Ultracold Neutrons and Neutron EDM

J. Martin

The University of Winnipeg

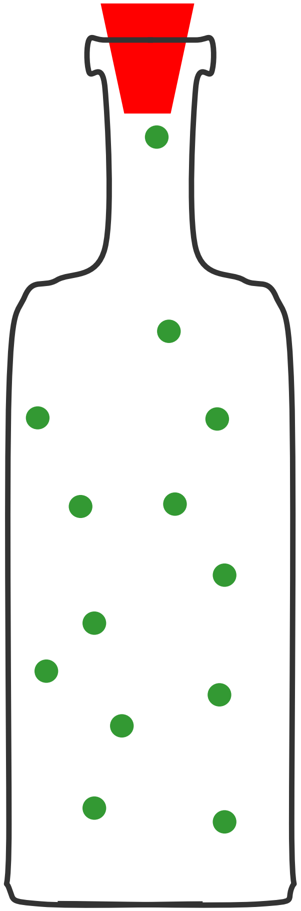
T. Adachi[1], E. Altiere[2], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Chin[5], C. Davis[5],
F. Doresty[4], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], B. Jamieson[3], S. Jeong[1], D. Jones[2],
K. Katsika[5], S. Kawasaki[1], T Kikawa[5,6,1], A. Konaka[5,8], E. Korkmaz[7] , M. Lang[3], T. Lindner[5], L. Lee[4,5],
K. Madison[2], J. Mammei[4], R. Mammei[3], J.W. Martin[3], Y. Masuda[1], R. Matsumiya[6], K. Matsuta[8], M. Mihara[8],
E. Miller[2], T. Momose[2], S. Page[4], R. Picker[5], E. Pierre[6,5], W.D. Ramsay[5], L. Rebenitsch[3,4],
J. Sonier[9], I. Tanihata[6], W.T.H. van Oers[4,5], Y. Watanabe[1], and J. Weinands[2]

[1]KEK, Tsukuba, Ibaraki, Japan
[2]The University of British Columbia, Vancouver, BC, Canada
[3]The University of Winnipeg, Winnipeg, MB, Canada
[4]The University of Manitoba, Winnipeg, MB, Canada
[5]TRIUMF, Vancouver, BC, Canada
[6]RCNP, Osaka, Japan (Osaka University, Osaka, Japan)
[7]The University of Northern BC, Prince George, BC, Canada
[8]Osaka University, Osaka, Japan
[9]Simon Fraser University, Burnaby, BC, Canada

Ultracold Neutrons (UCN)

- Neutrons that are moving so slowly that they bounce off surfaces and can be bottled.
  - $v < 8$ m/s = 30 km/h
  - $T < 4$ mK
  - K.E. < 300 neV

- Interactions:
  - Gravity: $V = mgh$ $mg = 100$ neV/m
  - Magnetic: $V = -\mu \bullet B$ $\mu = 60$ neV/T
  - Strong: $V = V_{eff}$ $V_{eff} < 335$ neV
  - Weak: $\tau = 886$ s = 15 mins.



What are the best experiments for UCN?

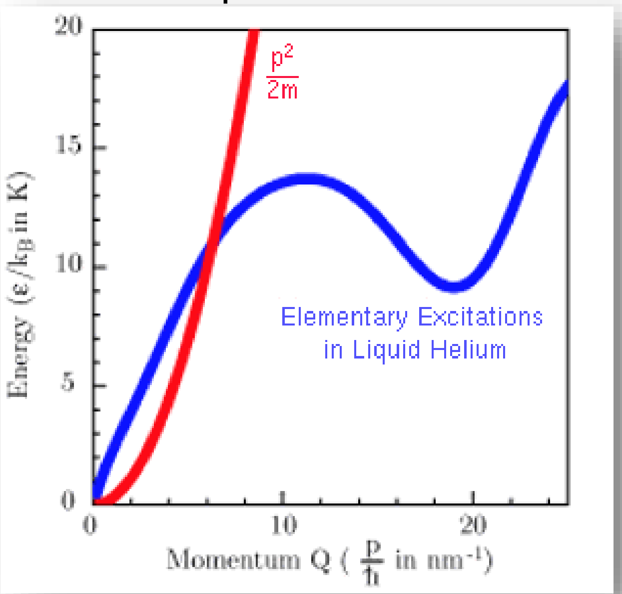
- Those best using their long storage/spin coherence time:
  - Neutron EDM (strong CP problem, SUSY CP problem, electroweak baryogenesis)
  - Neutron lifetime (BBN, V_{ud}/CKM unitarity)
  - Angular correlations, precision spectroscopy in beta decay (V_{ud}/CKM, scalar/tensor currents)
  - n-nbar oscillations? Quantum computing/error studies?
- Those best using their low energy
  - Neutron gravity levels above a mirror (gravity at μm scales, chameleon fields, fifth force, …)
  - Surface science of big organic molecules?
- Generally accepted that nEDM is top science priority for this field, given present UCN fluxes; it is our flagship experiment.
- Breakthrough in UCN production would improve precision of experiments, and open up new possibilities (free n target?)

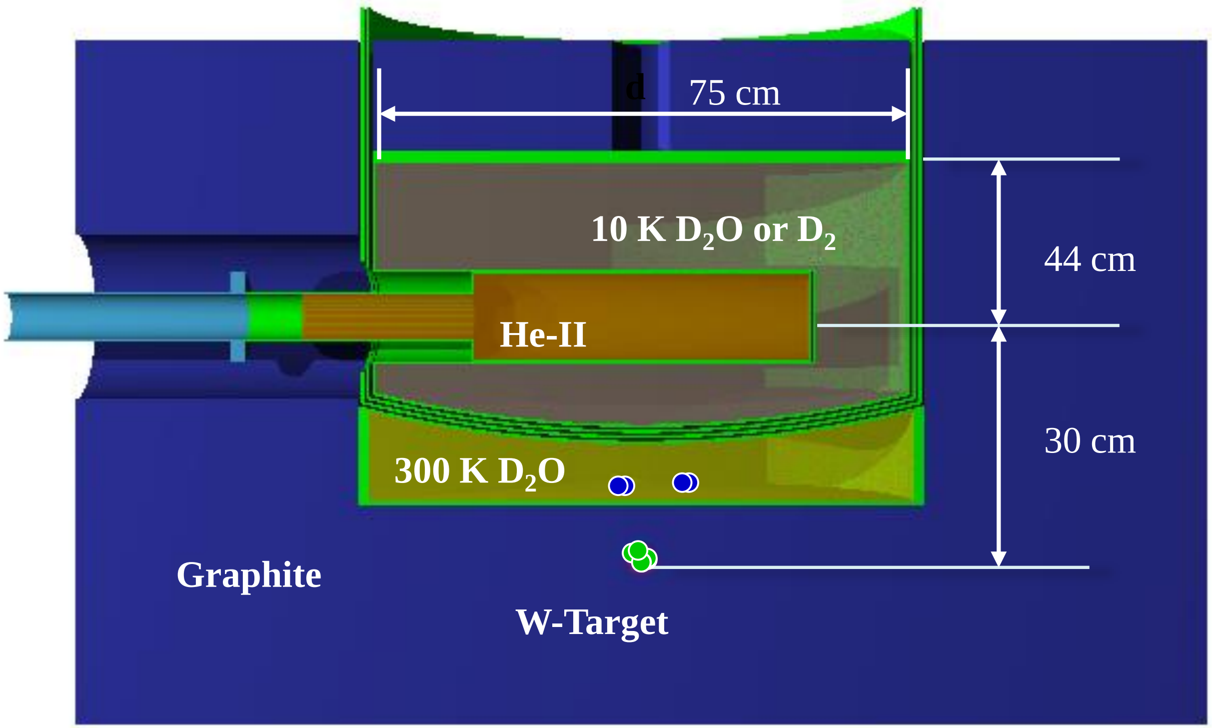
Spallation-driven Superfluid He-II UCN Source

UCN production recipe:

- *Spallation* – Liberate neutrons from W target
- *Moderation* – Thermalize, cool neutrons in D_20 ice
- *Conversion* – Convert cold neutrons to UCN in He-II

Cold neutron energy transferred to He-II via phonon emission





- **Thermal, Cold & Ultra-Cold neutrons**
- **MeV neutrons**

General Layout of UCN Source at RCNP Osaka

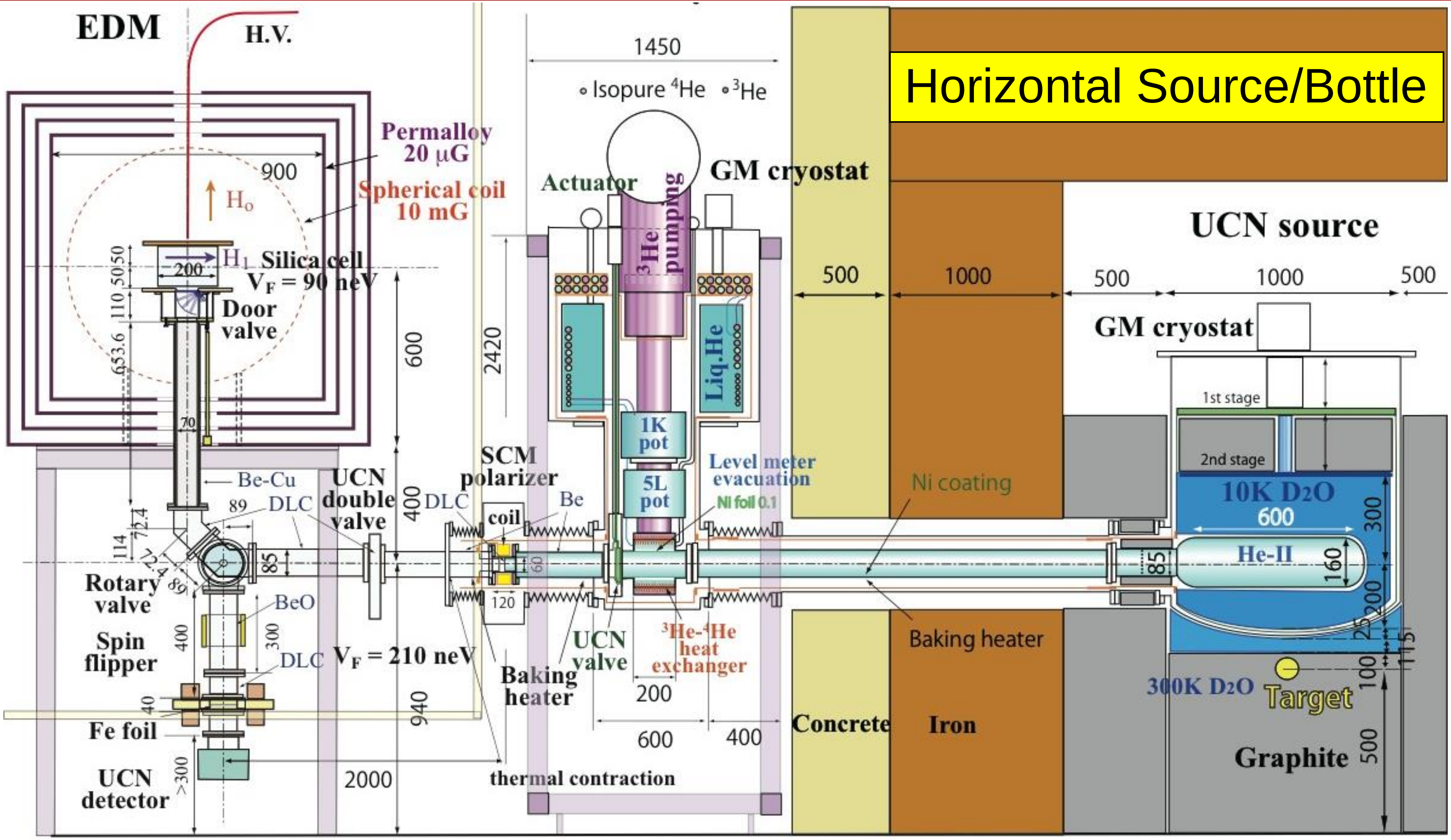
<u>Moderators</u>

Thermal: Graphite, 300K D_2O

Cold: 10K D_2O ice

400 MeV protons

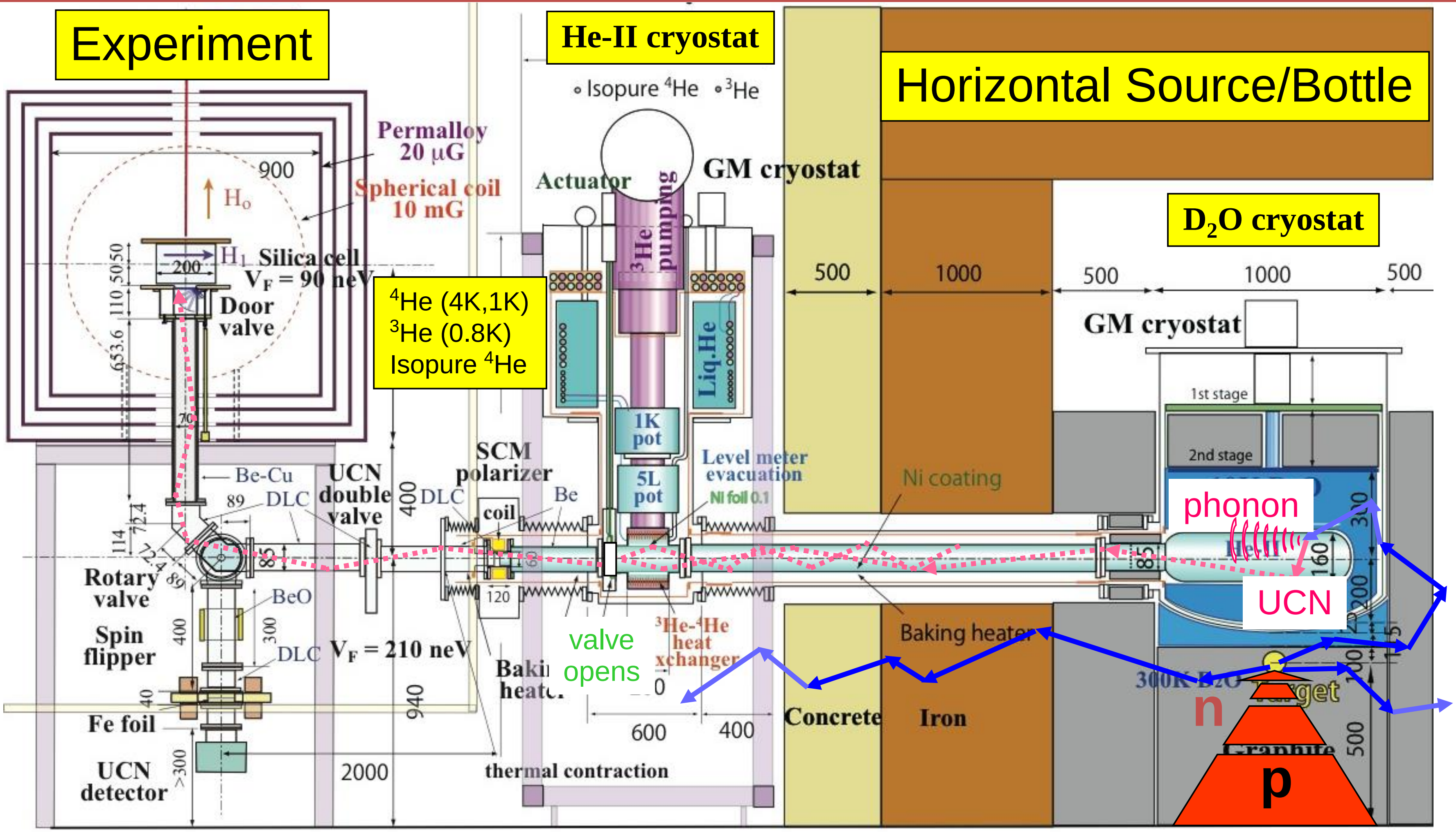
UCN Source (RCNP-TRIUMF)



Source developed and tested in Japan, shipping to TRIUMF in Oct. 2015

Beamline prepared at TRIUMF, for extended running periods at ~40x higher intensity

Connection to Phase I nEDM experiment



2012-2014: Develop/Test Source (& nEDM) at RCNP [1+ μA]

2015: Source moves to TRIUMF

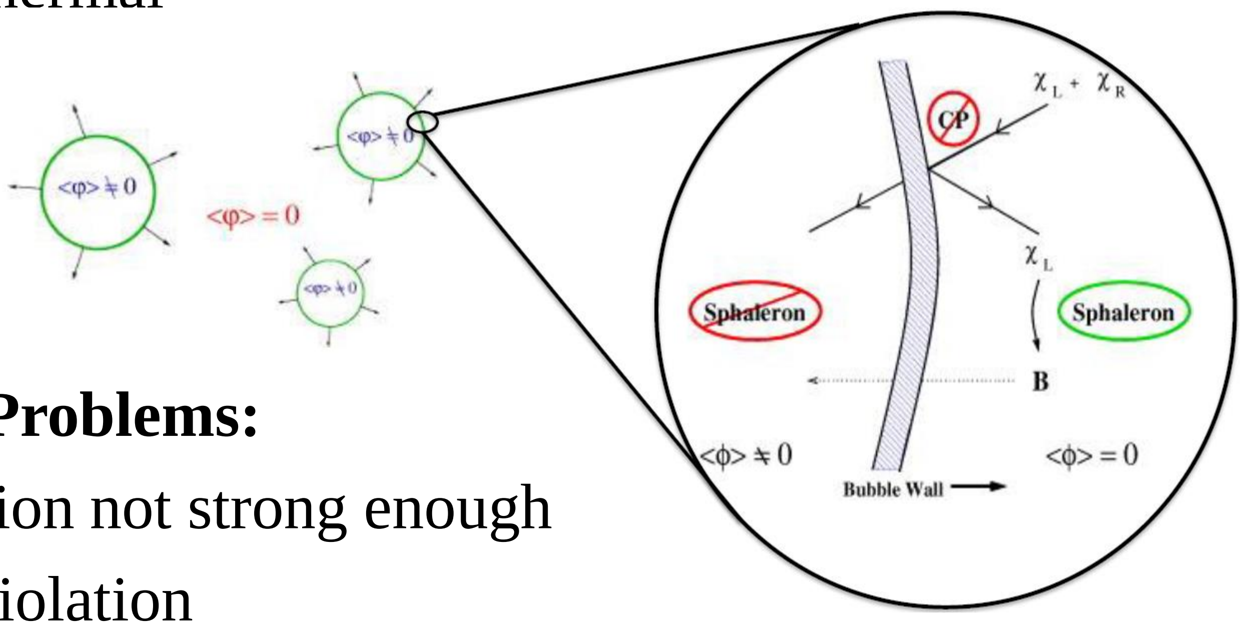
2016: Commission Source at TRIUMF [ramp to 40μA]

Sakharov's Criteria and EW Baryogenesis Solutions

Criteria

- Departure from thermal equilibrium
- B-violation
- CP-violation

EW Baryogenesis



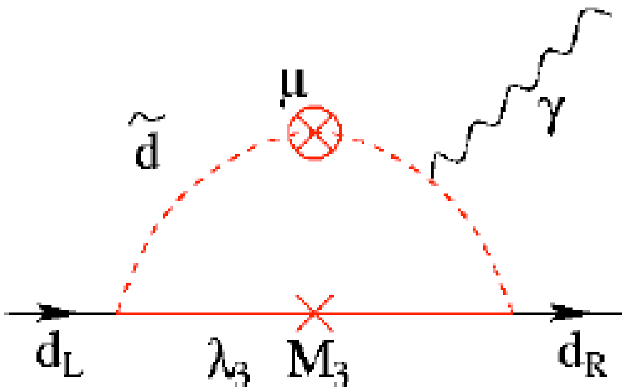
EW Baryogenesis Problems:

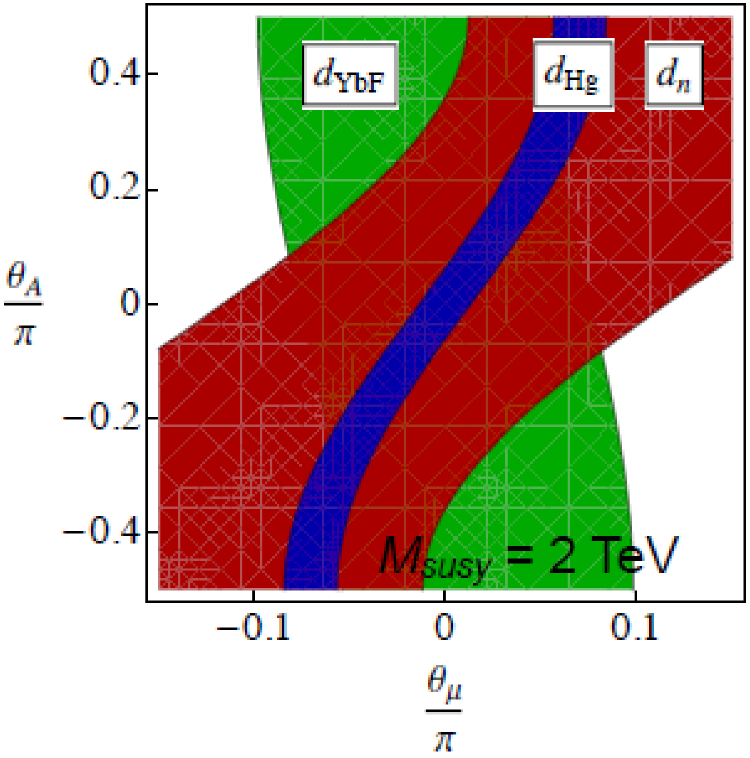
- EW phase transition not strong enough
- Not enough CP violation

D.E. Morrissey and M.J. Ramsey-Musolf, New J. Phys. 14, 125003 (2012).

Requires new physics and CP-violation near the EW scale

Sensitivity to new sources of CP violation





Induces: $d_q \sim \frac{\alpha}{\pi} \times \frac{m_q}{\Lambda^2_{SUSY}} \times \sin\theta_{CP}$

e.g. SUSY CP problem and relationship to LHC

M. Pospelov and A. Ritz,
A. Ritz, TRIUMF Summer Institute, 2012.

Sensitivity to SM sources of CP violation

- Strong sector may violate CP via θ term.
- Naively $\theta \sim 1$.
- Experimentally $\theta < 10^{-11}$, constrained mainly by nEDM.

Strong CP problem

Solution: Peccei-Quinn symmetry, axions(?)

- CKM CP violation is 10^{-31} e-cm background

Electric dipole moments and CP violation

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

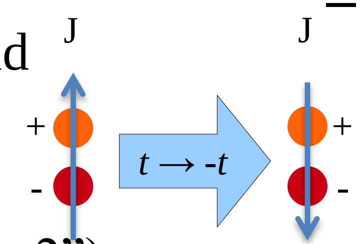
- The EDM (*d*) term violates CP.
- New sources of CP violation required in e.g. electroweak baryogenesis.

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

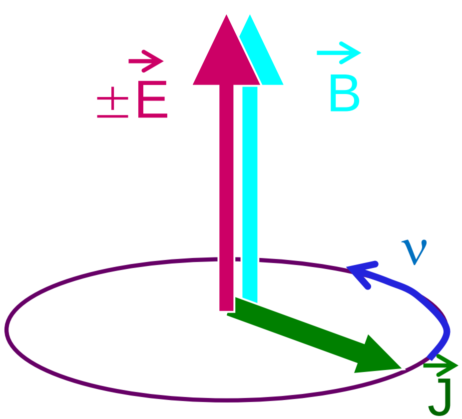
- Precision goal $\delta d_{\mathrm{stat}} = 1.4 \times 10^{-25}$ e-cm/cycle, 10^{-27} e-cm ultimately.

TRIUMF Neutron EDM Experiment

- Overview/Goals:
  - Our approach: Spallation-driven superfluid-helium UCN source connected to room-temperature nEDM experiment.
  - Present world's best limit (Sussex/RAL/ILL) $d_n < 3 \times 10^{-26}$ e-cm
  - SM (CKM) lower bound $d_n \gtrsim 10^{-31}$ e-cm
  - Our goal sensitivity: $\delta d_n \sim 10^{-27}$ e-cm ("phase 2") $\delta d_n \sim 10^{-28}$ e-cm (possible with source upgrades)

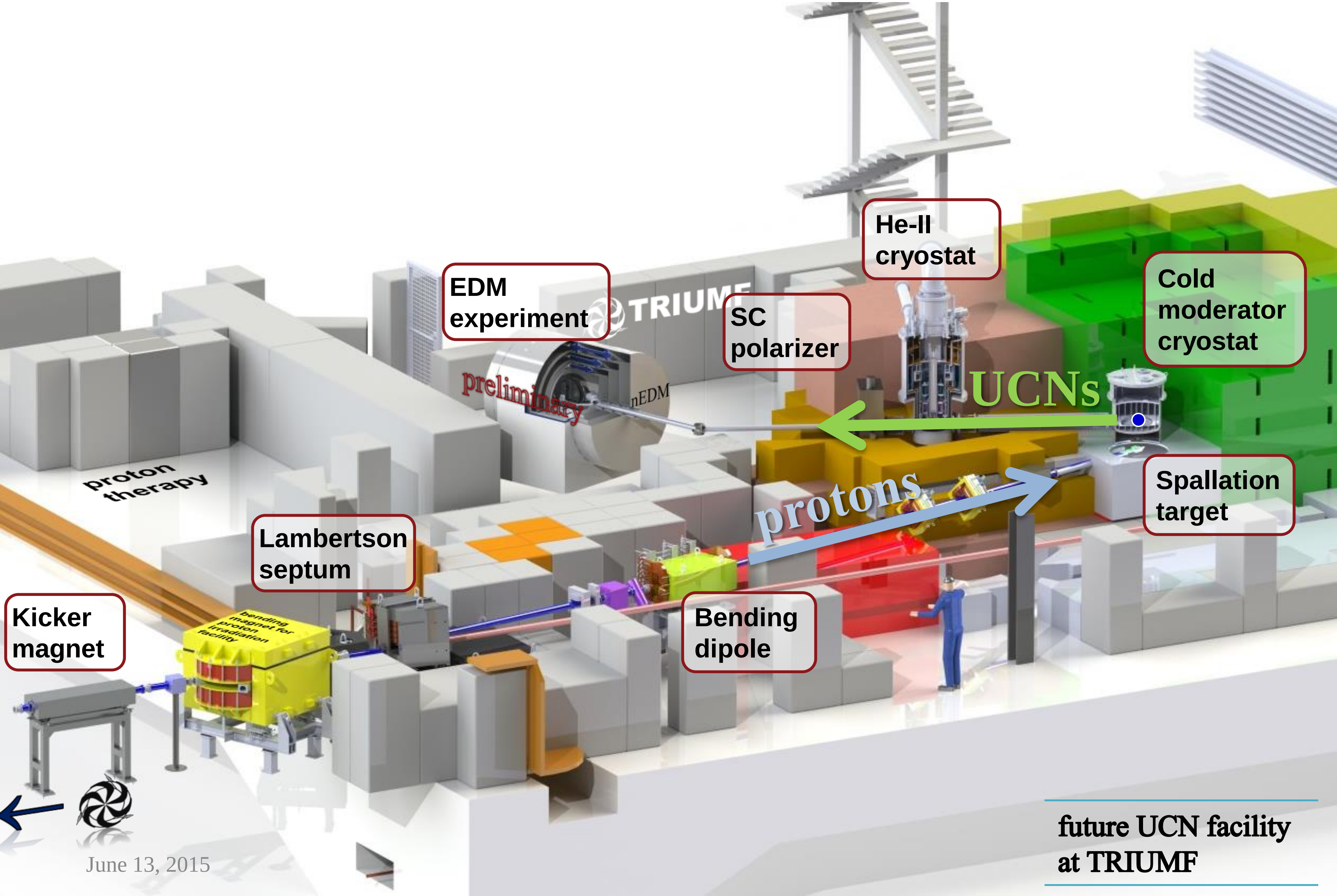


- Features of nEDM expt.:
  - New UCN source with potential world-leading density
  - Room temperature with flexibility e.g. to modify cell size in light of systematics vs. stats.
  - New dual ^{129}Xe 2-photon + ^{199}Hg comagnetometers
  - Improved magnetic field control, diagnostics.



$$h\nu = 2\mu_n B \pm 2d_n E$$

TRIUMF Facility Overview

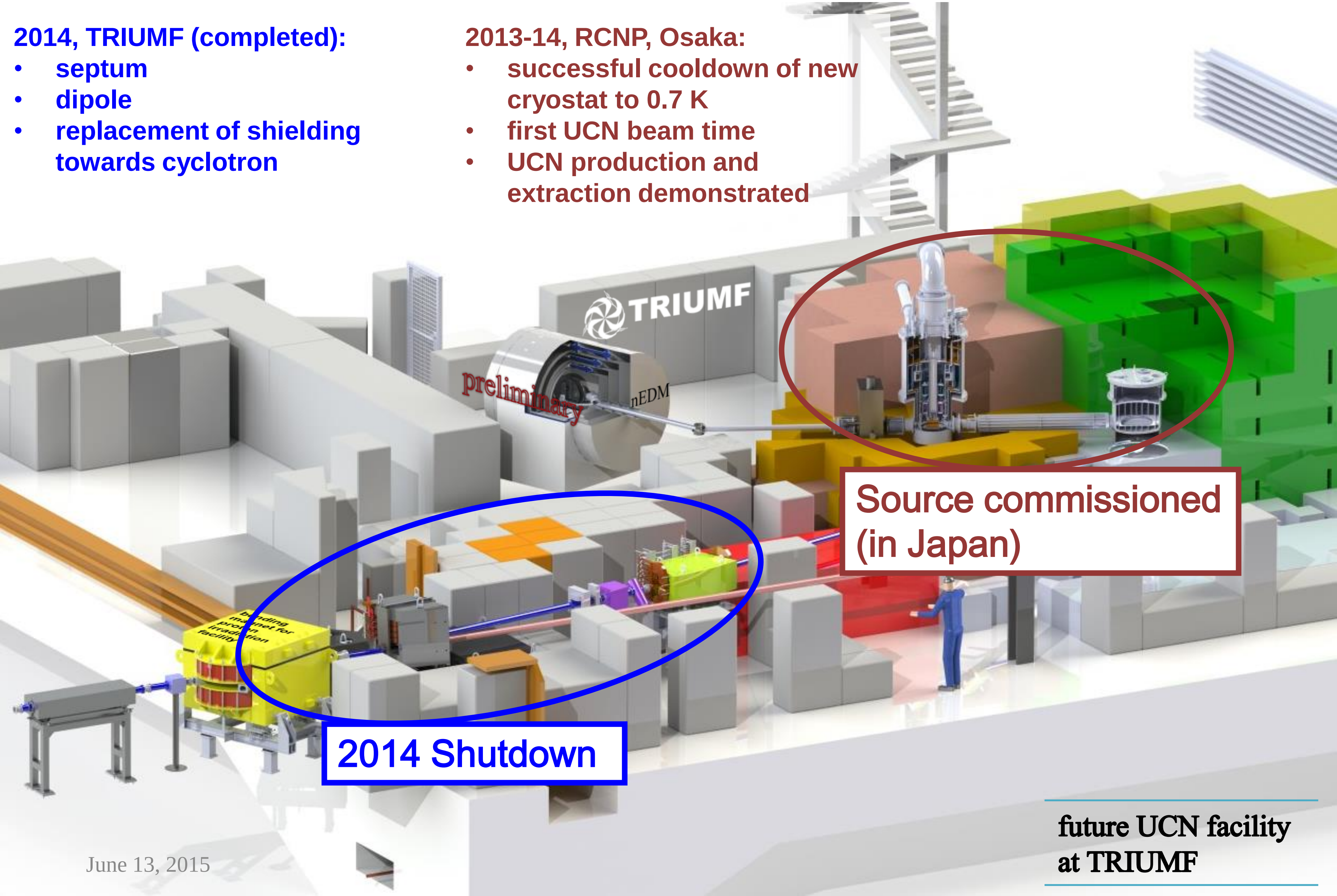


future UCN facility
at TRIUMF

Recent UCN highlights

2014, TRIUMF (completed):
- **septum**
- **dipole**
- **replacement of shielding towards cyclotron**

2013-14, RCNP, Osaka:
- **successful cooldown of new cryostat to 0.7 K**
- **first UCN beam time**
- **UCN production and extraction demonstrated**

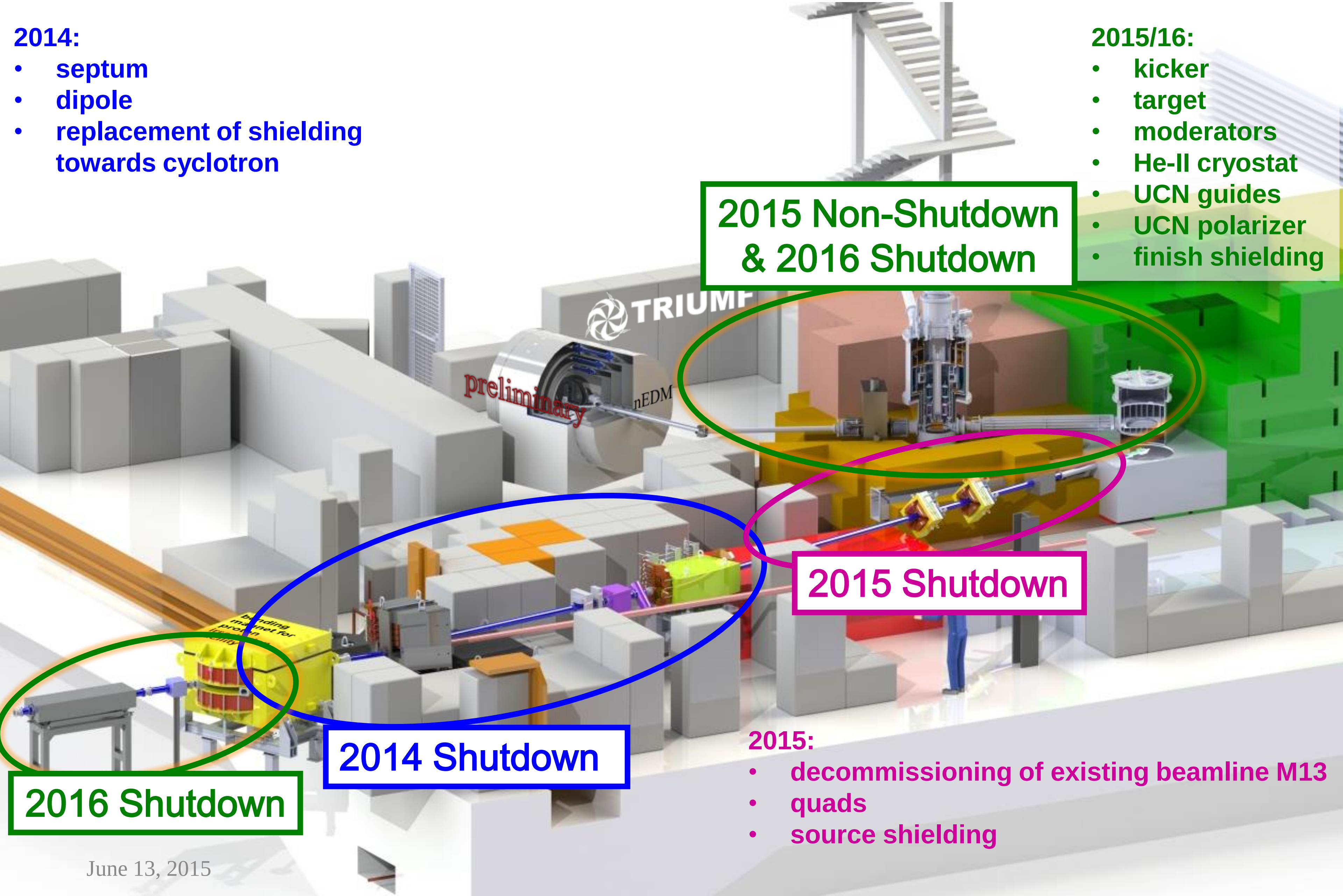


future UCN facility at TRIUMF

Plan for TRIUMF Installation periods: ~Jan-Apr each year

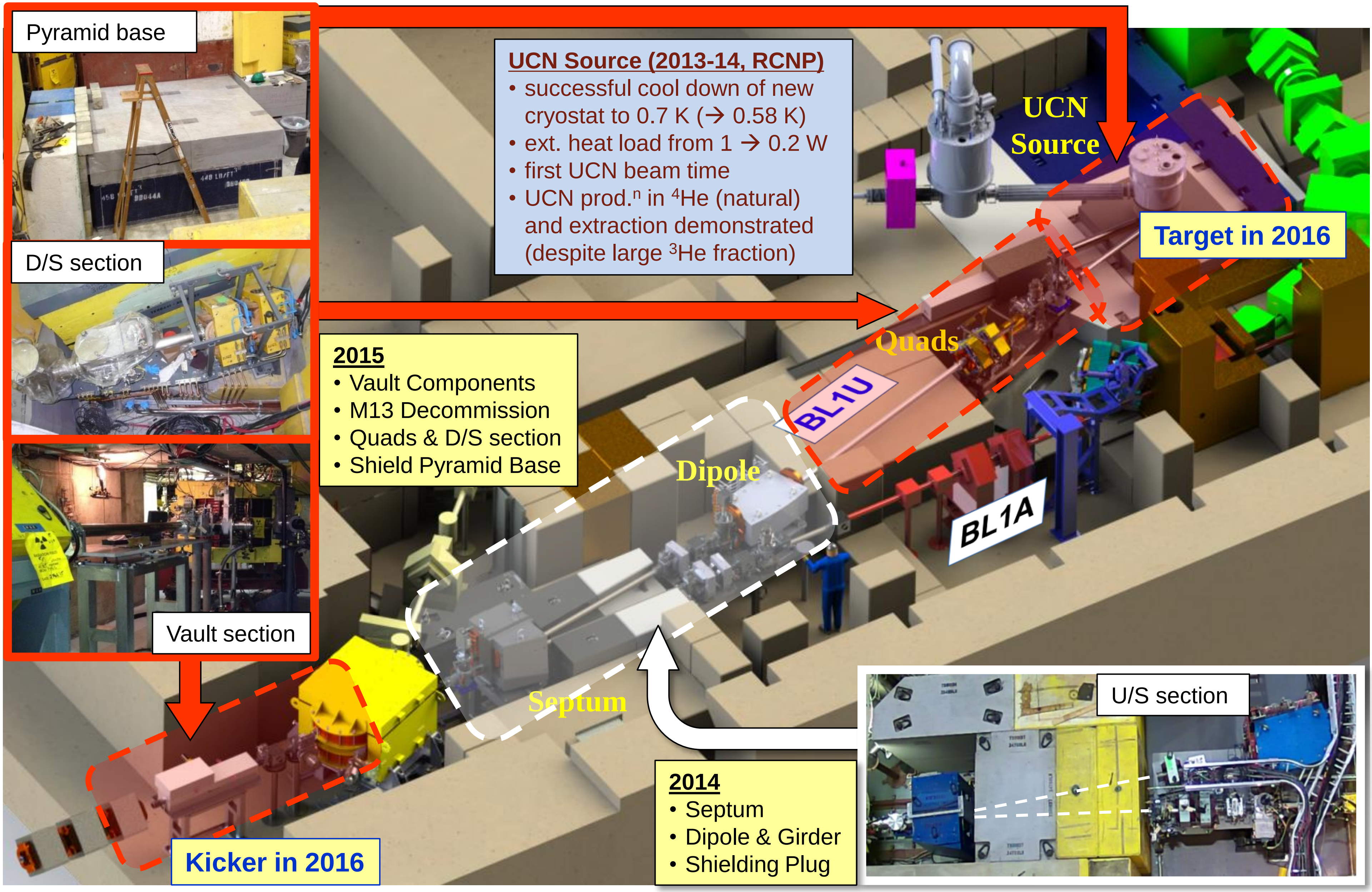
2014:
- septum
- dipole
- replacement of shielding towards cyclotron

2015/16:
- kicker
- target
- moderators
- He-II cryostat
- UCN guides
- UCN polarizer
- finish shielding



2015:
- decommissioning of existing beamline M13
- quads
- source shielding

Present Status of UCN Facility



UCN Source (2013-14, RCNP)

- successful cool down of new cryostat to 0.7 K (→ 0.58 K)
- ext. heat load from 1 → 0.2 W
- first UCN beam time
- UCN prod.^{n} in ^{4}He (natural) and extraction demonstrated (despite large ^{3}He fraction)

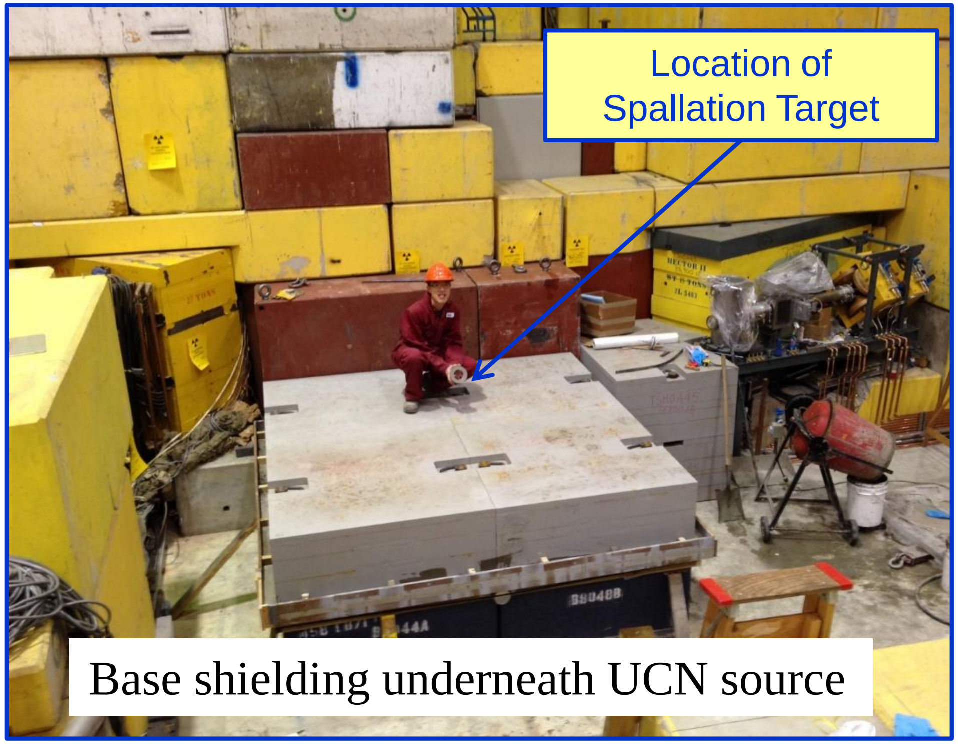
2015

- Vault Components
- M13 Decommission
- Quads & D/S section
- Shield Pyramid Base

2014

- Septum
- Dipole & Girder
- Shielding Plug

2015 Highlights and 2016 plans



Base shielding underneath UCN source

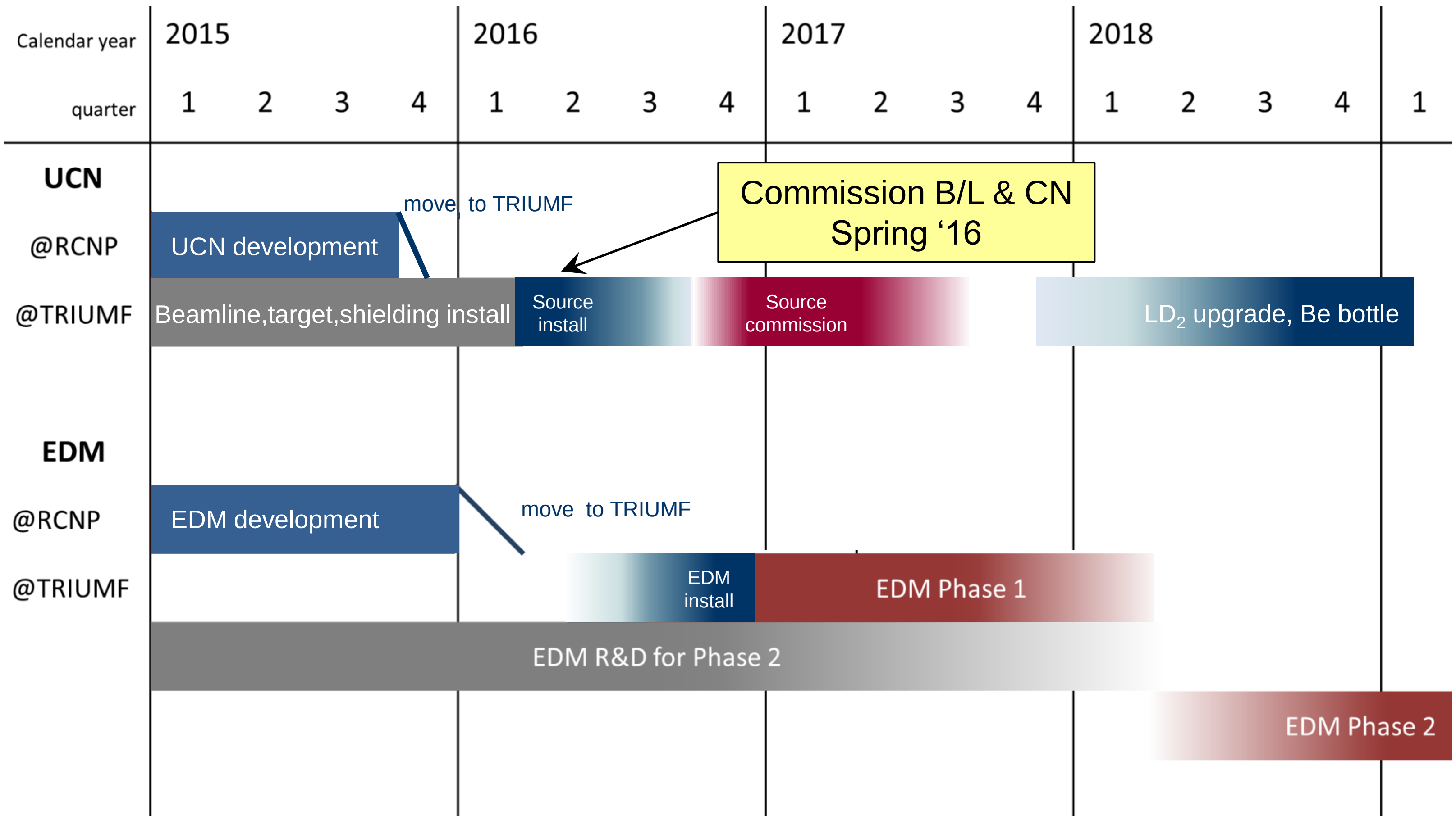
Last beamline elements before target

Kicker magnet completed, readying for testing

- Design/safety review June 2015
- Target design review July 2015
- UCN source shipment Oct. 2015
- More reviews
- Begin installation of final components January 2016.
- First UCN fall 2016.

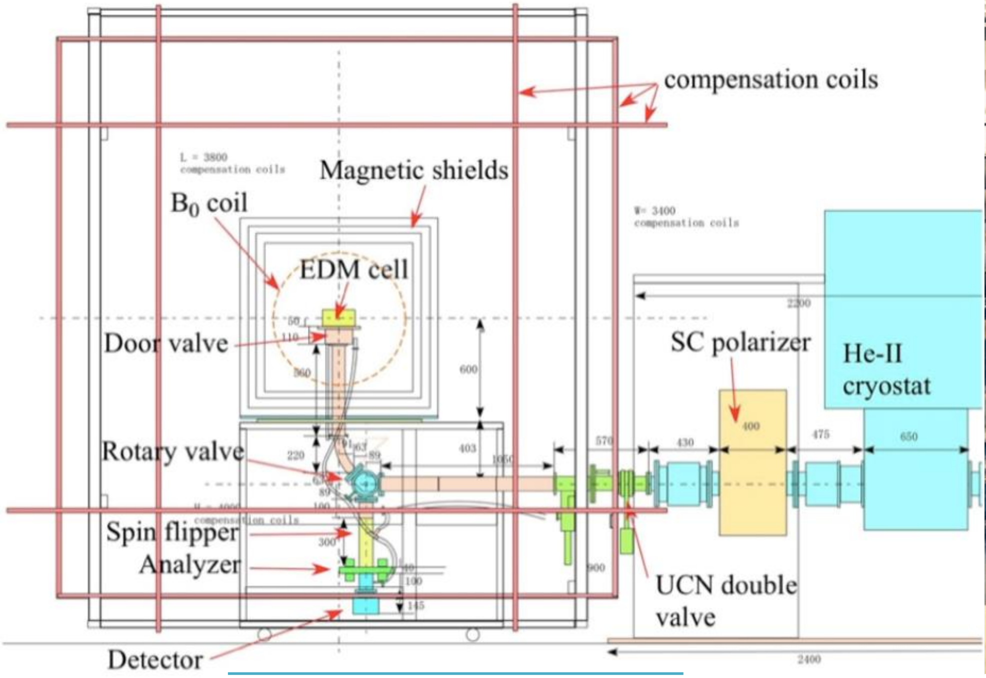
Roadmap Towards nEDM

nEDM experiment first priority (after UCN source commissioning)



nEDM Phase 1

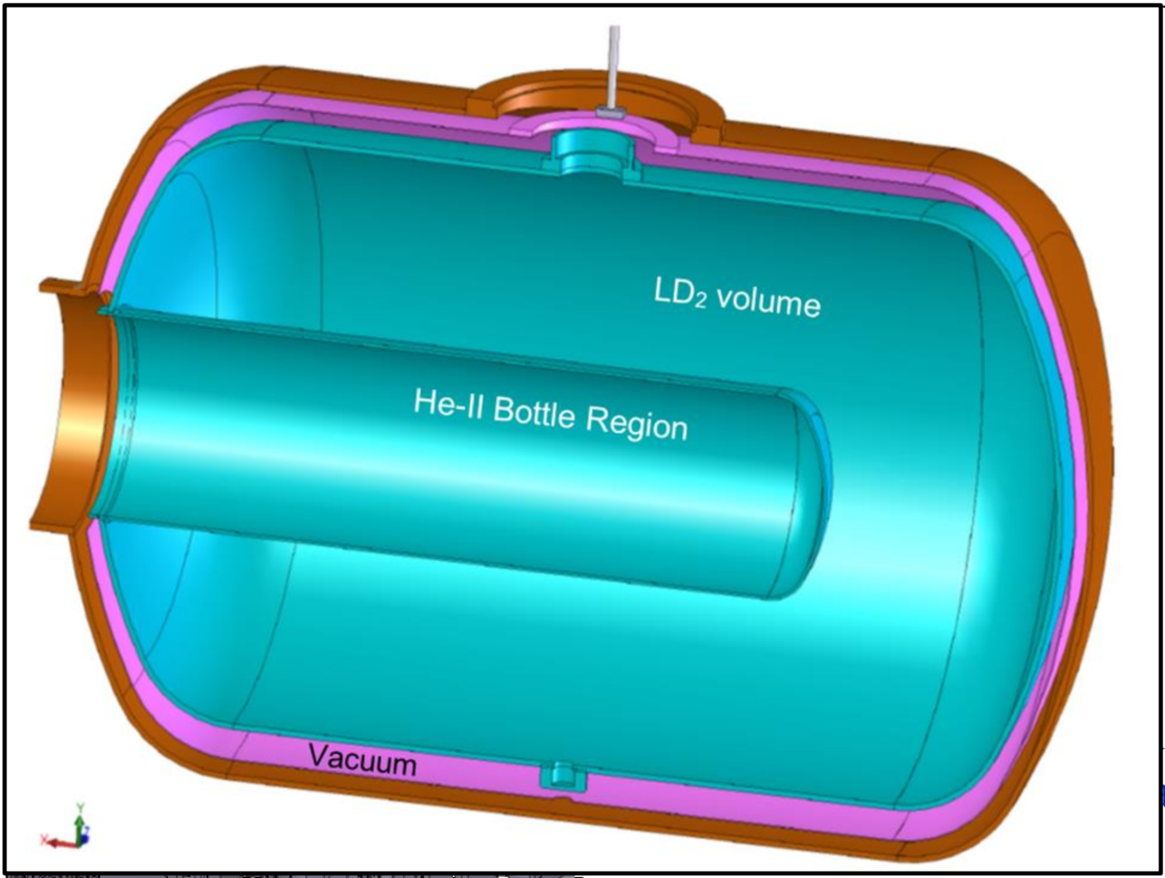
- use **existing** EDM Ramsey **apparatus** from RCNP, Osaka
- exploit **higher UCN density** at TRIUMF (also more beamtime available)
- room temperature, **1 small cell**, vertical loading, spherical B_0 coil
- small incremental improvements until replaced by Phase 2
  - **Active magnetic compensation system**
  - **high voltage**
  - **comagnetometer**
  - **high-flux detector**



EDM Phase 1 schematic

EDM Phase 1 at RCNP

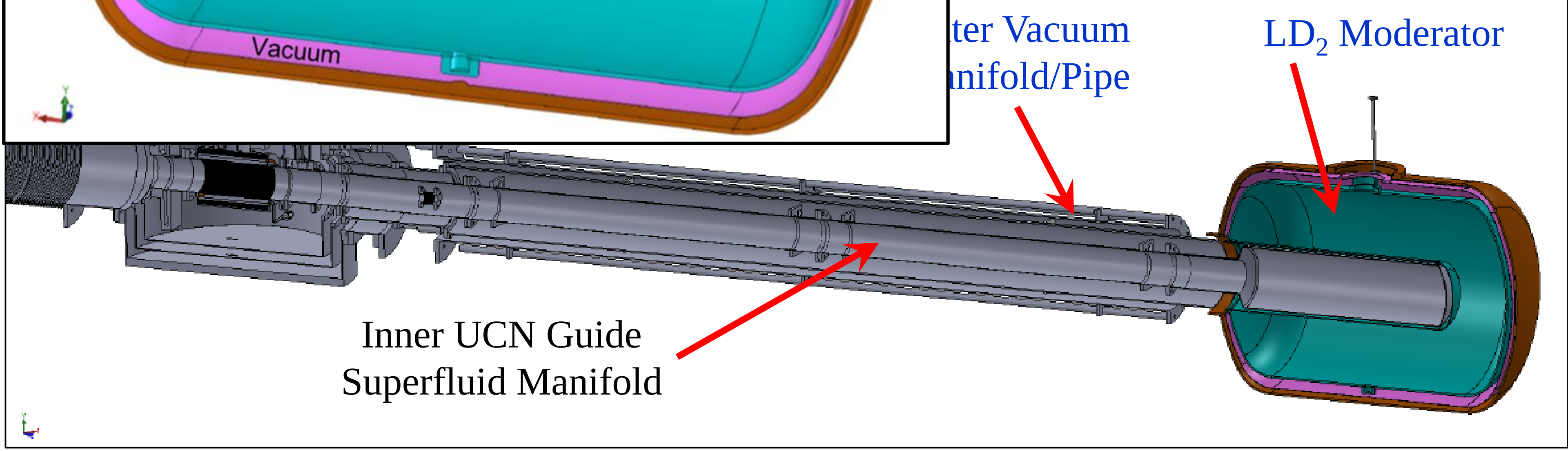
Phase 2: Cold Moderator Upgrade to LD_2



MCNPX Studies:
UCN yield increased by 5-7 when D_2O ice replaced by LD_2 and heat load on He-II cut in half!

LD_2 Cryostat System

- Aluminum Cryostat
- 125 Liquid Litres of D_2
- 90 W Heat Load
- Circulate LD_2 to remote condenser + cryo-cooler

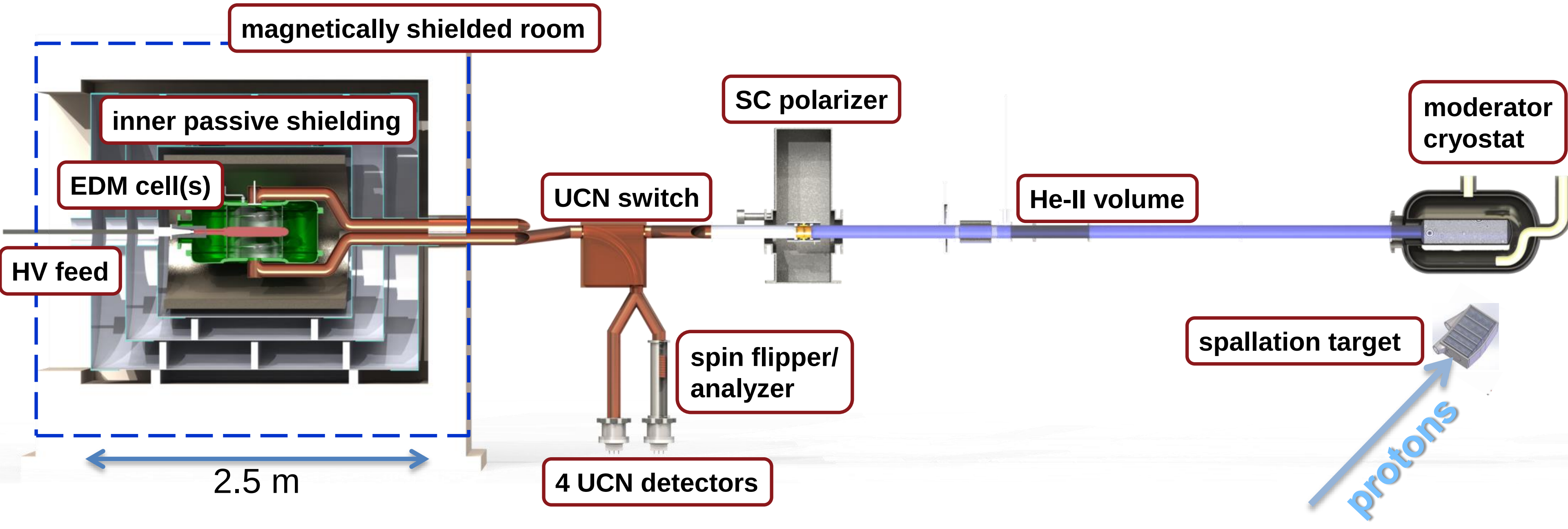


nEDM Phase 2 – circa 2019?

- room temperature
- improvements
  - higher UCN density with LD_2 moderator
  - 2 cells, probably "horizontal" loading
  - **dual Xe/Hg comagnetometer**
  - **improved magnetic environment**
  - simultaneous counting of both polarizations
- Sensitivity goal: $d_n < 10^{-27}$ e·cm

- ongoing extensive R&D program
  - Magnetic fields
  - UCN detector
  - comagnetometer
  - HV/EDM cell
  - simulations

possible topology



Canadian EDM R&D

Magnetic environment

- active shielding
- passive shielding
- creation of stable, homogeneous B fields
- Precision atomic magnetometry and SQUIDs

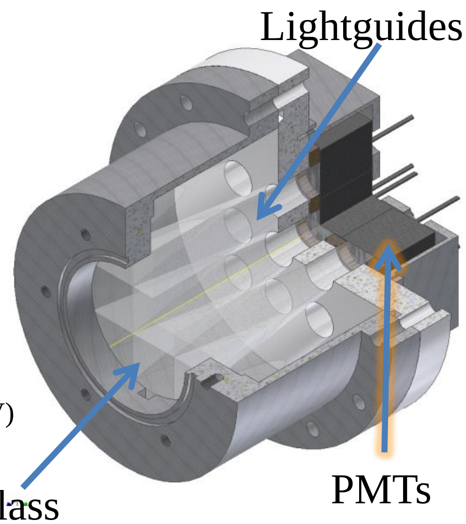
Cylindrical shells of the 4 layer FM shield

THE UNIVERSITY OF WINNIPEG

UCN detection

- Need faster detectors
- Li glass scintillators + lightguide + PMTs
- Test run in August 2015 at PSI
- R&D towards dual detectors which count both spin states simultaneously.

$n + {}^{6}Li \rightarrow {}^{3}H$ (2.74 MeV) $+ {}^{4}He$ (2.05 MeV)



UCN detection scheme

THE UNIVERSITY OF WINNIPEG
UNIVERSITY OF MANITOBA
TRIUMF

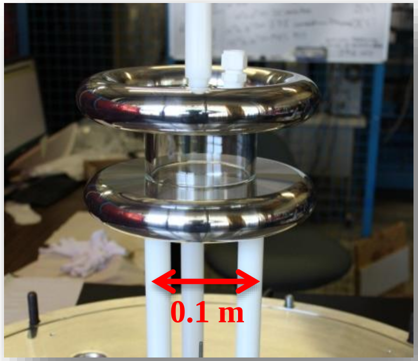
Dual Co-magnetometer

- Hg, Xe polarisation
- laser development
- 2-photon transition requires development of intense CW UV lasers.
- Xe EDM measurement

UBC
SIMON FRASER UNIVERSITY

Electric field, UCN cell

- dielectric strength of Xe at 10^{-3} mbar unknown
- 50x100 mm cylindrical test cell
- gas breakdown studies
- material studies



HV test cell

TRIUMF

Long-Range Plan

- **2017-2021**: improvements to UCN source and nEDM experiment
  - 2017-2018 CFI proposal for major upgrade to UCN source and nEDM experiment ($12M) leveraged by Japan support and TRIUMF 5YP support ($1.6M)
  - NSERC support ~$800k/yr (presently ~$500k/yr)
- **2022-2026**: development of facility and other UCN experiments
  - Neutron lifetime in a magnetic trap
  - Neutron gravity levels
  - Cost scale ~$5M/expt. Expect new international users and support for these experiments.

Summary

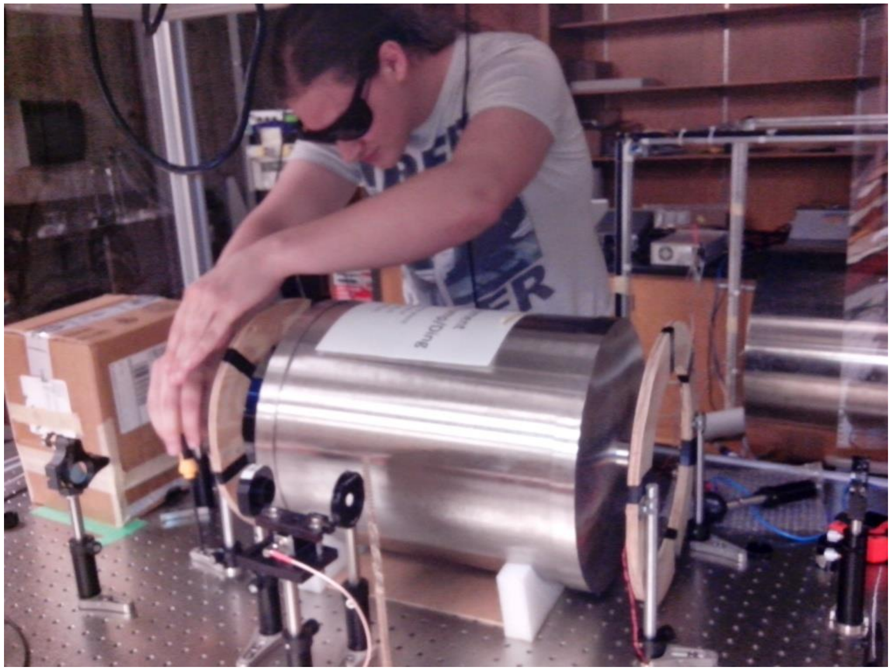
- UCN source testing (RCNP) and installation of beamline components (TRIUMF) proceeding on schedule.
- R&D progress for the neutron EDM experiment.
- Phase I nEDM operating by 2016-17
- Phase II application aiming at sub-10^{-27} e-cm precision planned for 2017-18.

More info and backups

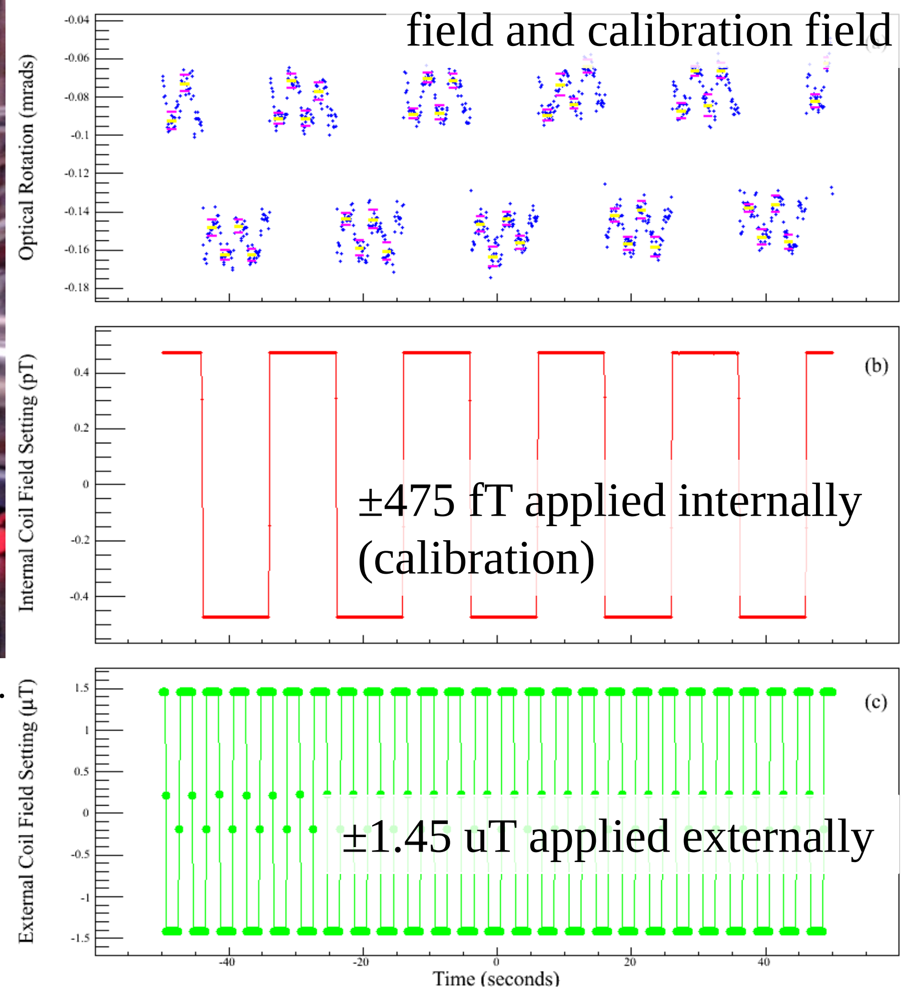
Recent achievements

- Recent publications on magnetic field R&D and UCN detector (see our draft brief)
- Recent MSc theses (several MSc and PhD in progress) (see draft brief)
- Conference proceedings/presentations (most recent one is Larry Lee at SSP2015, Victoria, BC, several others this week at CAP)
- Facility, installation at TRIUMF (see this talk and Larry’s talk at SSP)

Example nEDM R&D achievement: Precision atomic magnetometry with Rb



Wolfgang Klassen (UM/UW) installing external coils.



- Magnetometer at 20 fT precision!
- (Your brain thinking ~ 1000 fT)
- Shielding factor = 1.3 x 10^7 couldn't have been measured with any other magnetometer.

"Large magnetic shielding factor measured by nonlinear magneto-optical rotation," J.W. Martin, R.R. Mammei, W. Klassen, C. Cerasani, T. Andalib, C.P. Bidinosti, M. Lang, and D. Ostapchuk, Nucl. Instr. Meth. A 778, 61-66 (2015).

NSERC Faculty Research FTE's

Name	Institution	FTE
C. Bidinosti	U. Winnipeg	0.4
J. Birchall	U. Manitoba	0.3
M. Gericke	U. Manitoba	0.1
B. Jamieson	U. Winnipeg	0.5
D. Jones	UBC	0.3
A. Konaka	TRIUMF	0.2
E. Korkmaz	UNBC	0.3
T. Lindner	TRIUMF/U. Winnipeg	0.1
K. Madison	UBC	0.3
J. Mammei	U. Manitoba	0.1
R. Mammei	U. Winnipeg	0.9
J. Martin	U. Winnipeg	0.8
T. Momose	UBC	0.3
W. van Oers	U. Manitoba/TRIUMF	0.3
S. Page	U. Manitoba	0.1
R. Picker	TRIUMF	1.0
J. Sonier	SFU	0.1
Joint Position	TRIUMF/U. Winnipeg	0.9
Total		**7.0**

- This is list expected for our next renewal April 2015
- Also ~4 Japan faculty FTE's
- Expect 1-2 more Canadians to join over next 5YP period, and some Japanese
- More international users once facility is operational and time can be dedicated to other experiments (2022-)

Full Collaboration List (06/2015)

T. Adachi[1], E. Altiere[2], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Chin[5], C. Davis[5], F. Doresty[4], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], B. Jamieson[3], S. Jeong[1], D. Jones[2], K. Katsika[5], S. Kawasaki[1], T Kikawa[5,6,1], A. Konaka[5,8], E. Korkmaz[7] , M. Lang[3], T. Lindner[5], L. Lee[4,5], K. Madison[2], J. Mammei[4], R. Mammei[3], J.W. Martin[3], Y. Masuda[1], R. Matsumiya[6], K. Matsuta[8], M. Mihara[8], E. Miller[2], T. Momose[2], S. Page[4], R. Picker[5], E. Pierre[6,5], W.D. Ramsay[5], L. Rebenitsch[3,4], J. Sonier[9], I. Tanihata[6], W.T.H. van Oers[4,5], Y. Watanabe[1], and J. Weinands[2]

[1]KEK, Tsukuba, Ibaraki, Japan
[2]The University of British Columbia, Vancouver, BC, Canada
[3]The University of Winnipeg, Winnipeg, MB, Canada
[4]The University of Manitoba, Winnipeg, MB, Canada
[5]TRIUMF, Vancouver, BC, Canada
[6]RCNP, Osaka, Japan (Osaka University, Osaka, Japan)
[7]The University of Northern BC, Prince George, BC, Canada
[8]Osaka University, Osaka, Japan
[9]Simon Fraser University, Burnaby, BC, Canada

Grad students highlighted in red
Typically 8-10 undergraduates per year (not listed)

More collaborators always welcome:
- nEDM R&D, future UCN source R&D, future experiments R&D