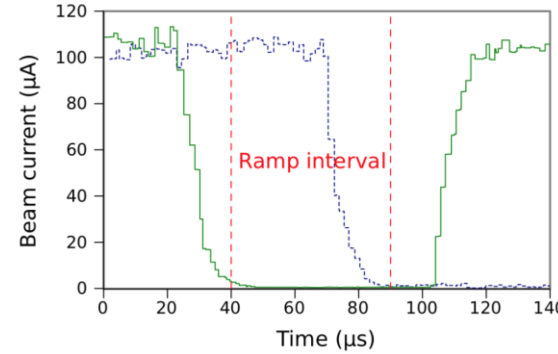


First beam on UCN target
Nov 22, 2016

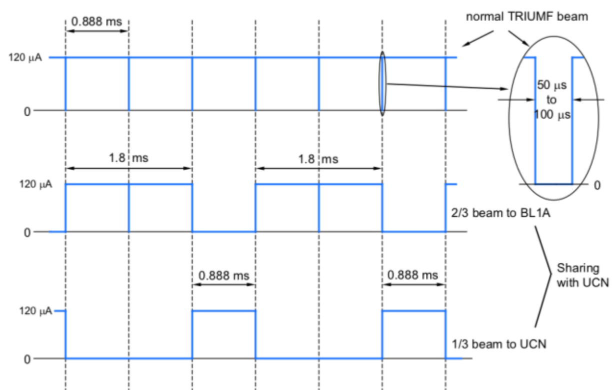
Nucl. Inst. And Methods A 927 (2019) 101

UCN Kicker Magnet Commissioning

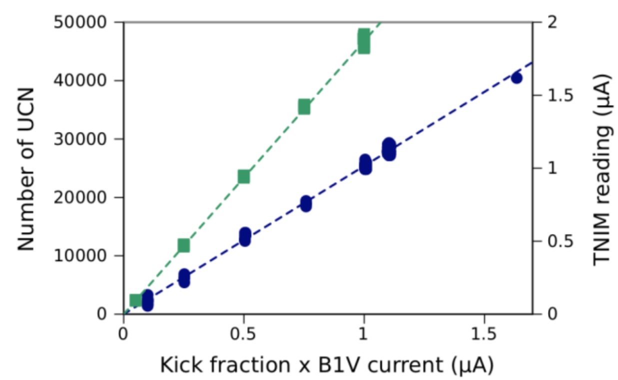




Beam notch monitor



Sharing of TRIUMF beam to UCN beamline

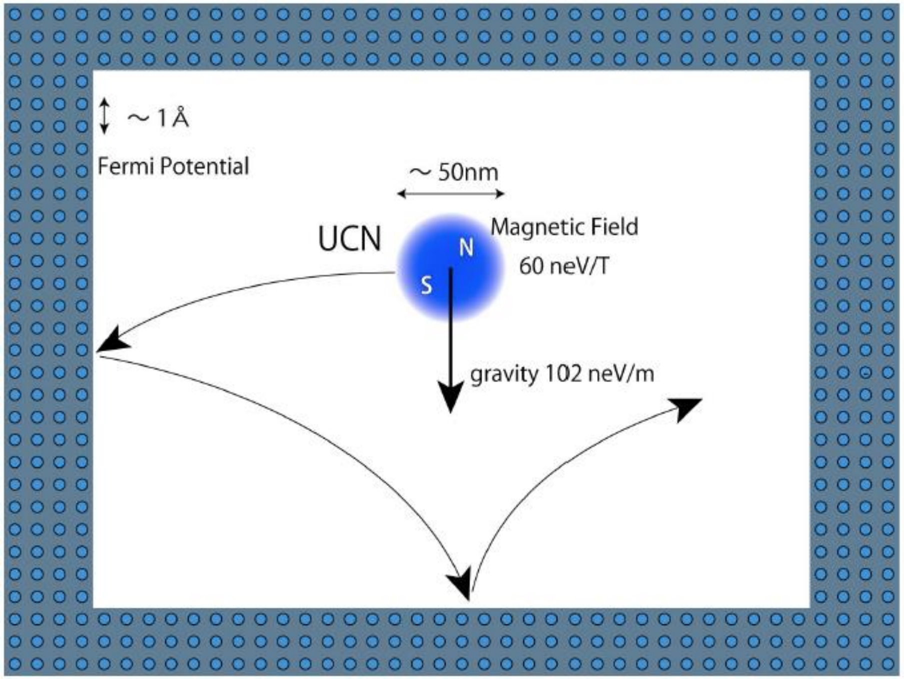


Linearity of UCN production with beam sharing.

https://arxiv.org/abs/1905.08857
Submitted to PRAB

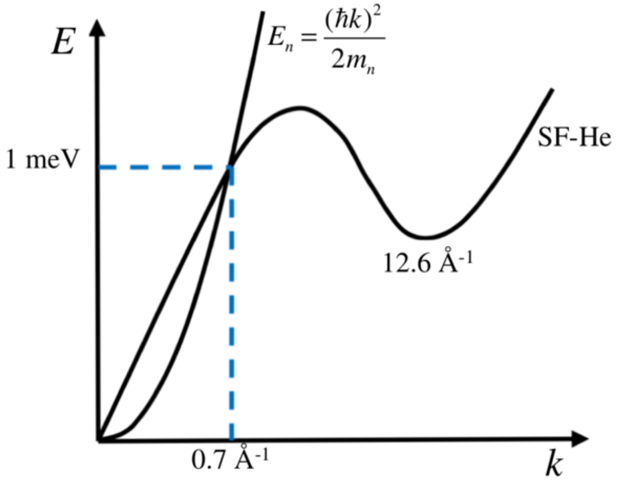
Why Ultracold Neutrons?

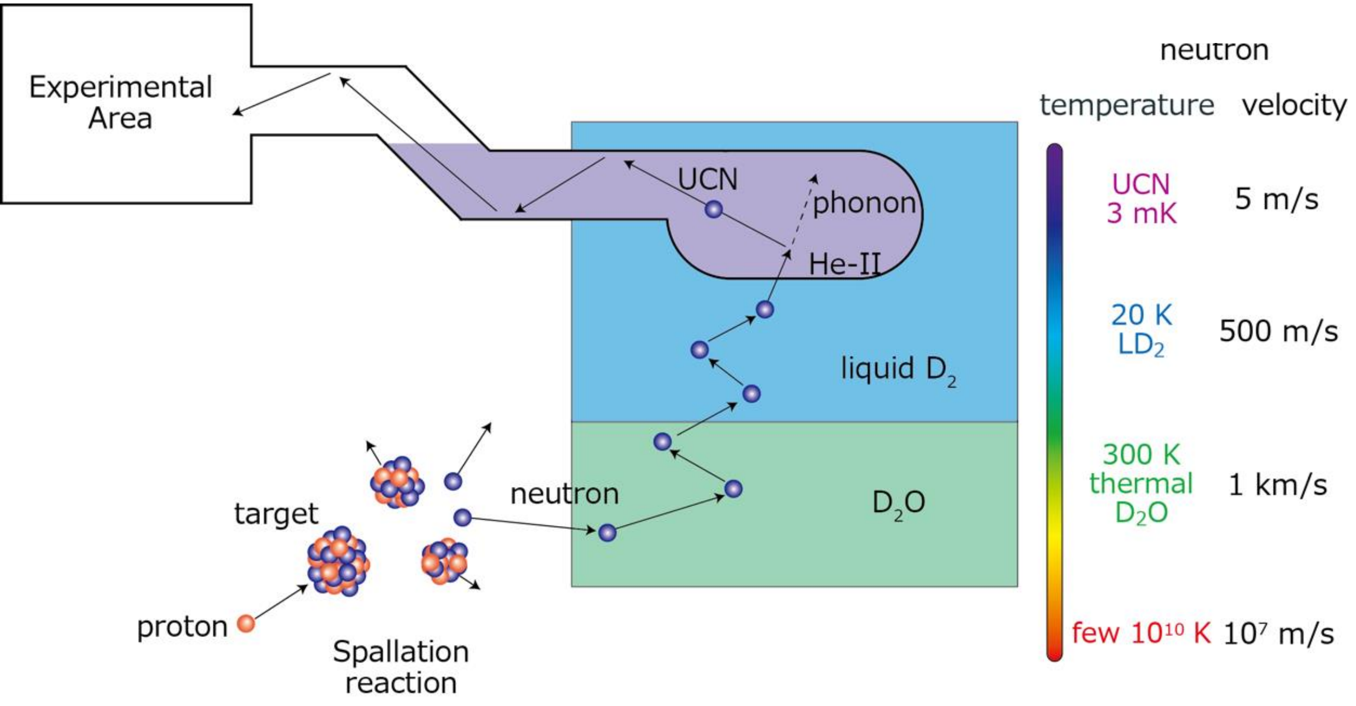
- Ultracold neutrons (UCNs) moving so slowly they reflect from material walls
  - Velocities < 7 m/s
  - Temperature < 4 mK
  - Kinetic energy < 300 neV
- UCNs can be stored in a bottle → UCN can be effectively transported away from production point and stored for long nEDM measurement cycle.



How to make UCN?

- 480 MeV protons on tungsten target produce spallation neutrons
- Moderators thermalize neutrons
- Down-scatter by interaction phonons / rotons in He-II to ultracold

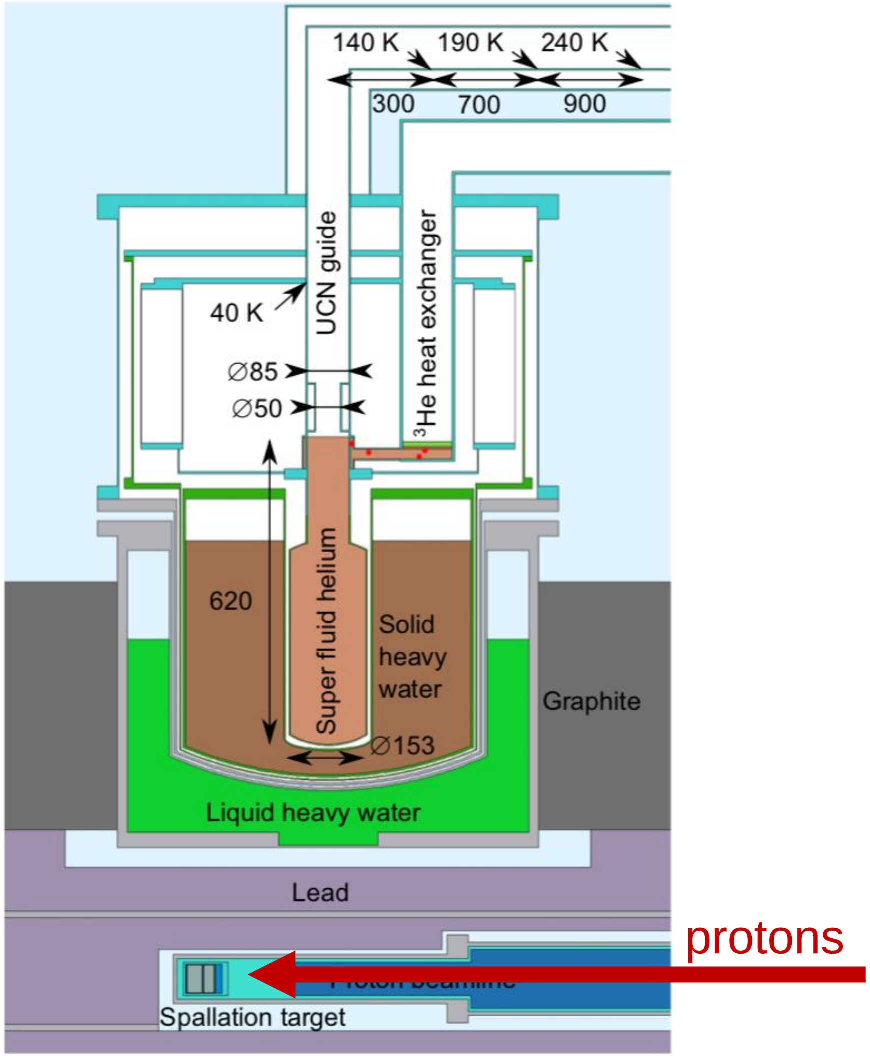




KEK/RCNP Vertical Source

- 300 K moderators: lead, graphite and liquid D_2O
- 10 K moderator: solid D_20
- <1 K moderator: He-II produced by custom ^{3}He dilution refrigerator

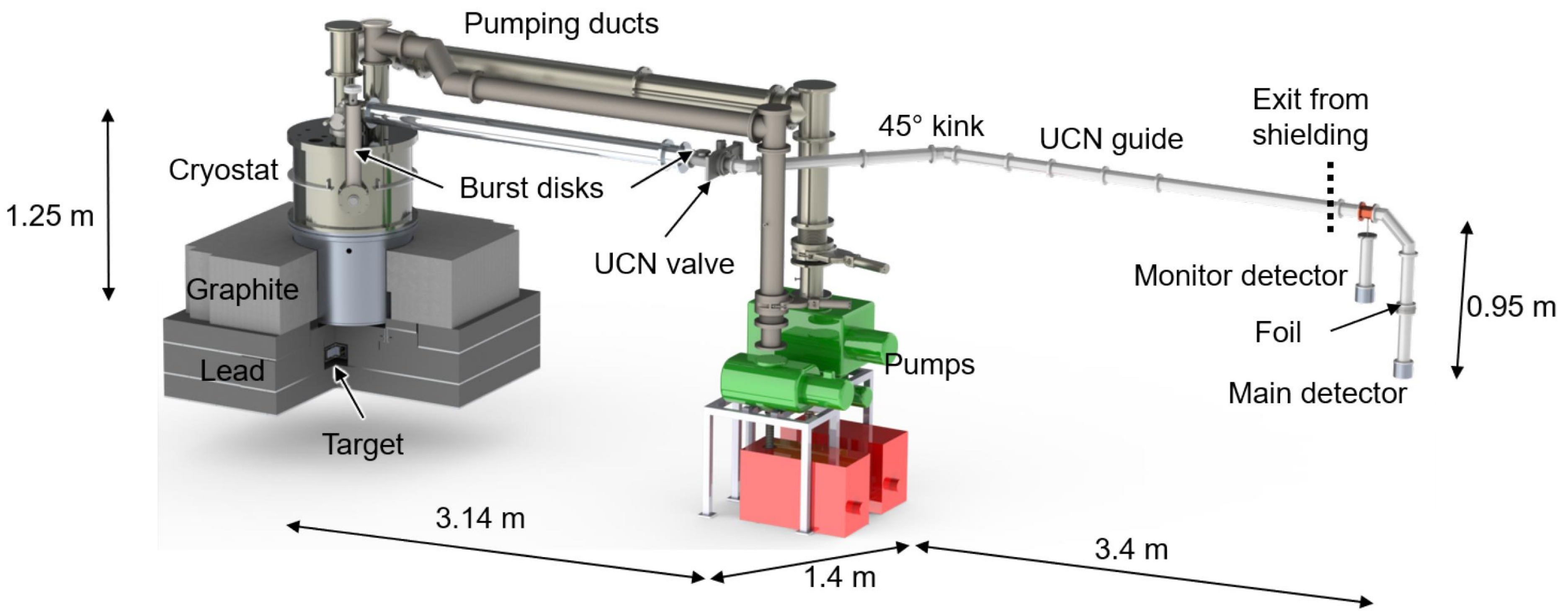
Moved to TRIUMF in 2016



Phys. Rev. Lett. 108, (2012) 134801
Phys. Rev. C 99 (2019) 025503

Current TRIUMF Source Configuration

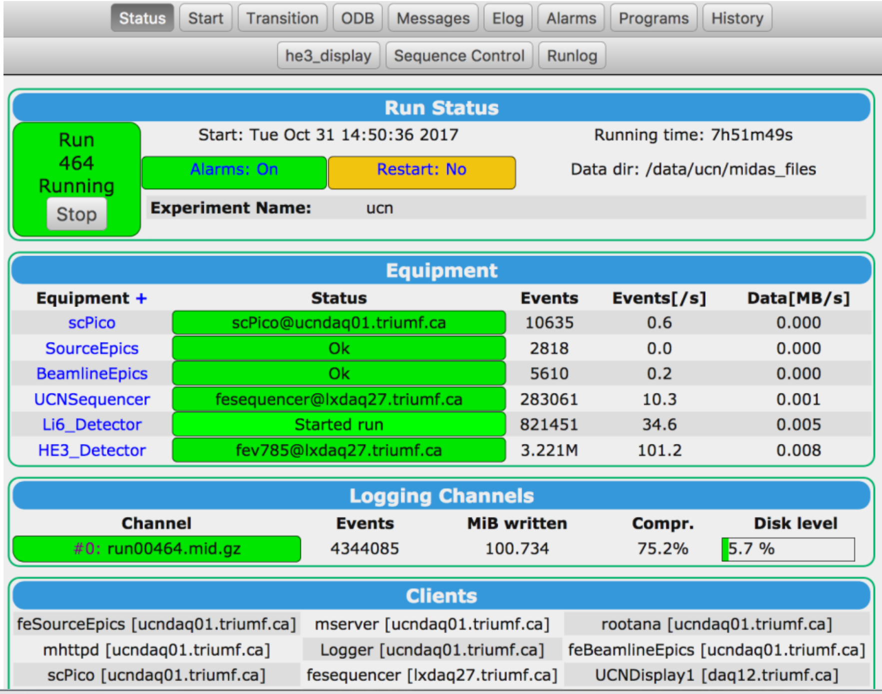
- Goals with current setup:
  - Characterize existing source (validate simulations)
    - Critical for design of new source
  - Validate components for new source and nEDM experiment

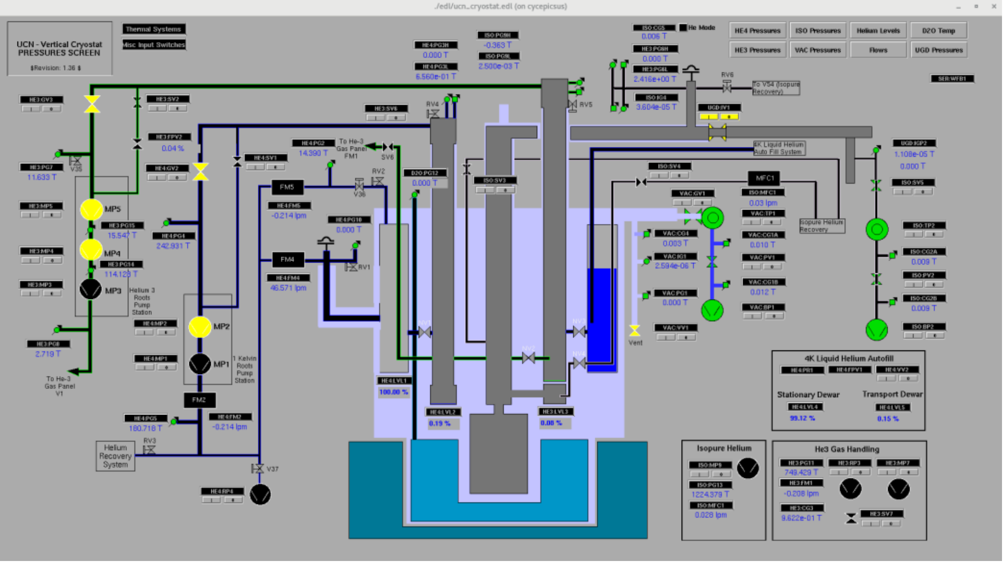


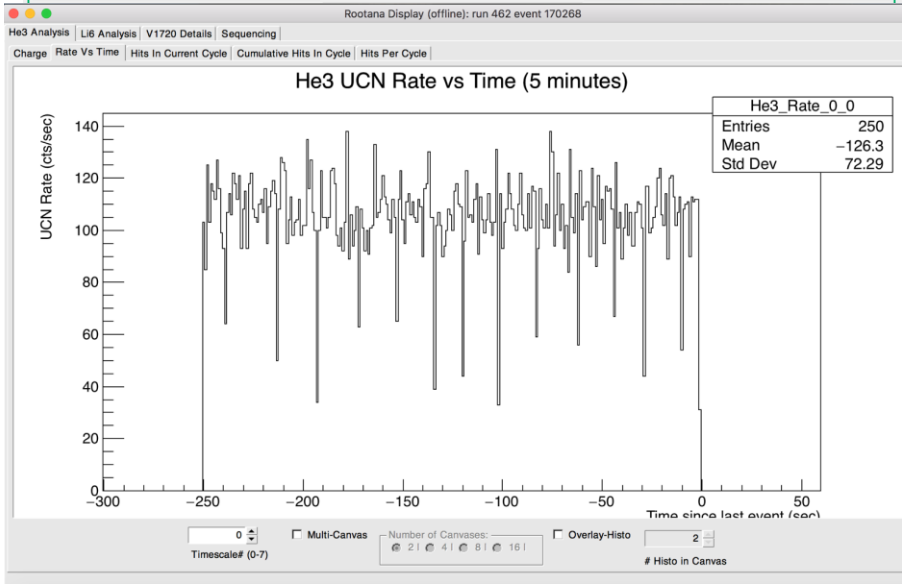
TRIUMF

UCN Source and Experimental DAQ

- Developing modern controls and DAQ scheme for TUCAN source and nEDM experiment.
- Source controlled by PLC with EPICS overlay.
- nEDM experiment controlled by DAQ based on MIDAS framework.



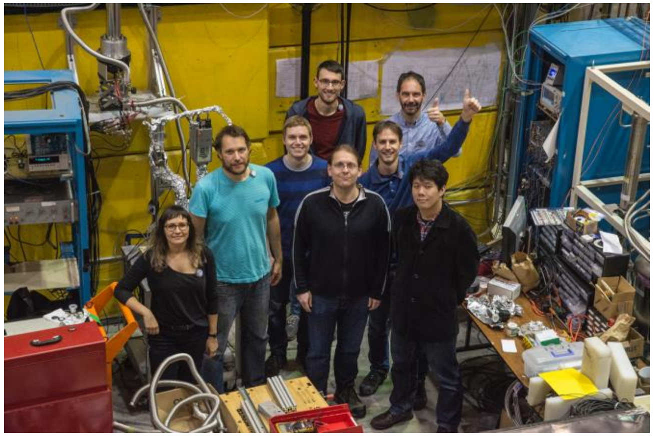


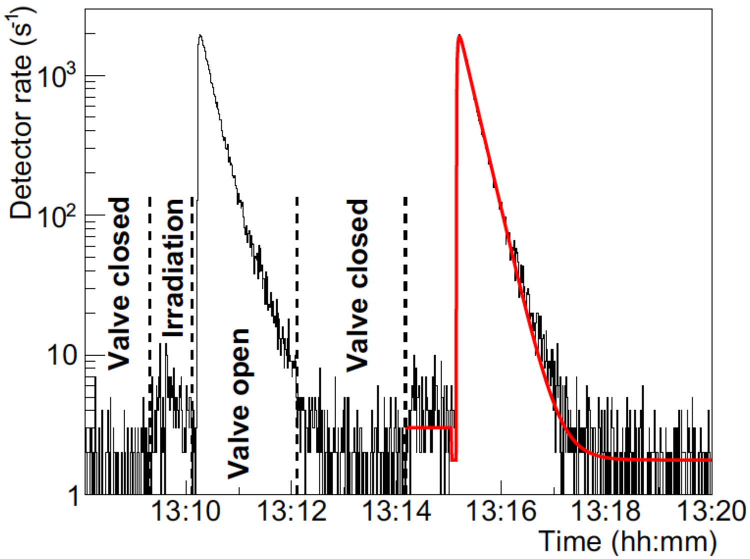


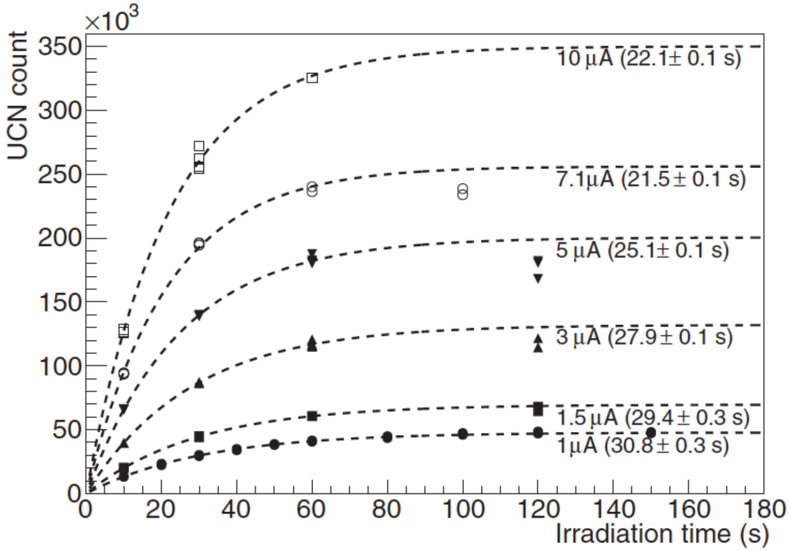
https://midas.triumf.ca/MidasWiki/index.php/Main_Page

First UCN at TRIUMF (Fall 2017)

- Successful produced UCN at TRIUMF on Nov 13, 2017
- Excellent data set for validating models about UCN production and transport.







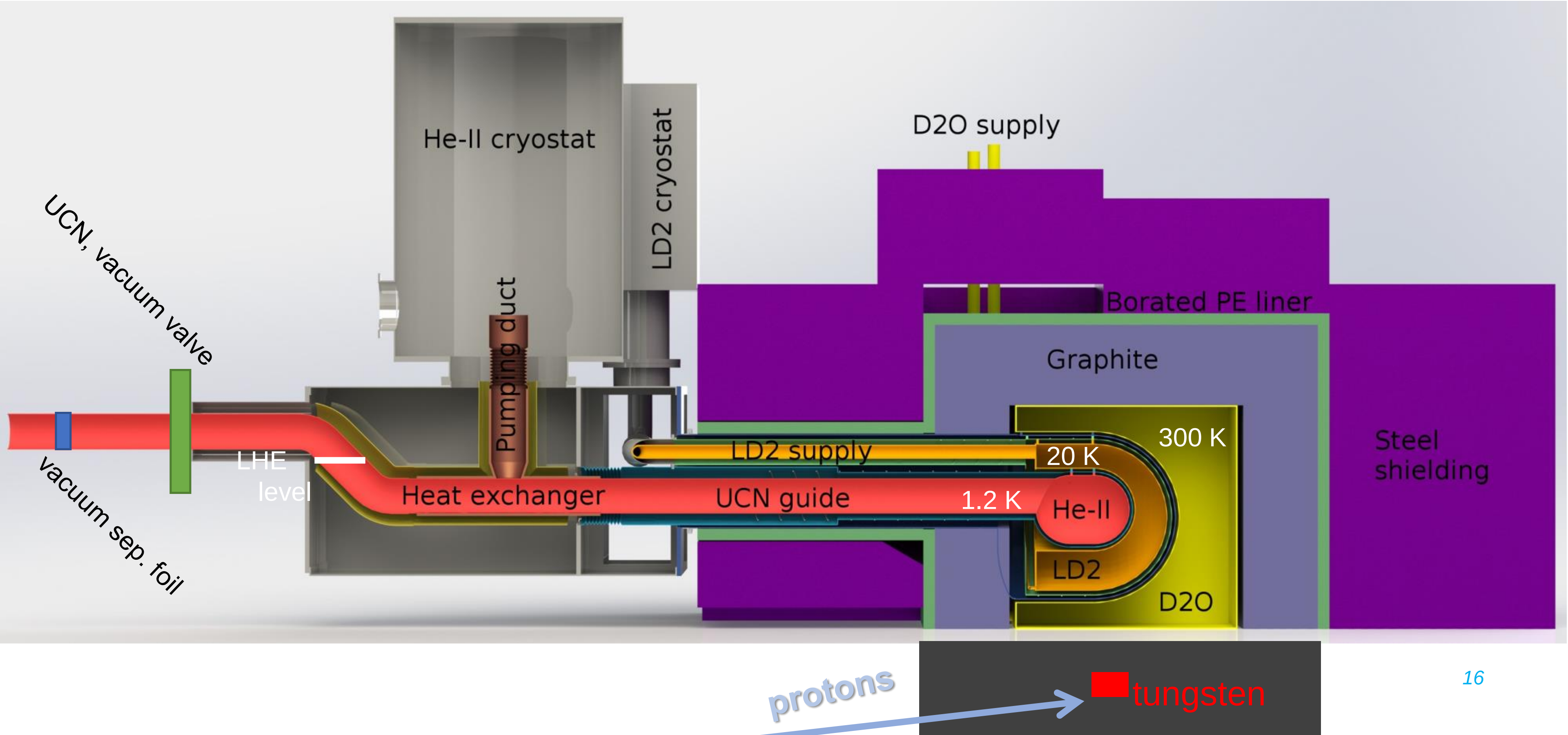
Phys. Rev. C 99 (2019) 025503

New TUCAN UCN Source

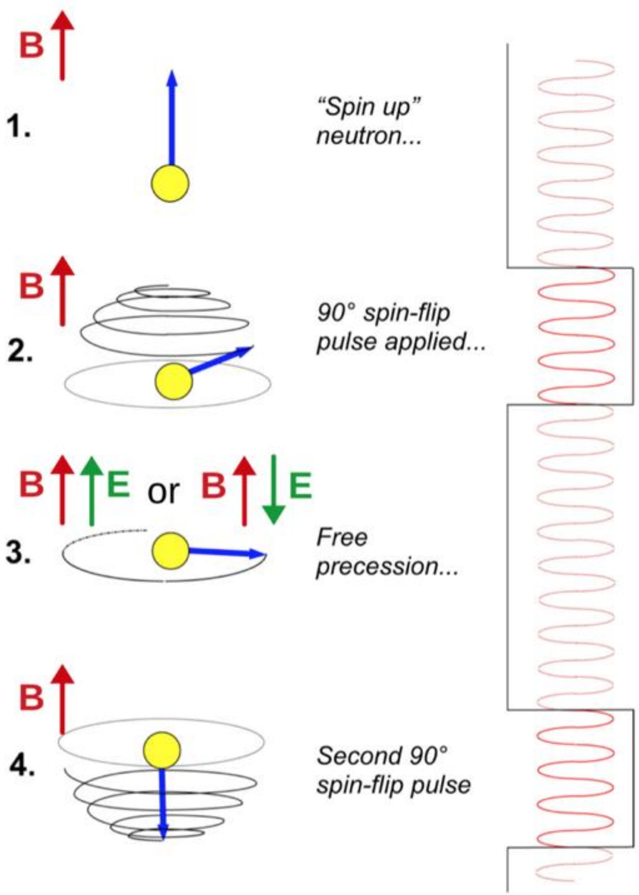
- Beam current : 1uA → 40uA
- Cooling power: 0.3W → 10W
- Cold moderator: sD_20 → LD_2
- Production volume: 8L → 28L
- Horizontal extraction of UCN

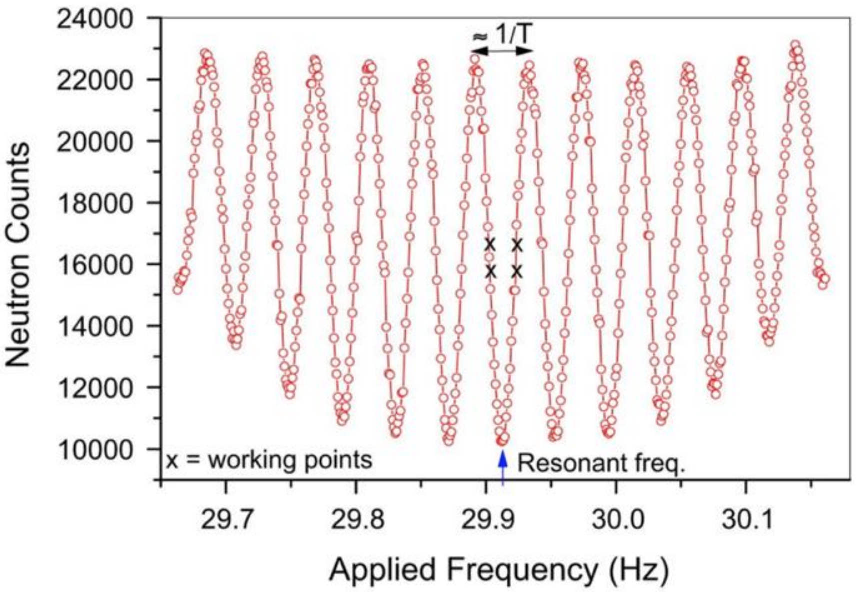
TUCAN combination of spallation neutron production and superfluid helium UCN conversion is unique.

After optimization, expected UCN production:
0.2 x 10^5 UCN/s → 1.7 x 10^7 UCN/s



Ramsey Cycle for EDM Measurement





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

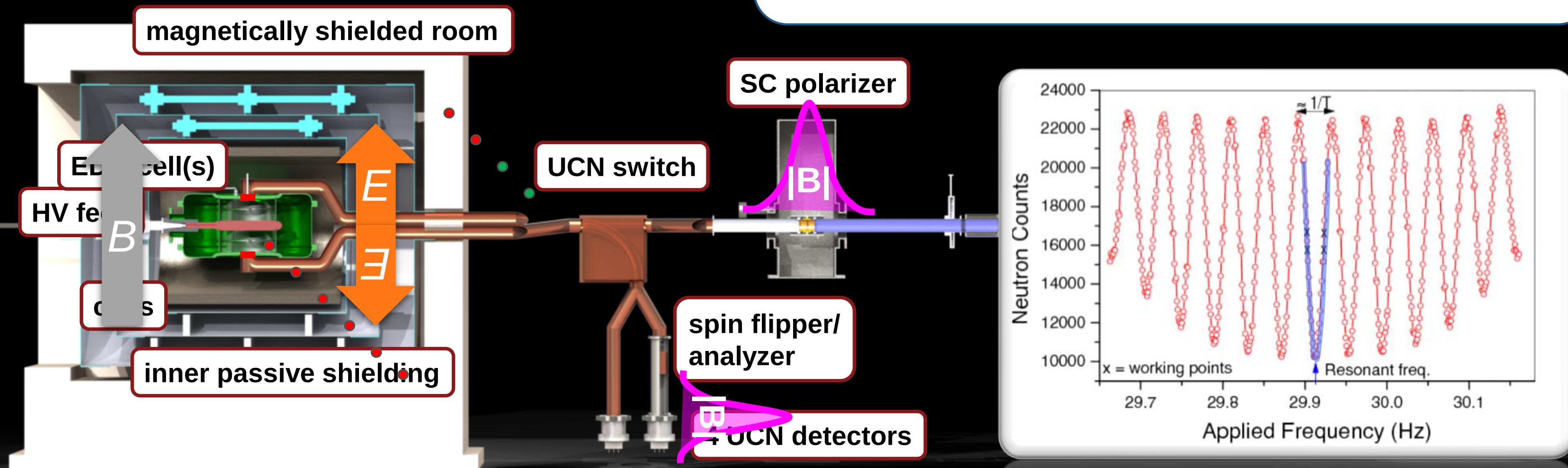
α Visibility (spin polarization)
E Electric field
T Spin precession time
N Number of UCN

Pendlebury et al., Phys. Rev. D 92, 092003, 2015

TUCAN EDM experiment hardware & cycle

(1) Polarization:
- 4 T magnet creates 240 neV barrier for one spin species of UCN

(2) Ramsey cycle:
- two π/2 spin flips turn a larmor precession change into a polarization change
- $H_{\mathrm{int}} = -\mu_{\mathrm{n}} \cdot \vec{\sigma}\vec{H} \pm d_{\mathrm{n}} \cdot \vec{\sigma}\vec{E}$



(3) Analysis:
- spin sensitive neutron counting

⇒polarization measurement

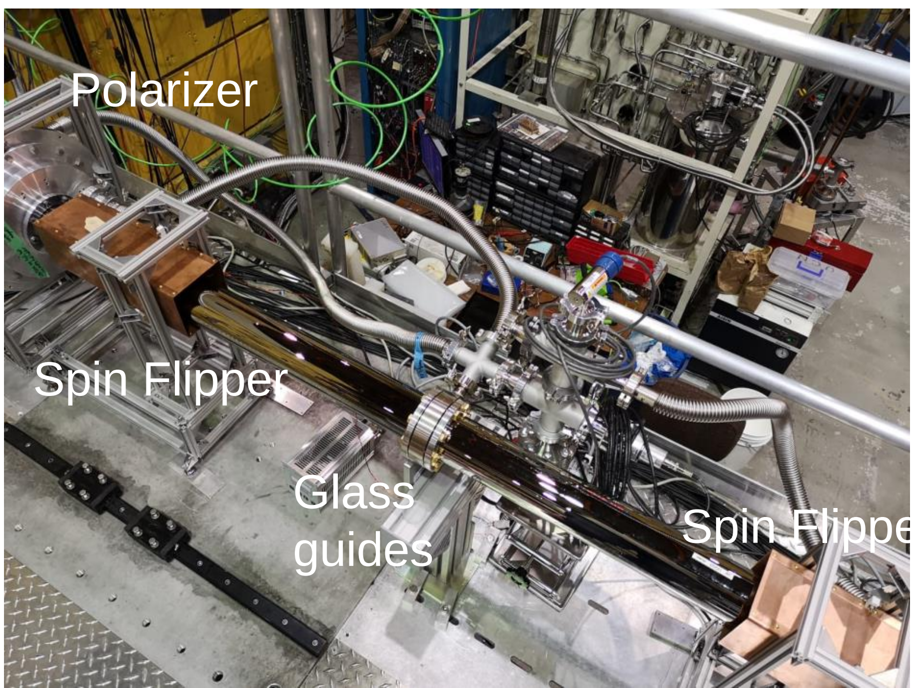
- fit the Ramsay curve to determine larmor frequency
- change in frequency under field reversal?

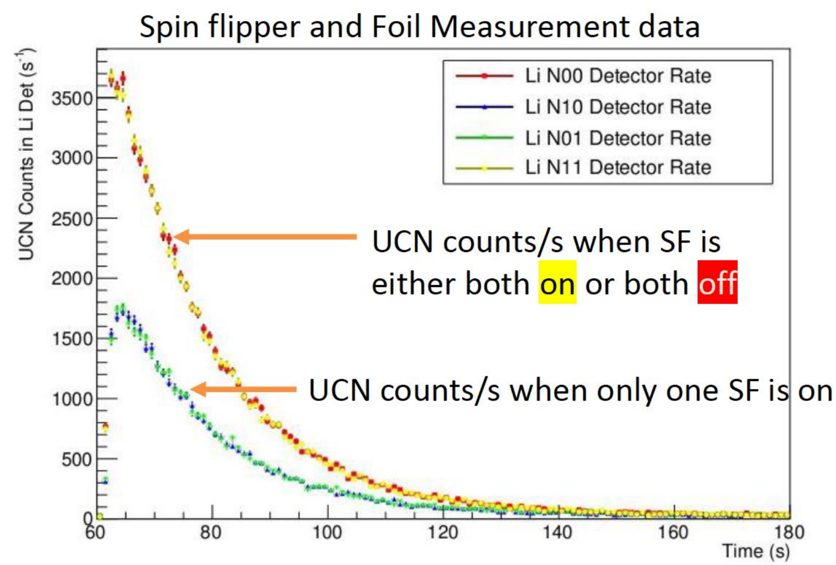
$$\Delta\epsilon = \hbar|\Delta\nu| = 4Ed_{\mathrm{n}}$$

Figure from R. Picker

nEDM Experimental Tests (2018)

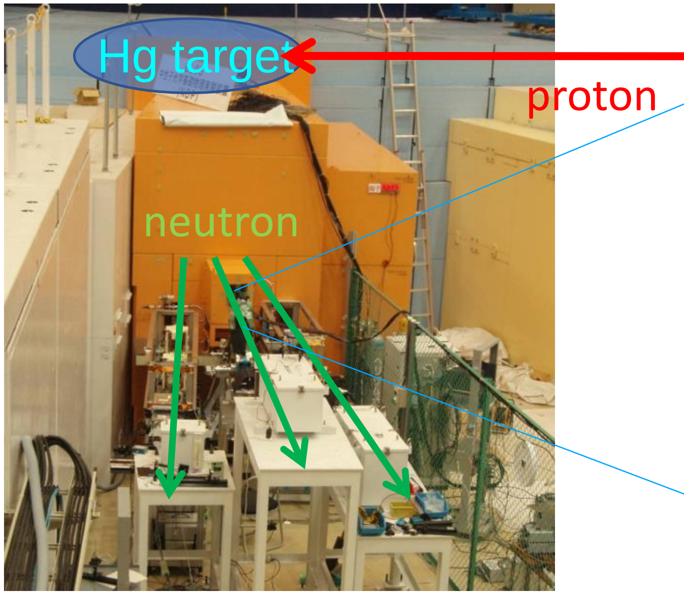
- First tests with polarized UCN
  - Issues found and being resolved.
- Also many other tests of UCN guides, valves and storage volumes.

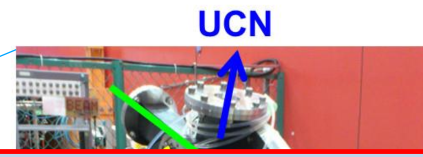




J-PARC UCN Source

Beamline 05 in J-PARC MLF





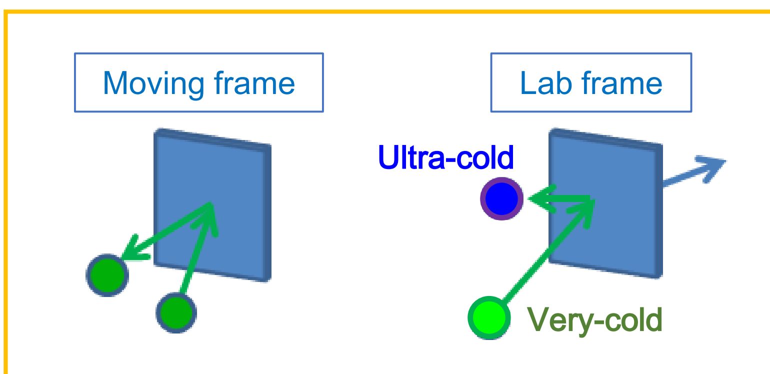
Pulsed BL05 UCN Source valuable tool:

- Used for UCN transmission measurements.

Also BL16 neutron reflector can make valuable measurement of candidate materials

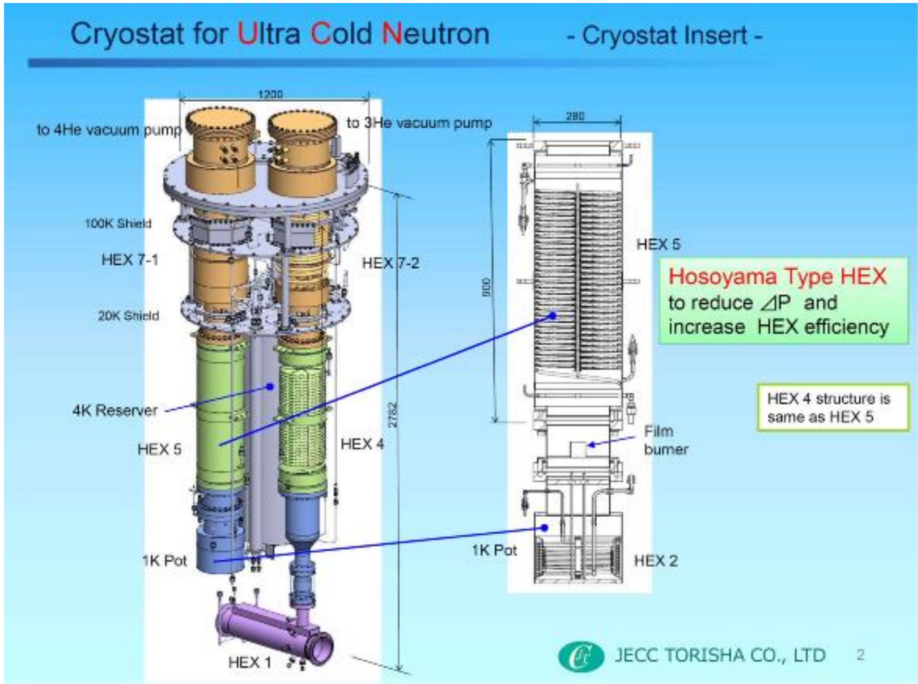
- Important for understanding properties of TUCAN UCN guides.

Doppler-shifter UC



TUCAN Status and Timeline

- UCN Source:
  - Superfluid helium cryostat fabrication in Japan starts August 2019
    - Great progress by KEK and Torisha
  - LD2 system will be built 2020
  - Source commissioning in 2021
- nEDM Experiment:
  - Conceptual design report being written
  - MSR installation 2021



HEX7 Test Stand

Conclusion

- Discovery of a non-zero nEDM could point to solutions for several unsolved problems in particle physics
- Many nEDM experiments around the world.
- The TUCAN experiment is actively building the world's most intense UCN source and sensitive nEDM experiment.

Backup

EDM Measurements in General

- Atomic EDM measurements more precise.
- nEDM more directly coupled to underlying models than atomic EDMs

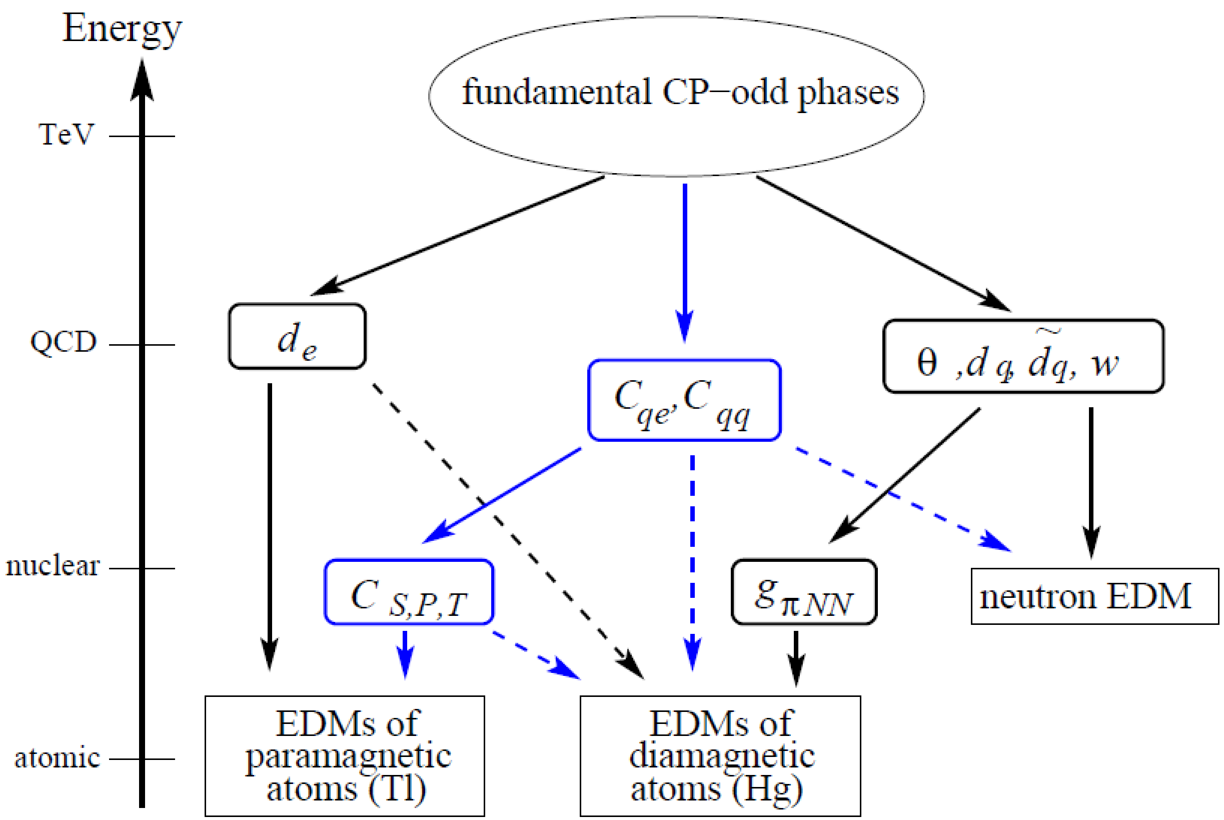
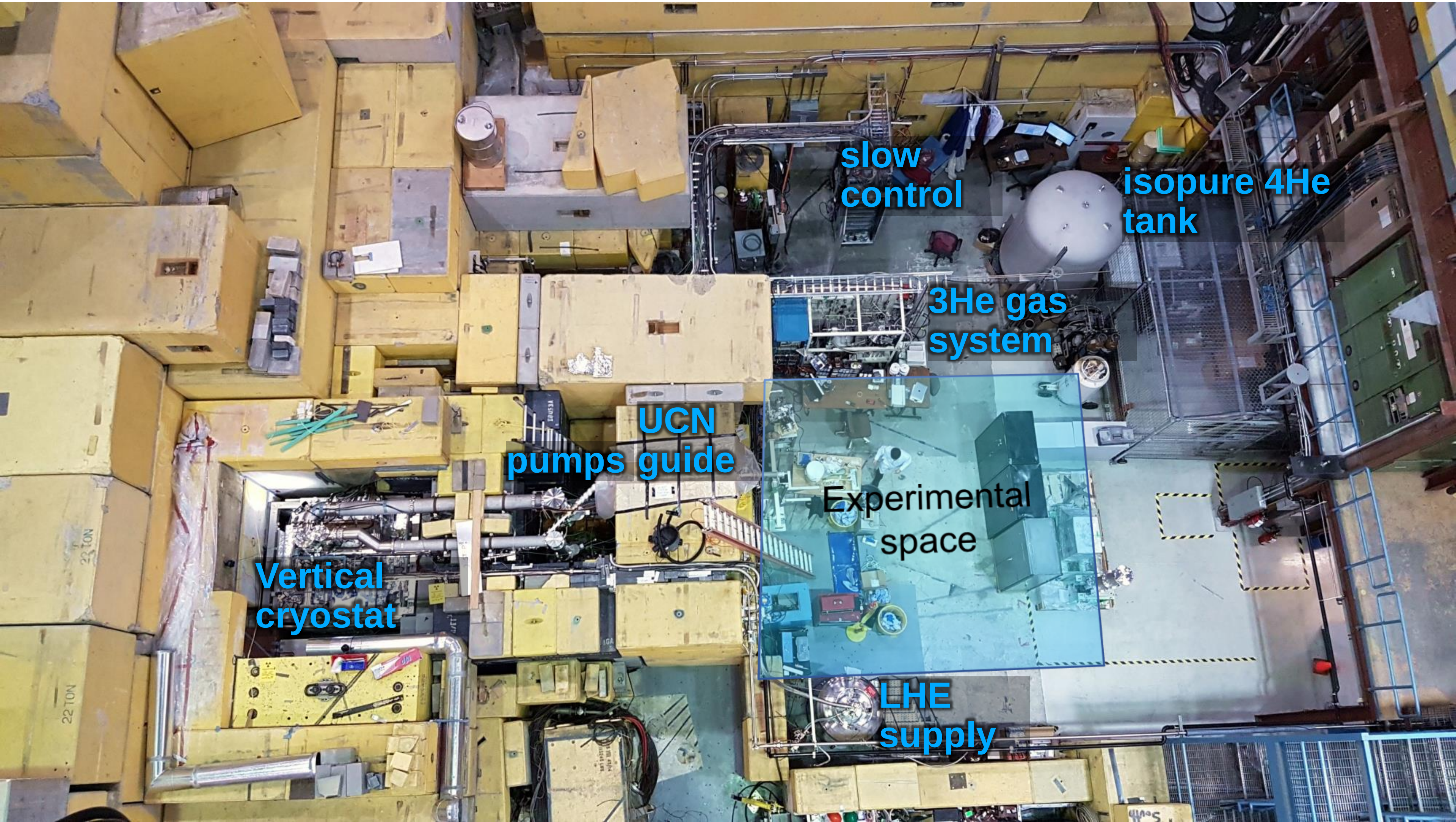


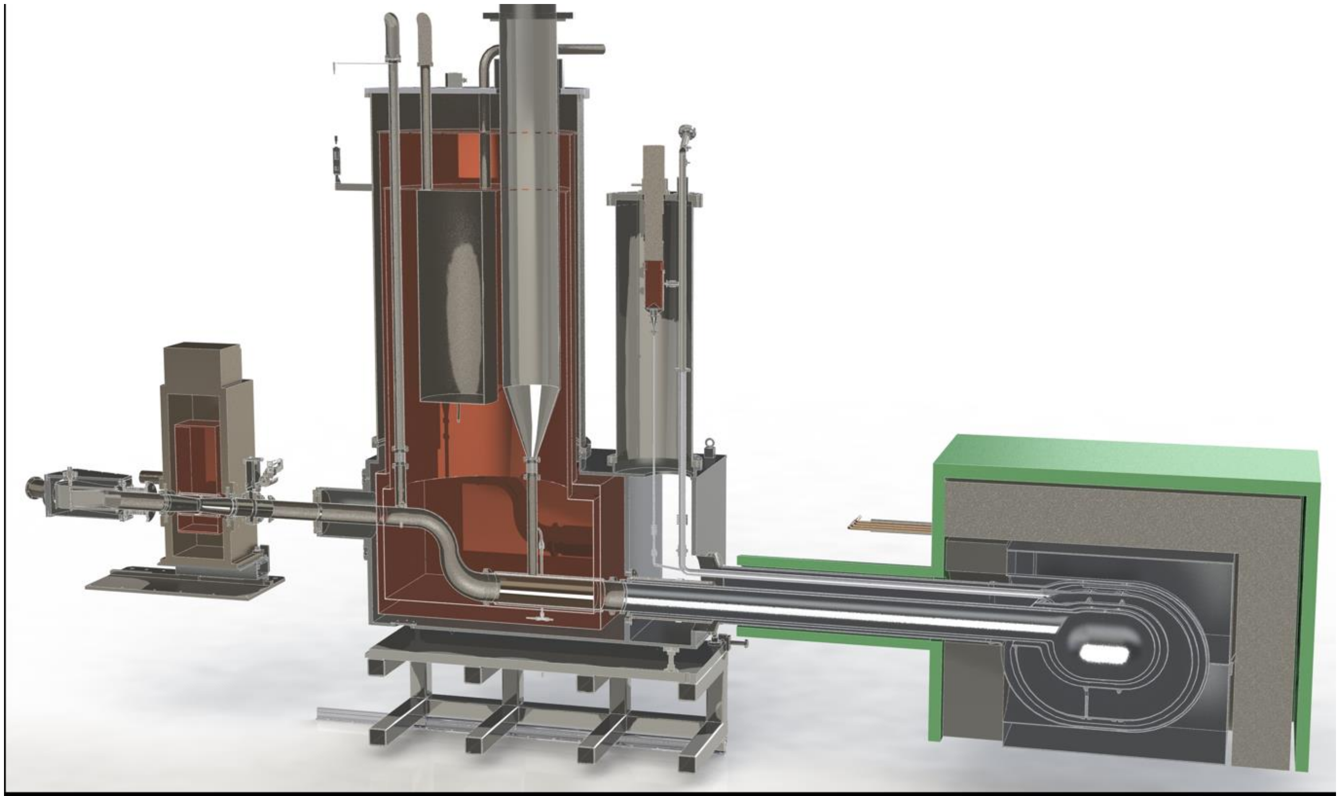
Figure: Pospelov & Ritz, Ann. Phys. (2005)

Top view with radiation shielding removed



Optimization of New Source

- Detailed MCNP + PENTrack simulations done to optimize source design
  - varying dimensions and materials, accounting for different heat loads, lifetime, transport
- After optimization, expected UCN production increase is:
  0.2×10^5 UCN/s → 1.7×10^7 UCN/s



nEDM Experimental Optimization

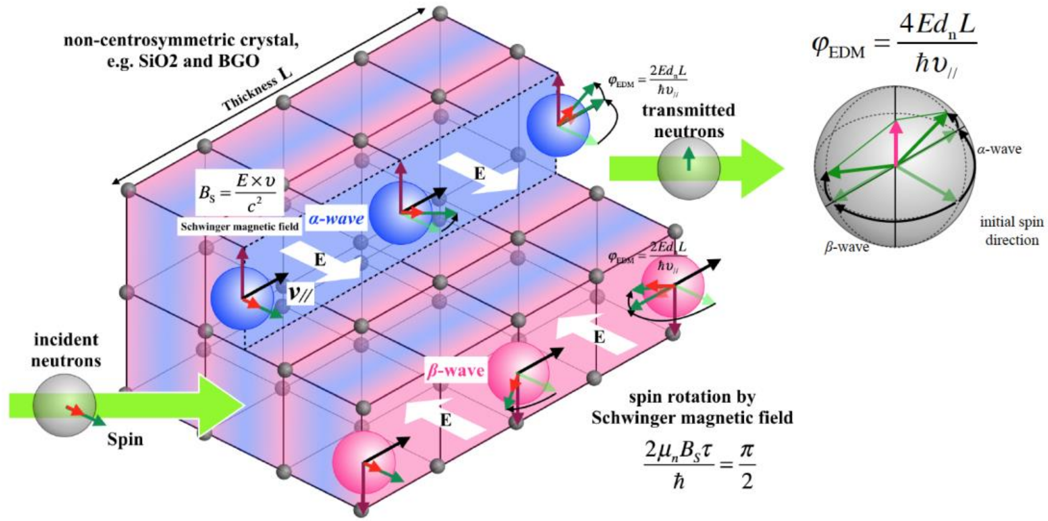
$$\sigma(d_n) \approx \frac{\hbar}{2\alpha T_{\mathrm{Ramsey}} E \sqrt{N_{\mathrm{det}}}}$$

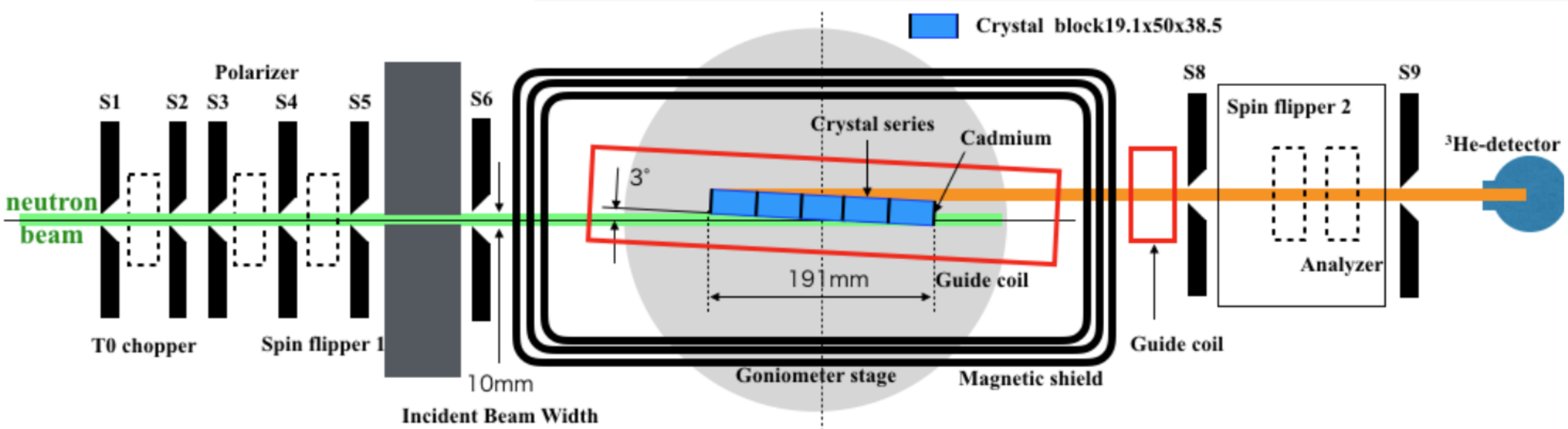
- Program to optimize the statistical sensitivity of nEDM experiment.
  - Figure of merit: number of days to reach $\sigma(dn) \quad = 1 \times 10^{-27} e\mathrm{cm}$
- Number of detected UCN depends on many parameters:
  - Fill time, storage time, emptying time
  - UCN guide shape, width, height, properties
  - Energy spectrum of UCN
- Current optimization favors lower energy UCN (better storage time)
  - Requires longer transport times.

Controlling systematic uncertainties also critical!

Crystal EDM at J-PARC:

Neutrons with parallel spin to the *E*-field will get a spin polarization perpendicular to initial spin direction by the inversive electric field and Schwinger magnetic field of α-wave and β-wave respectively.





10 crystal blocks is seriesed, but only 5 blocks is showed in this figure.