Plans for Ultra Cool Neutrons at TRIUMF

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The University of Winnipeg

WNPPC 2012
Mont Tremblant, Québec

Outline for Talk

- Properties of Ultra Cold Neutrons (UCN)
- Production of UCN – TRIUMF source
- Probing physics of neutrons with UCN
- Electric Dipole Moment of neutrons
- Schedule for TRIUMF neutron EDM expt.
- Conclusions

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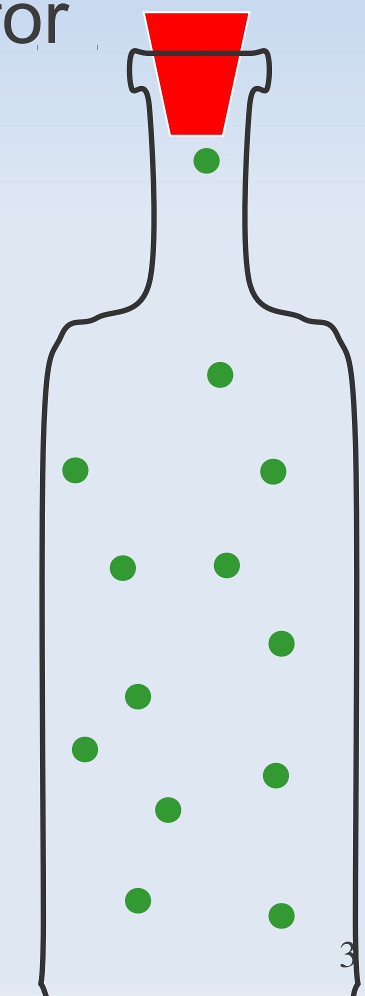
Ultracold Neutrons (UCN)

- UCN are neutrons that are moving so slowly that they are totally reflected from a variety of materials.
- So, they can be confined in material bottles for long periods of time.
- Typical parameters:
  - velocity < 8 m/s = 30 km/h
  - temperature < 4 mK
  - kinetic energy < 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: $\tau = 885.7$ s = 15 mins



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How to make lots of neutrons: Liberate them from nuclei!

1) In a nuclear reactor (fission).

2) At an accelerator (spallation).

Accelerator

Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

Reactor

Insititut Laue-Langevin,
Grenoble, France, www.ill.fr

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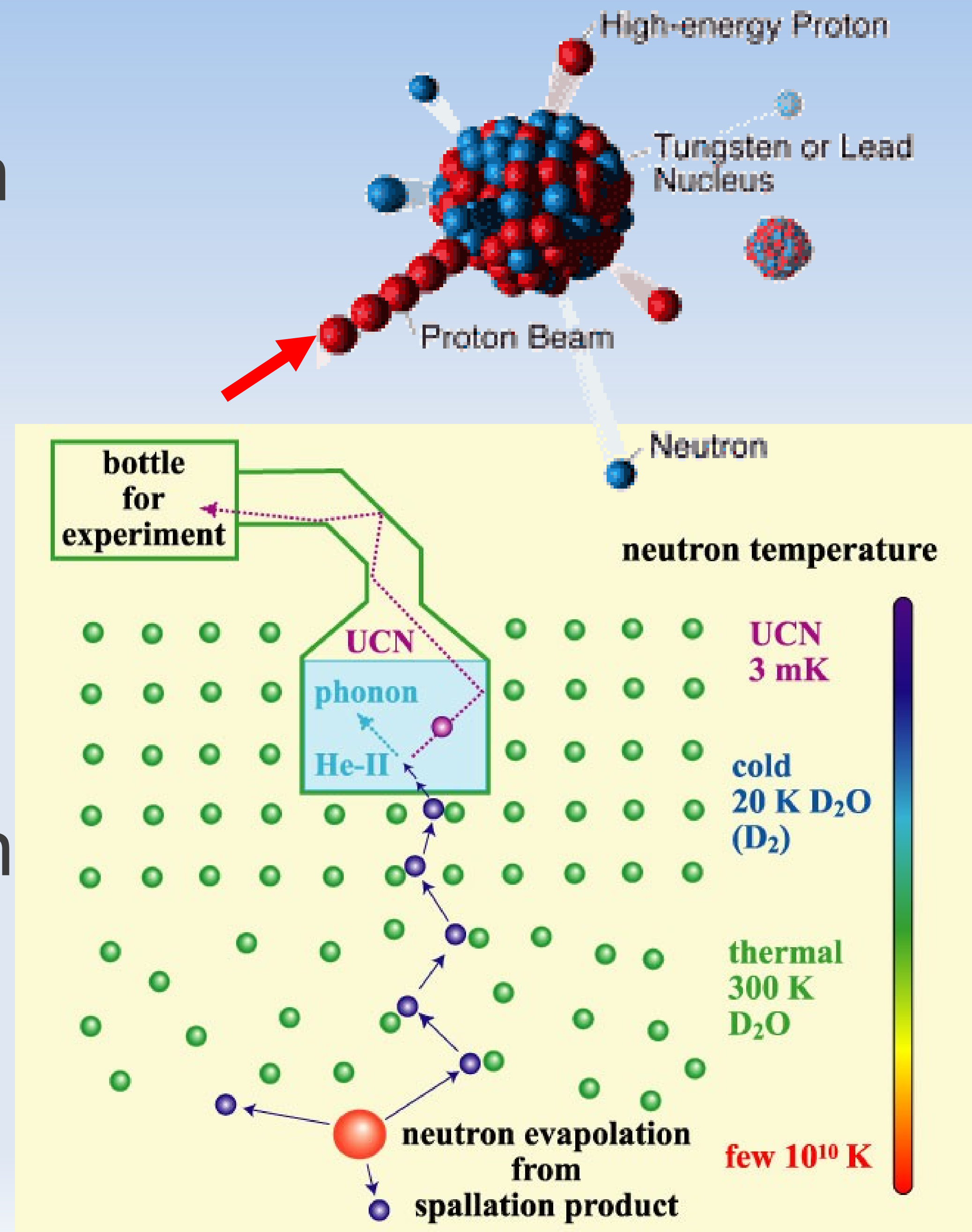
TRIUMF UCN spallation neutron source concept

- Liberate neutrons by proton-induced spallation (several n per p).
- Moderate (thermalize) in cold (20 K) D_2O.
- Cold neutrons then “downscatter” to near zero energy (4 mK) in superfluid helium through phonon production.



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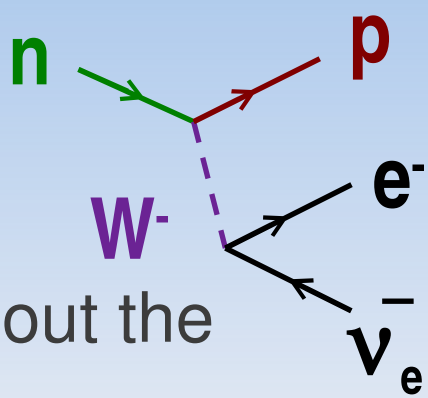
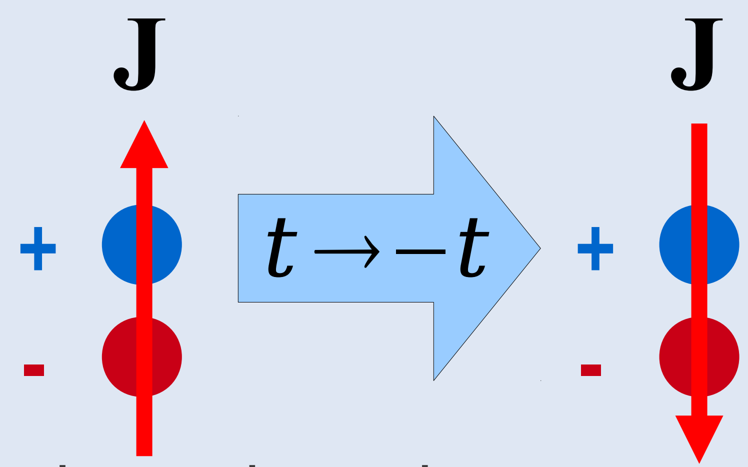
Fundamental Physics with UCN

- How fast do neutrons decay? BBN.



- Details about how neutrons decay tell us about the weak nuclear force. (V_{ud})

- Does the neutron possess an electric dipole moment? The predominance of matter over antimatter in the universe.



- Interactions of neutrons with gravity and are there extra dimensions?

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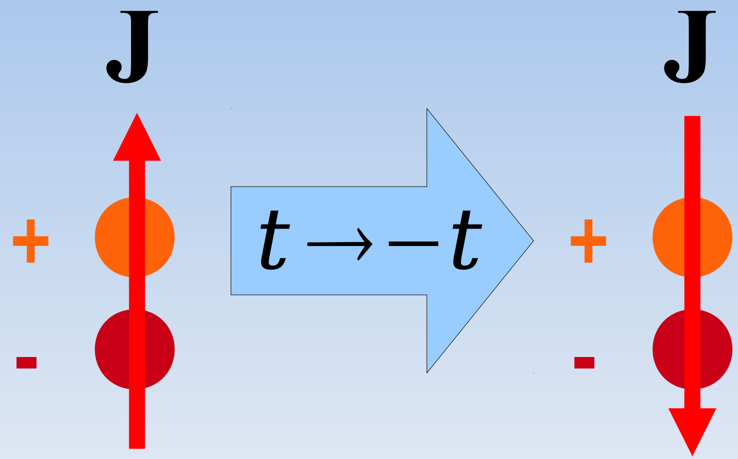
Neutron Electric Dipole Moment (n-EDM, d_n)



$$d_n \Rightarrow \not{T} \Rightarrow \not{CP}$$

New sources of CP violation are required to explain the baryon asymmetry of the universe.

- Complementary to Rn-EDM, Fr-EDM @ TRIUMF.

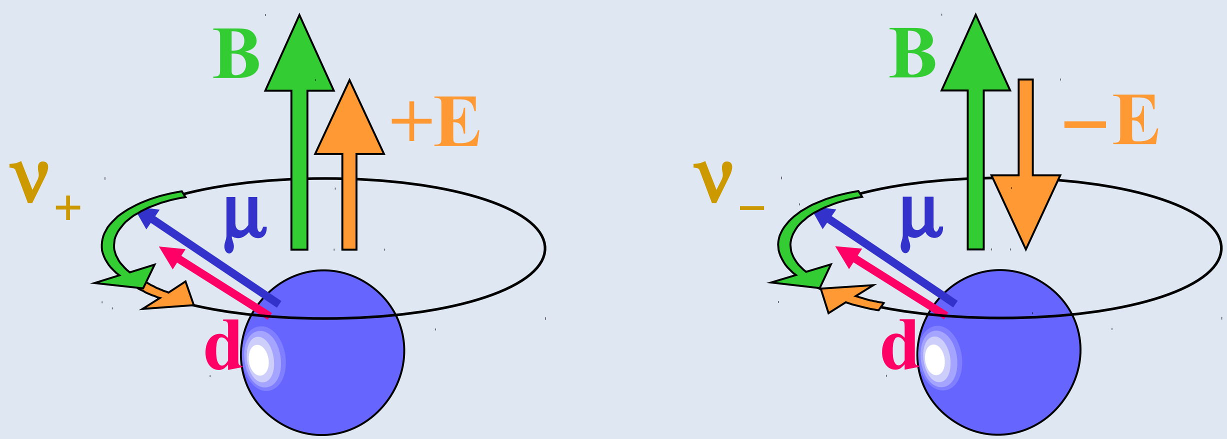
Experimental technique:

- put UCN in a bottle with *E*-, *B*-fields
- search for a change in spin precession frequency (at Larmor frequency) upon *E* reversal.

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

Electric Dipole Moment:

$$d_n = (h/2E)(\nu_+ - \nu_-)$$



Precesses Faster

Precesses Slower

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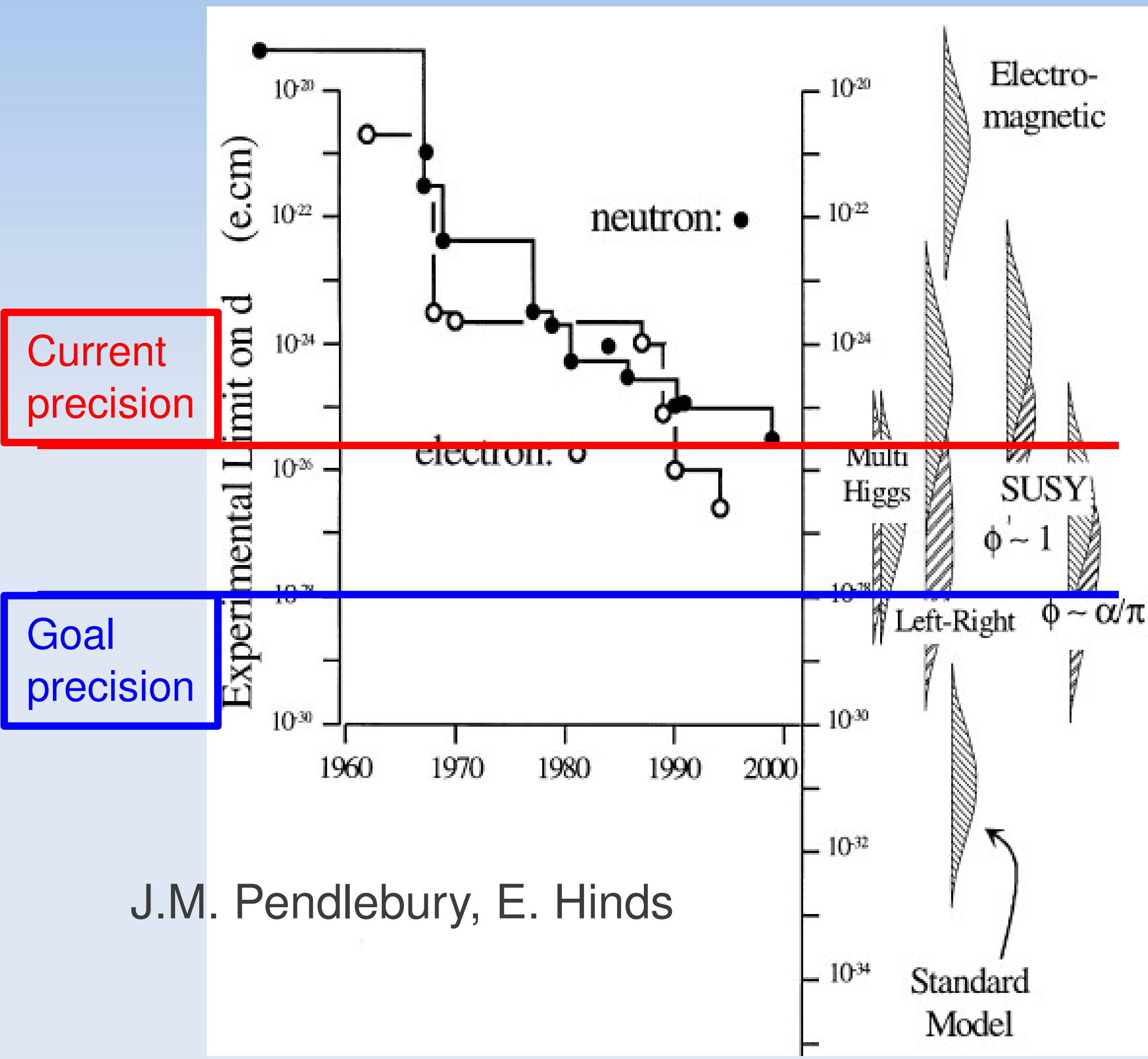
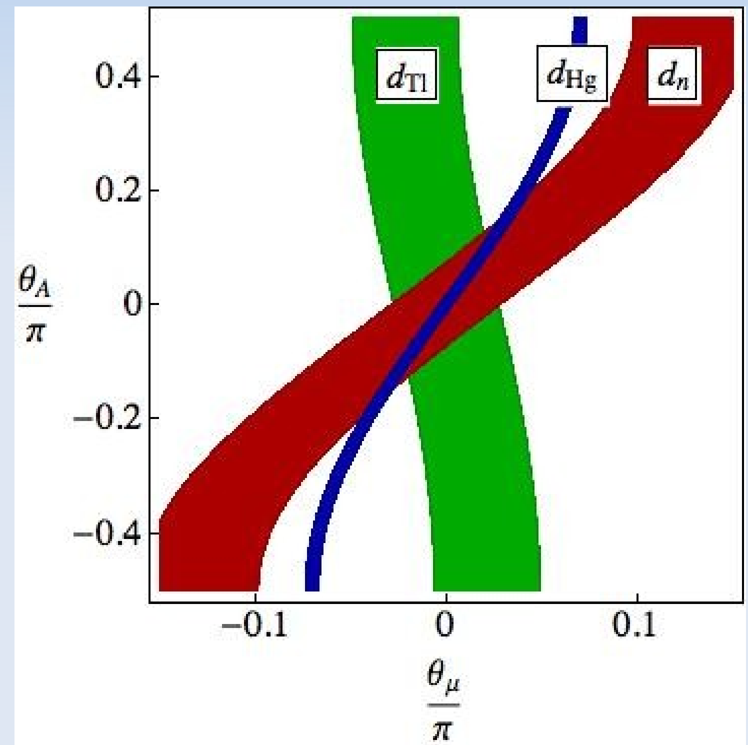
EDMs, the SM, and beyond



J.M. Pendlebury, E. Hinds

A. Ritz, M. Pospelov, et al

SUSY M = 1 TeV, tanβ = 3



- “n-EDM has killed more theories than any other single experiment!”

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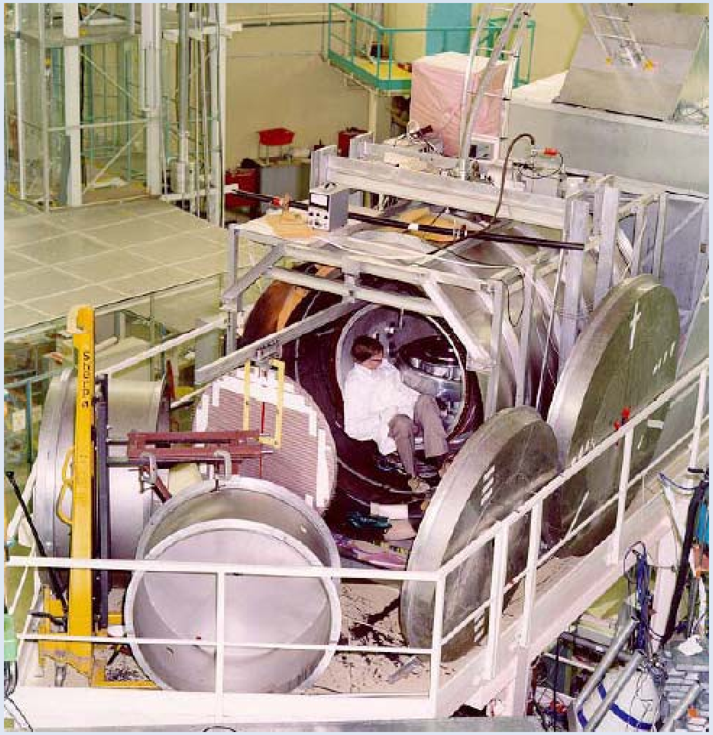
Past and Future n-EDM efforts

- Sussex-RAL-ILL expt. ($d_n < 3\times10^{-26}$ e-cm)
  - 0.7 UCN/cc, room temp, in vacuo
- New experiments:
  - CryoEDM (ILL)
  - SNS (USA)
  - PSI
  - Ours (Japan-Canada)
  - Munich, PNPI, J-PARC, ...
- Different superthermal sources
- Various approaches for EDM



Sussex-RAL-ILL experiment

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Neutron Electric Dipole Moment Search with a Spallation Ultracold Neutron Source at TRIUMF

Spokespeople: Y. Masuda (KEK), J.W. Martin (Winnipeg)

Collaborators: T. Adachi, K. Asahi, M. Barnes, C. Bidinosti, J. Birchall, L. Buchmann, C. Davis, T. Dawson, J. Doornbos, W. Falk, M. Gericke, R. Golub, K. Hatanaka, B. Jamieson, S. Jeong, S. Kawasaki, A. Konaka, E. Korkmaz, E. Korobkina, M. Lang, L. Lee, R. Mastumiya, K. Matsuta, M. Mihara, A. Miller, T. Momose, W.D. Ramsay, S.A. Page, Y. Shin, H. Takahashi, K. Tanaka, I. Tanihata, W.T.H. van Oers, Y. Watanabe

(KEK, Titech, Winnipeg, Manitoba, TRIUMF, NCSU, RCNP, UNBC, UBC, Osaka)

Summer students at TRIUMF (2011): Moritz Hahn, Florian Fischer, Gary Yang, Eric Miller

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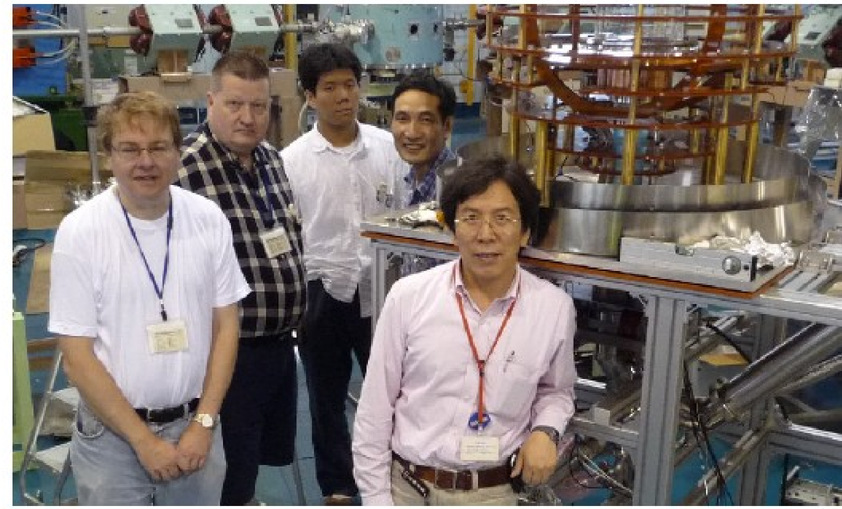
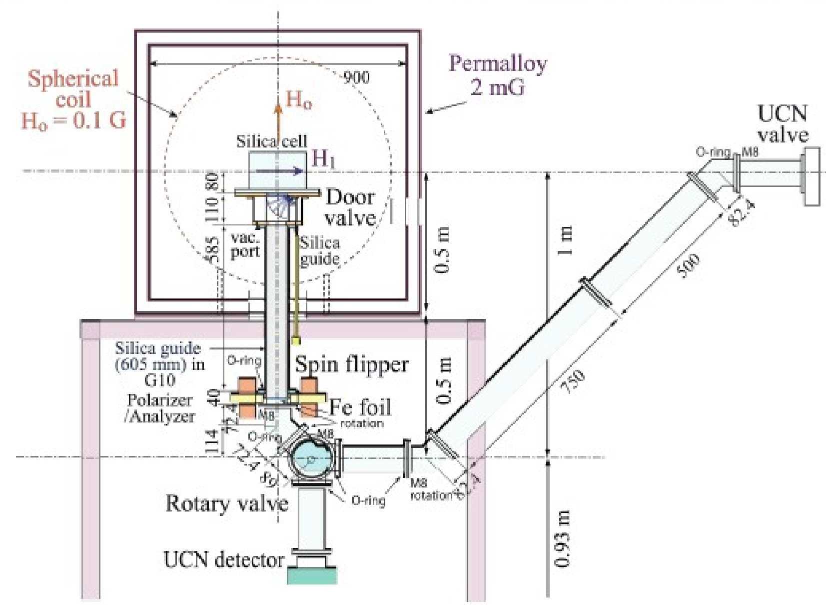
Japan-Canada nEDM experiment

- Spherical coil for DC field
- Xe-129 nuclear-spin buffer-gas comagnetometer
- Room-temp experiment, keeping EDM cell size small, anticipating gains in UCN density
- Modern magnetic shielding, cost reduced with cell size
- Superfluid He-4 UCN source
- Basic prototype in operation





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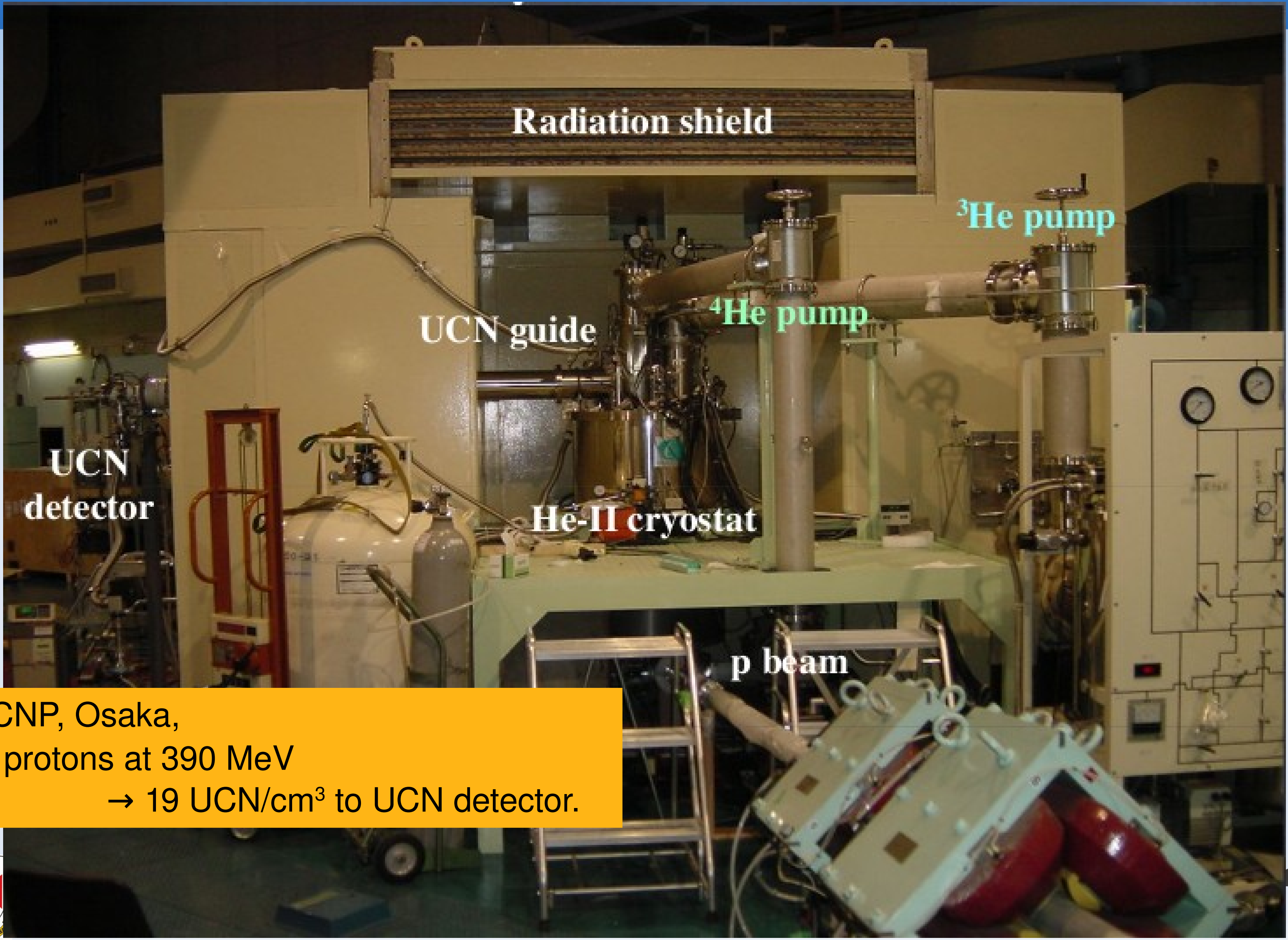
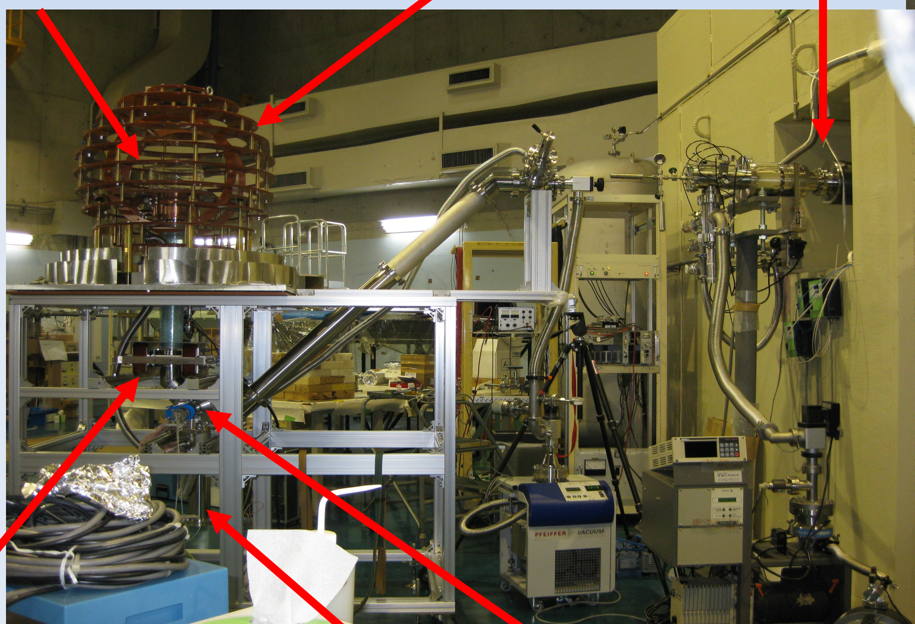
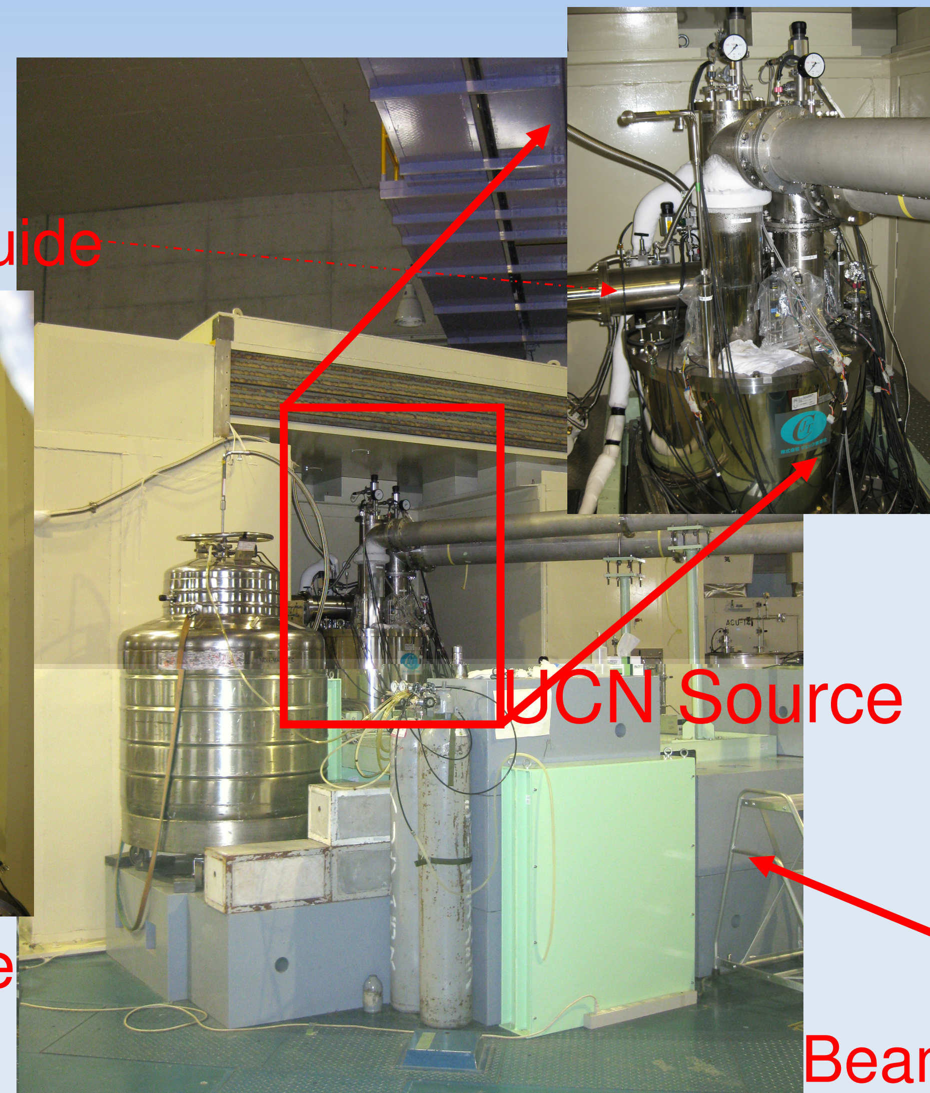
KEK-RCNP UCN Source



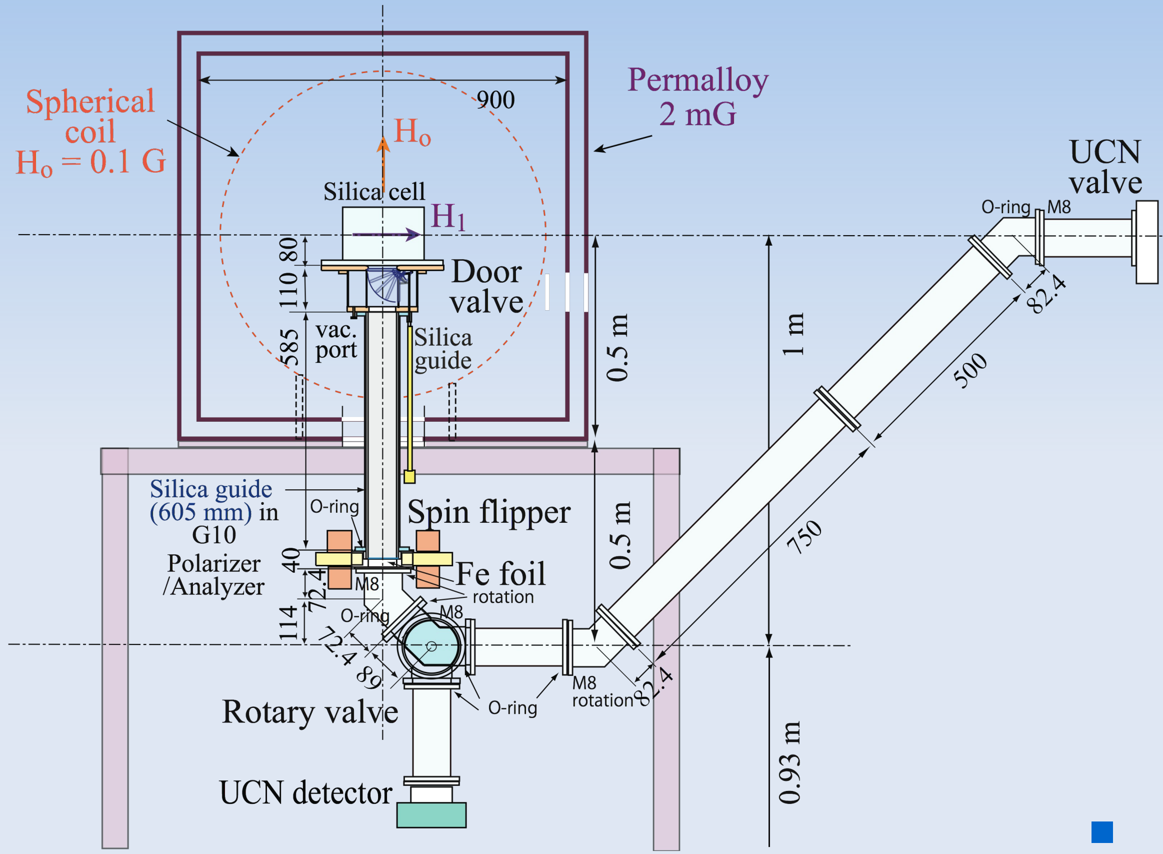
At RCNP, Osaka,
1 μA protons at 390 MeV
→ 19 UCN/cm³ to UCN detector.

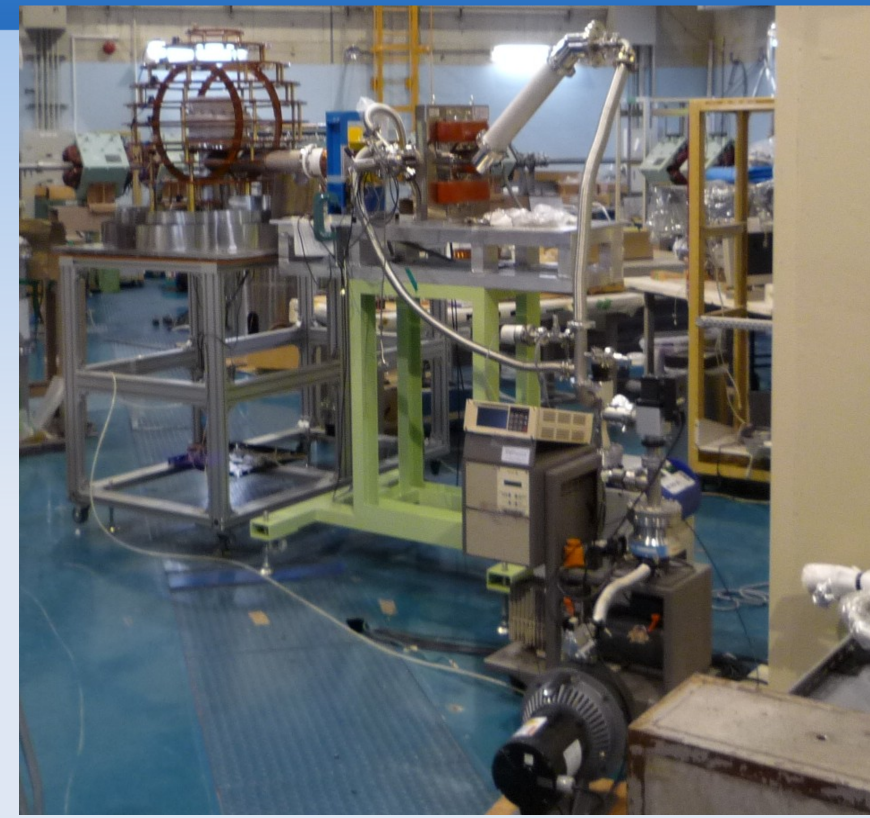
Experimental Setup





n-EDM development in Japan





Masuda, et al. Beam tests July, December 2009, April 2010, February 2011, October 2011.

- Development of:
  - Comagnetometers
  - Ramsey resonance
  - New B-field geometry
  - HV, EDM cell

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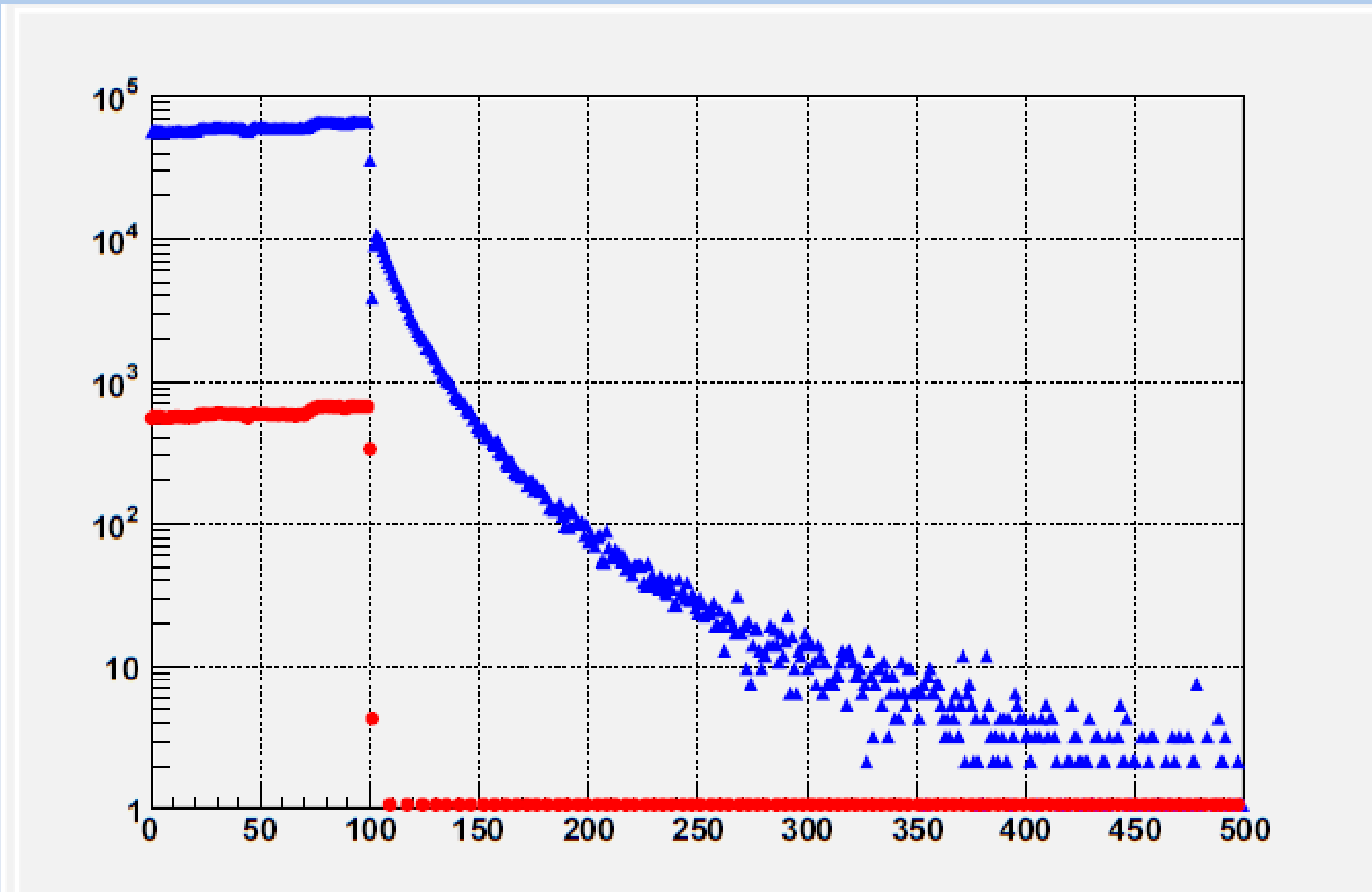
Proton Beam 1μA x 100 s



Time [s]

~15 UCN/cc in region just outside shield wall.
a remarkably reliable source of UCN!

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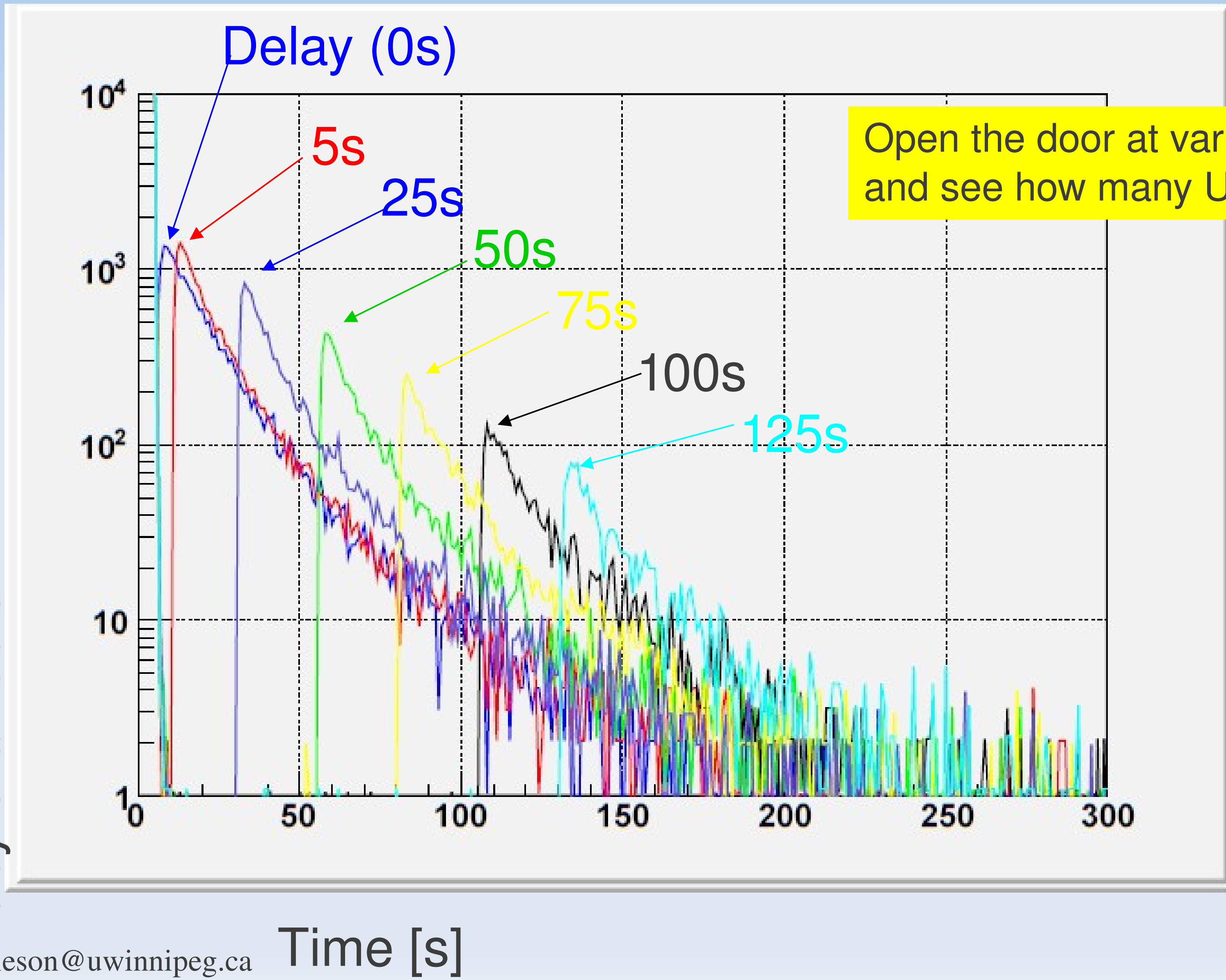
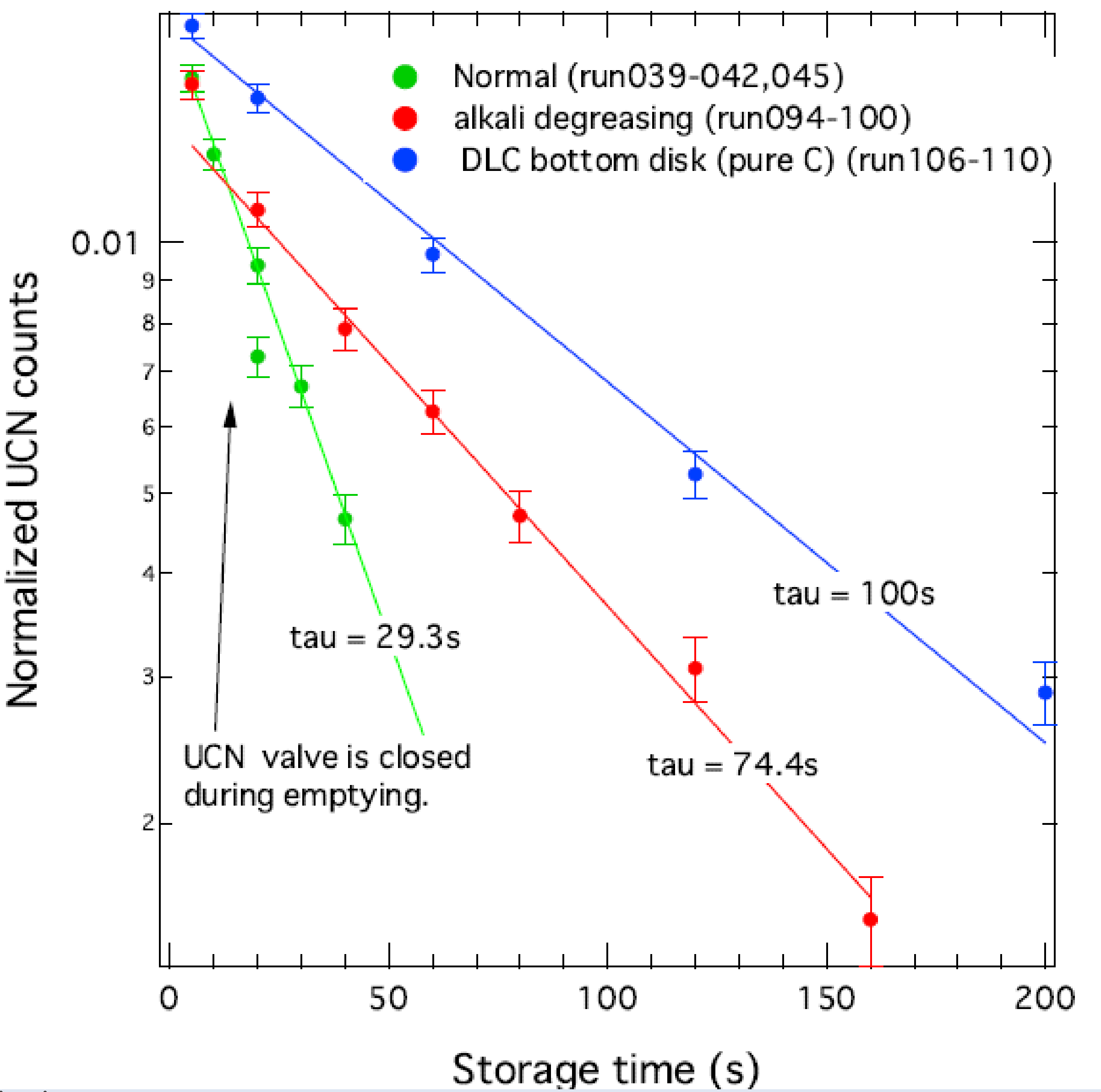
Upstream UCN Storage Time



Open the door at various times and see how many UCN come out!

Storage Time in EDM Cell



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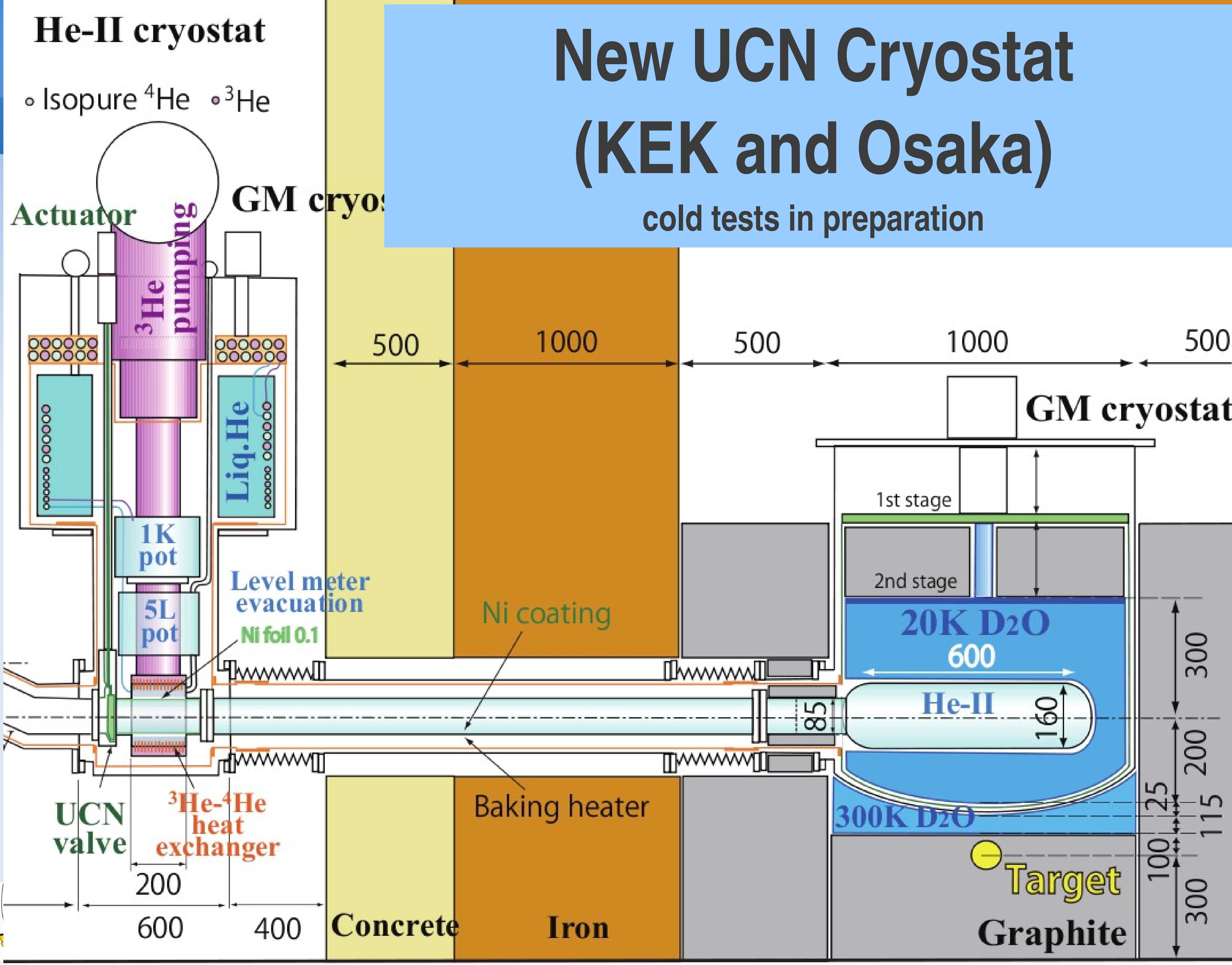
New UCN Cryostat (KEK and Osaka)

cold tests in preparation



TRIUMF UCN Source

Plan for highest intensity UCN source

- Gain Factors (40 µA @ 500 MeV):
  - Beam energy, power x 70
  - Production volume x 1.5
  - Storage lifetime x 2.5
  - Transport eff x 2
  - $E_c^{3/2}$ (from 90 to 210 neV) x 3.5
- Goal: 5000 UCN/cm^3 in EDM cell.
- Lumi. upgrade at RCNP to 10 µA allows tests thru 2014.
- Longer running time at TRIUMF (8 months/yr vs few weeks)

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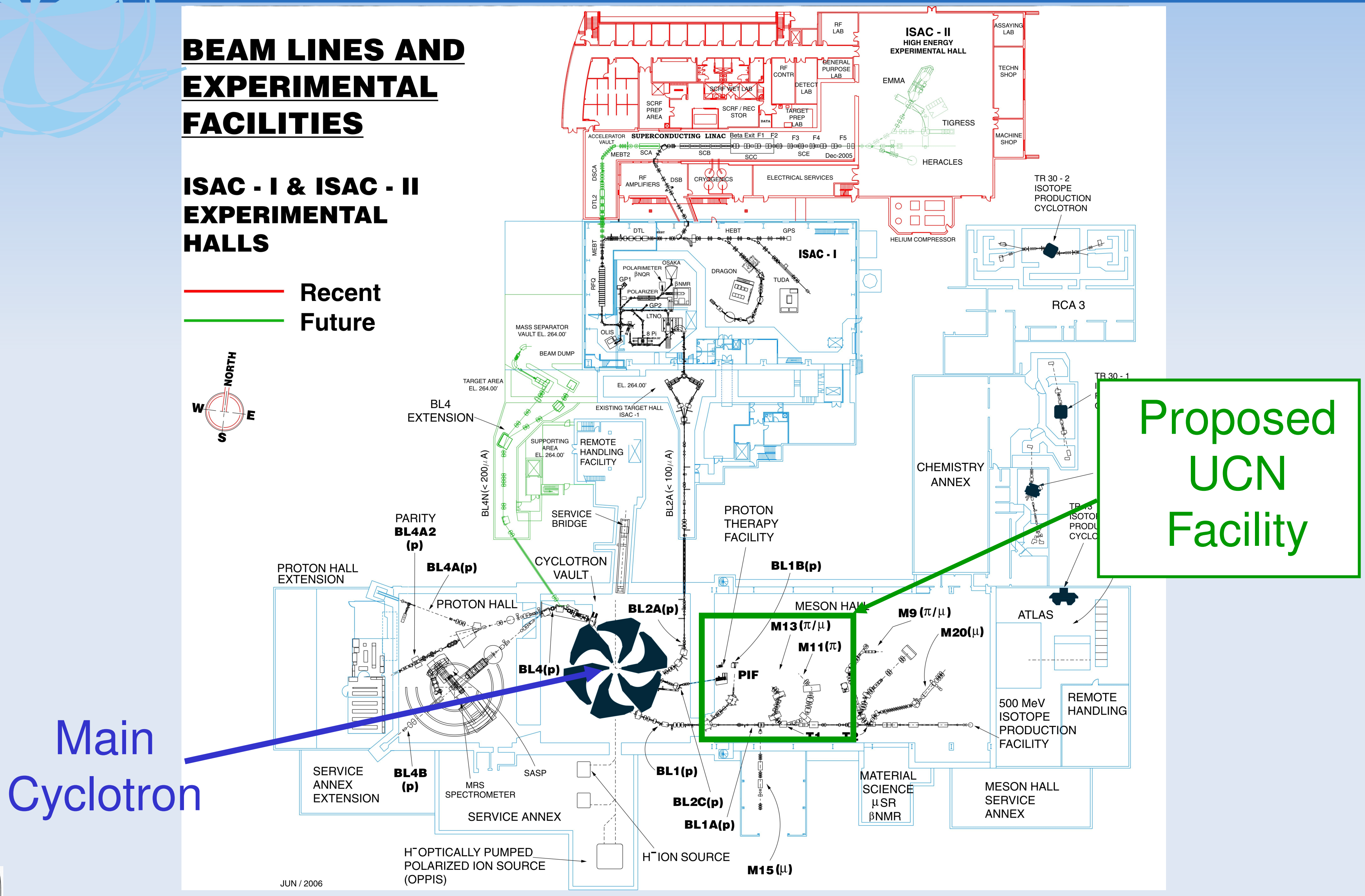
TRIUMF



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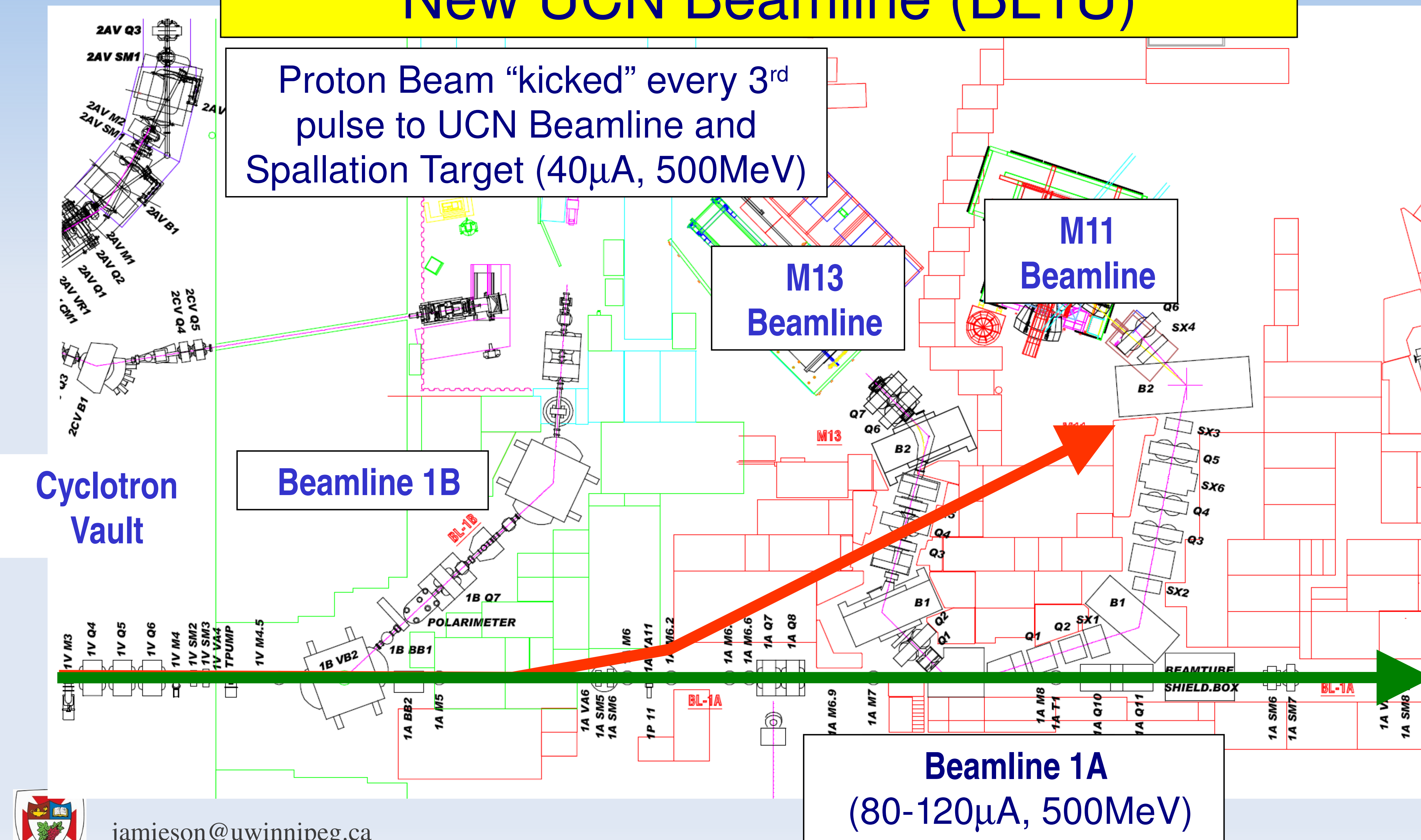
TRIUMF Meson Hall

New UCN Beamline (BL1U)



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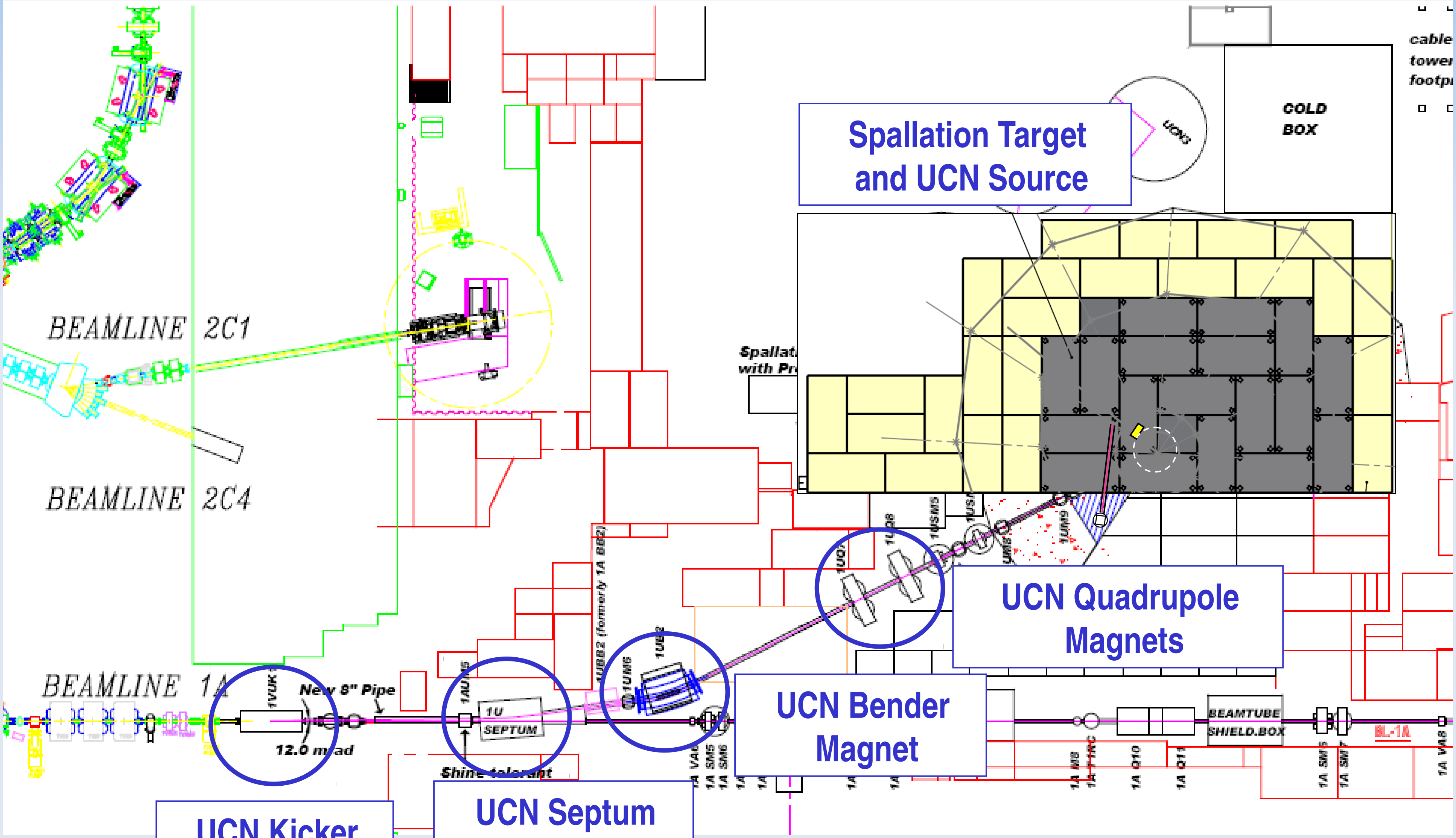
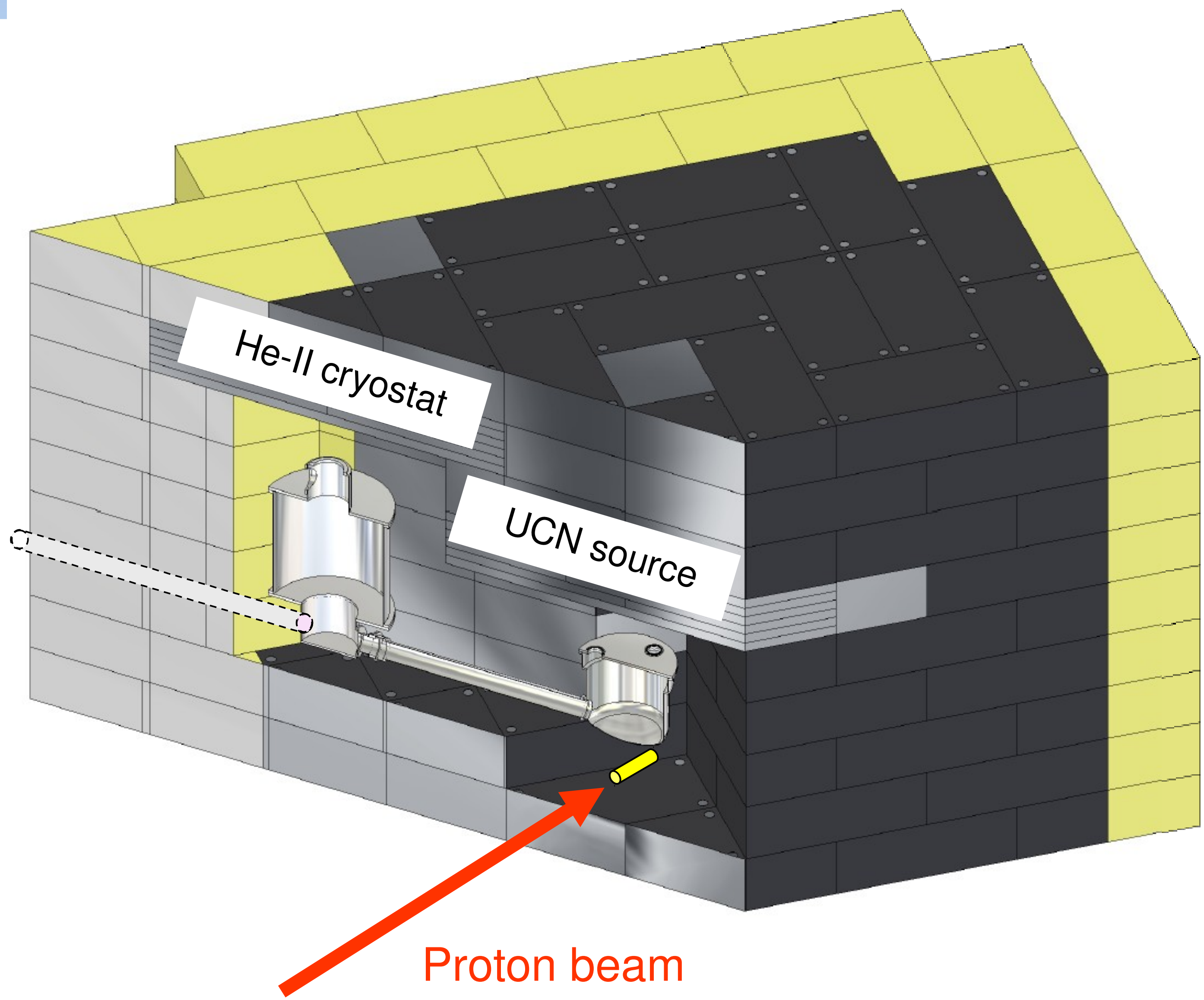
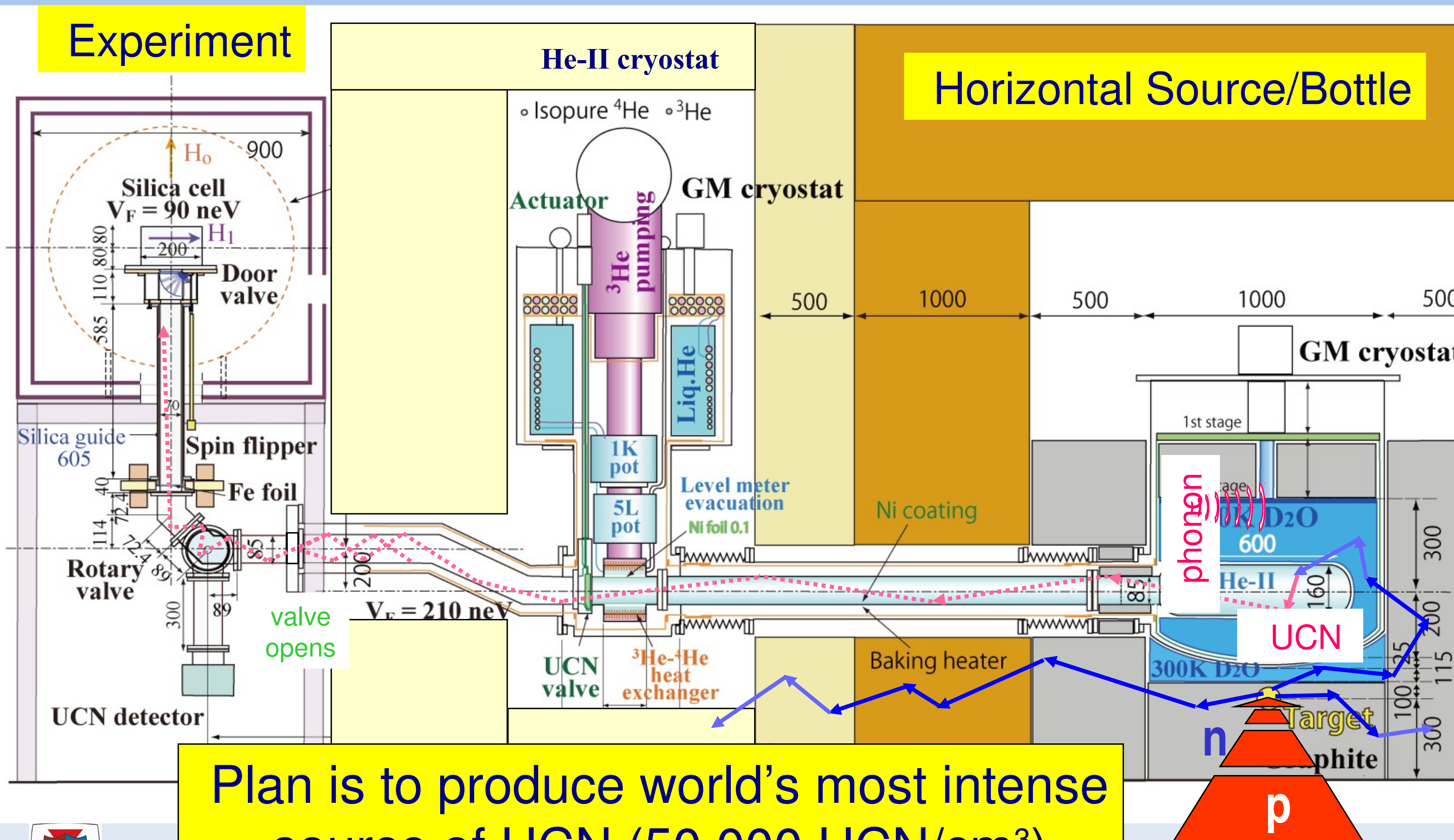
UCN Facility at TRIUMF



Spallation Target & UCN Source

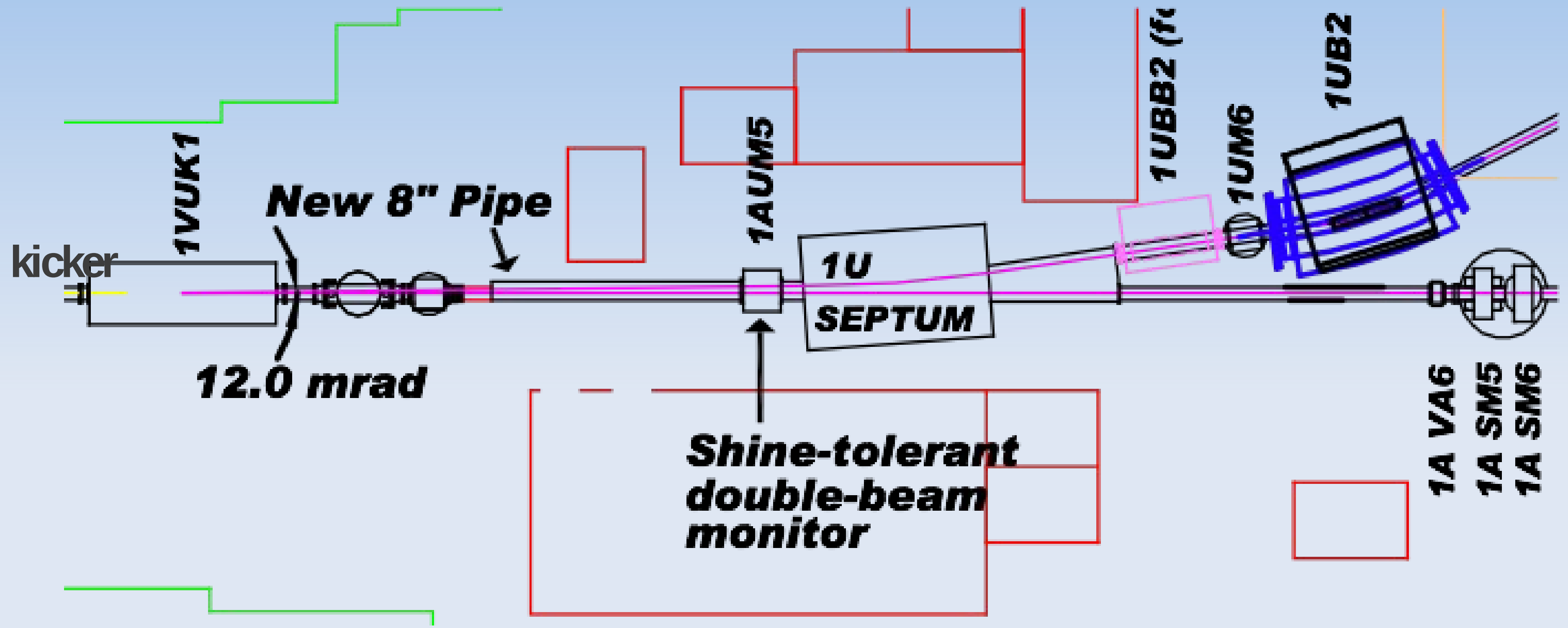


UCN Source at TRIUMF



Plan is to produce world's most intense source of UCN (50,000 UCN/cm³)

UCN beam line magnets



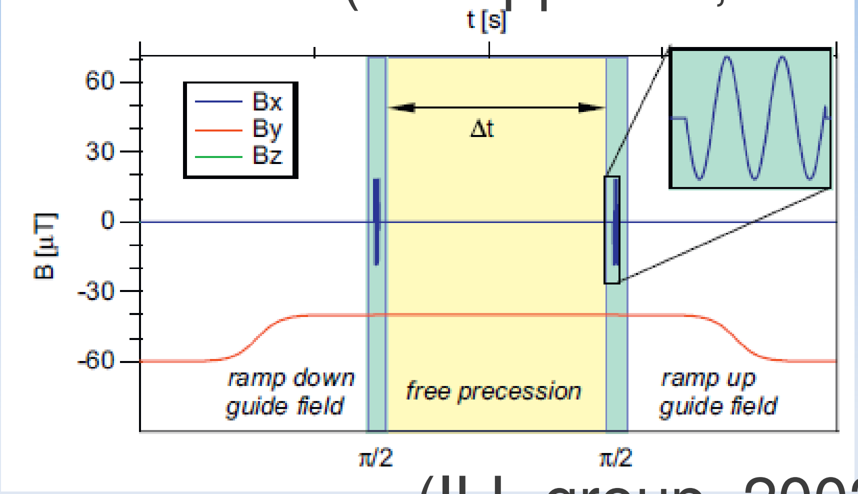
- Septum/bender magnets built by KEK
  - Lambertson design considered for septum
  - Sector design for bender (under construction this FY)

K. Tanaka, A. Miller

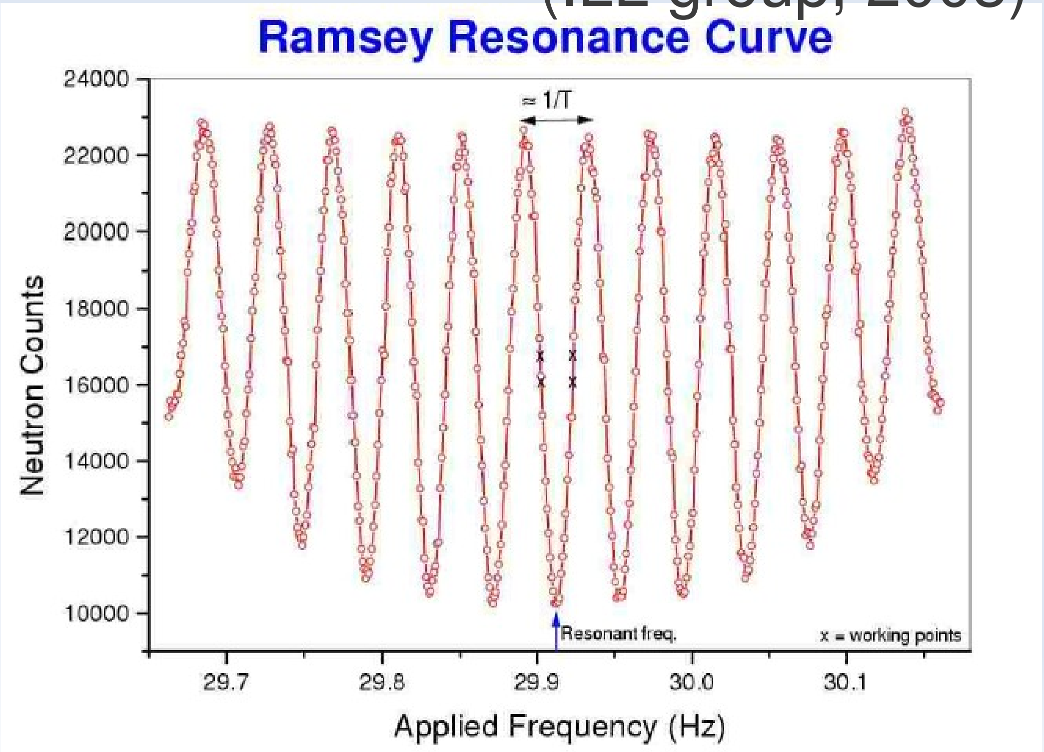
Ramsey Resonance

- π/2 pulse
- free precession time τ
- π/2 pulse
- For $\omega = g_n \mu_N = \frac{e g_n B}{2 m_p}$, min. UCN
- Vary ω and narrow "Ramsey fringes" are observed.
- Width of fringe ~ 1/τ

(S.Filipp et al, 2009)



(ILL group, 2003)



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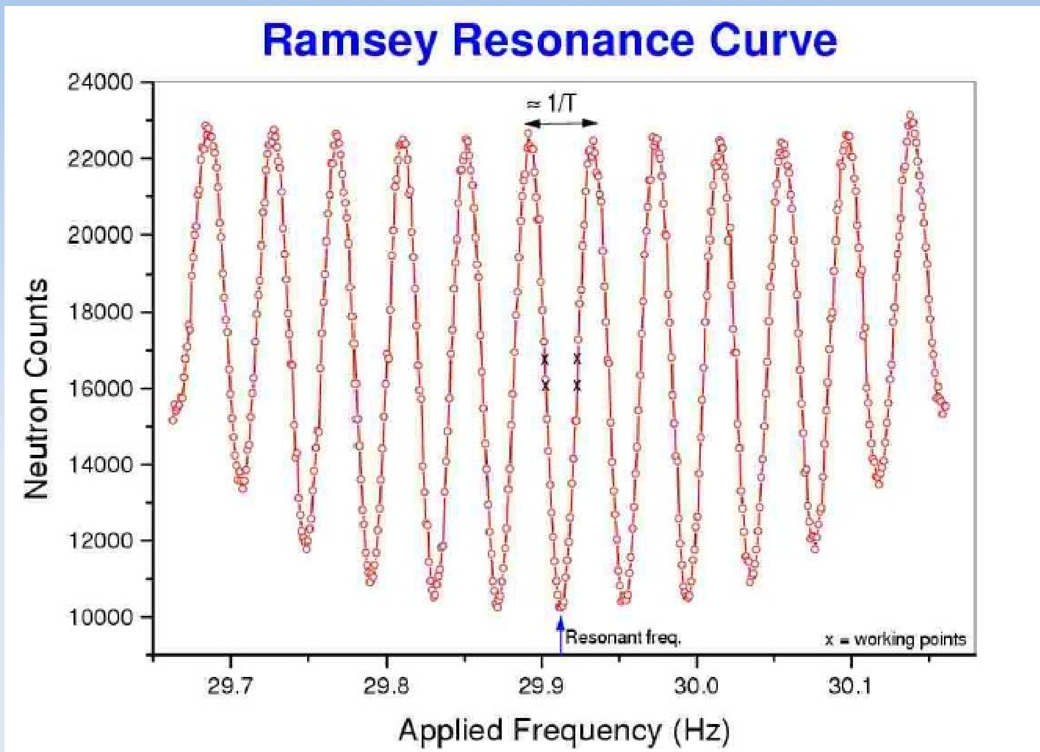
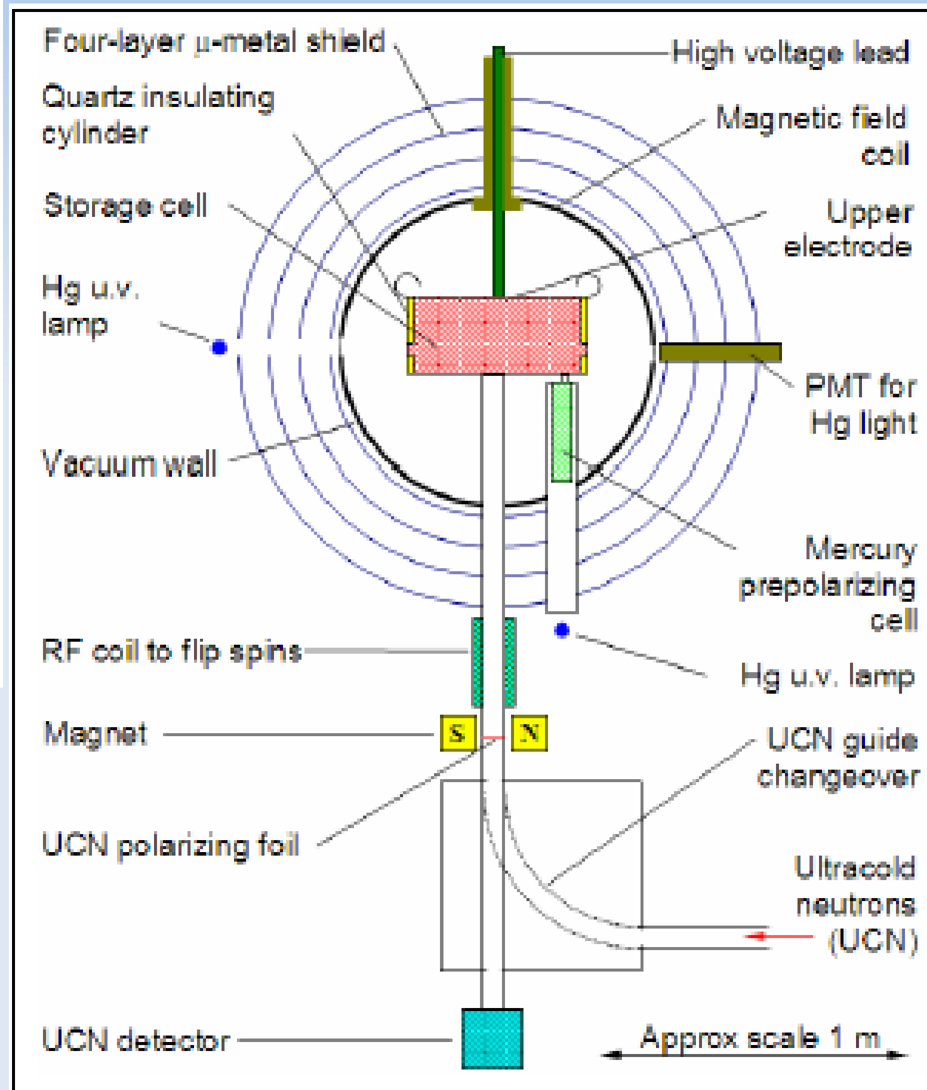
EDM Method





Sit at the steepest slope and watch for any change in neutron counts under E-field reversal.

$$d_n = \frac{(N_{1\uparrow\uparrow} - N_{2\uparrow\uparrow} - N_{1\uparrow\downarrow} + N_{2\uparrow\downarrow})\,\hbar}{2\alpha ETN}$$

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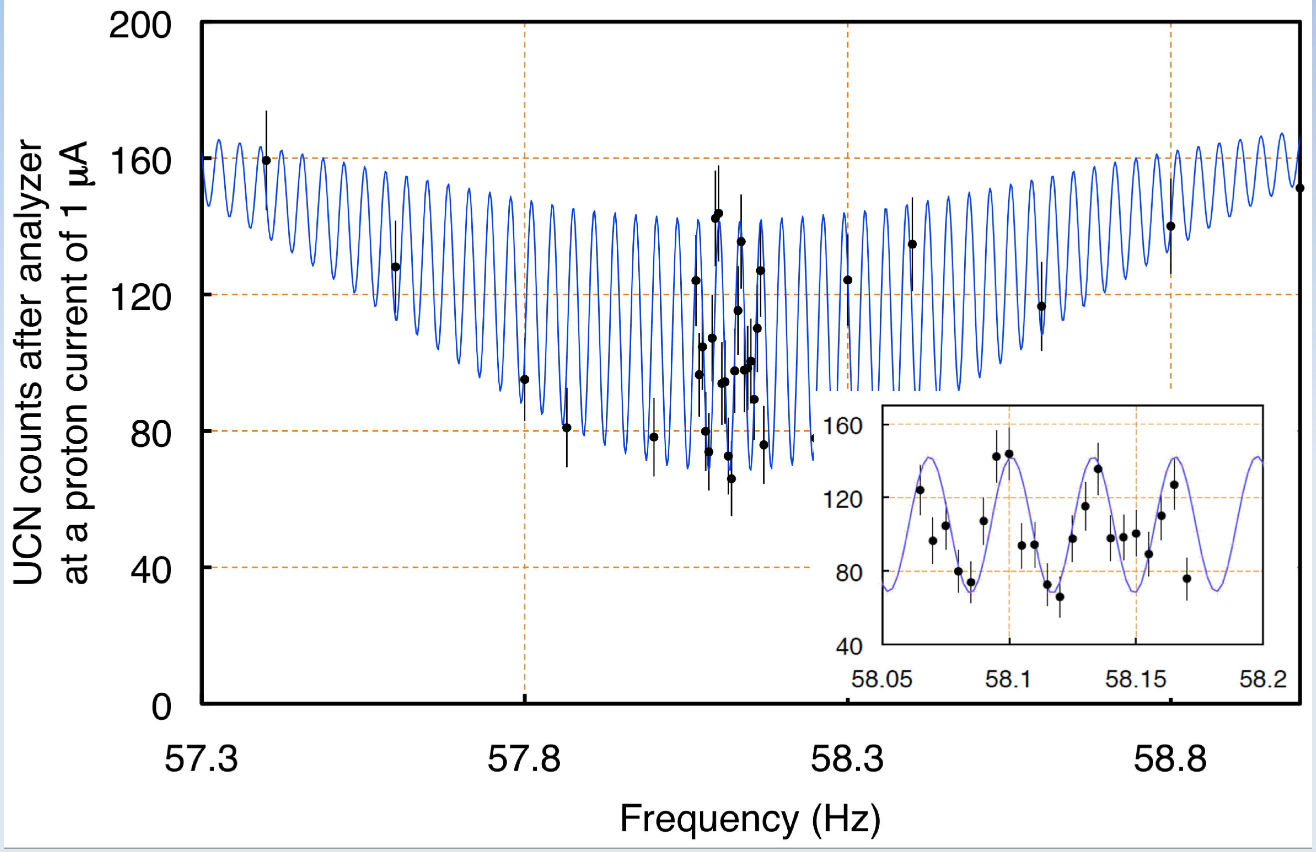
Ramsey Resonance Results



Dec. 2009, achieved:
T_2 ~ 300 ms

April 2010, achieved:
T_2 > 30 s

becoming competitive with ILL, where T_2 = 120 s (typ.)

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$ (stat)

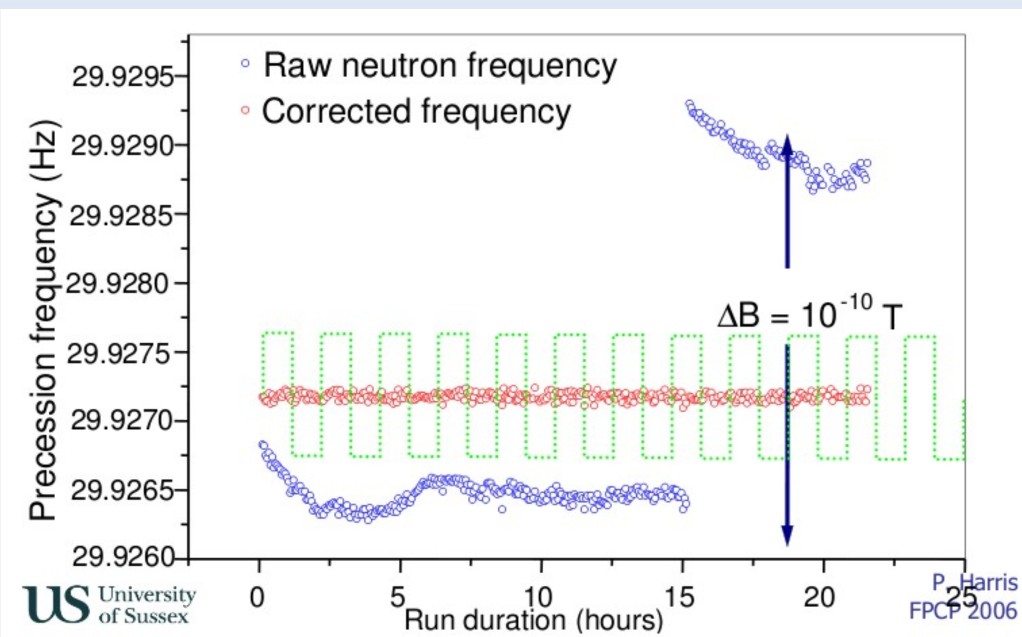
Nearing state-of-the-art in low-field NMR!

- Successful demonstration of technique behind precision EDM measurements.
- February, October 2011: B-field homogeneity and stability studies with UCN

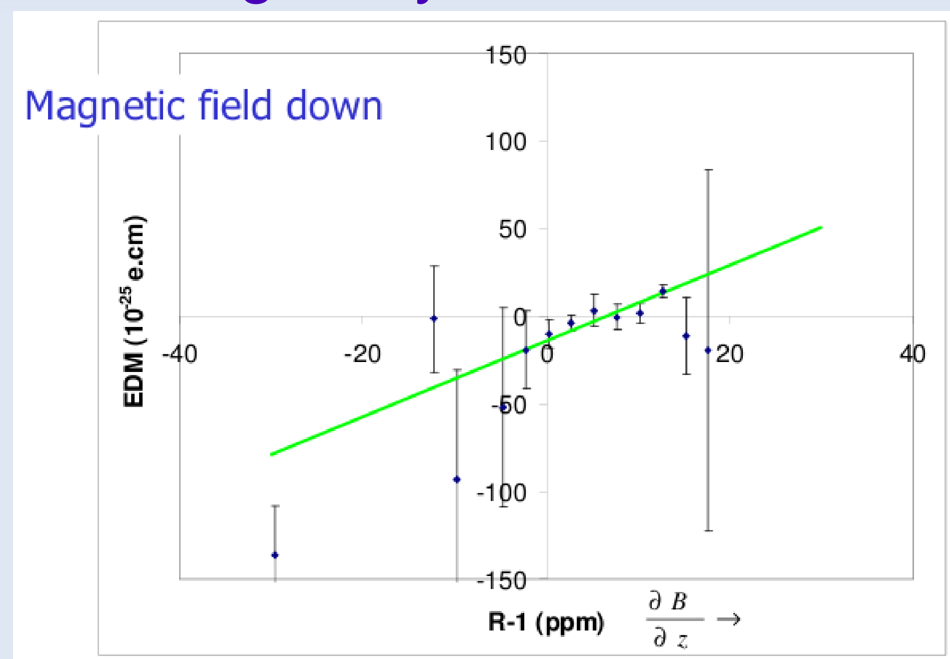
n-EDM Systematics

- magnetic field variations
- leakage currents
- geometric phase effect
  - false EDM arising from B-field inhomogeneity and E x v.

(co)magnetometry



comagnetometry



false EDM (GP) effect

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Xe-129 buffer-gas nuclear spin comagnetometer

- Masuda-san's idea: leak polarized Xe-129 into the EDM cell with the neutrons and watch spins precess.
- Xe-129 pressure must be large
  - Xe-Xe Collisions -> small MFP -> small GPE.
  - Ring-down signal picked up by SQUID.
- Xe-129 pressure must be small
  - Electrical breakdown at higher pressures.
  - UCN absorption by Xe-129.
- There is a range of pressures in mTorr range that seems to work!

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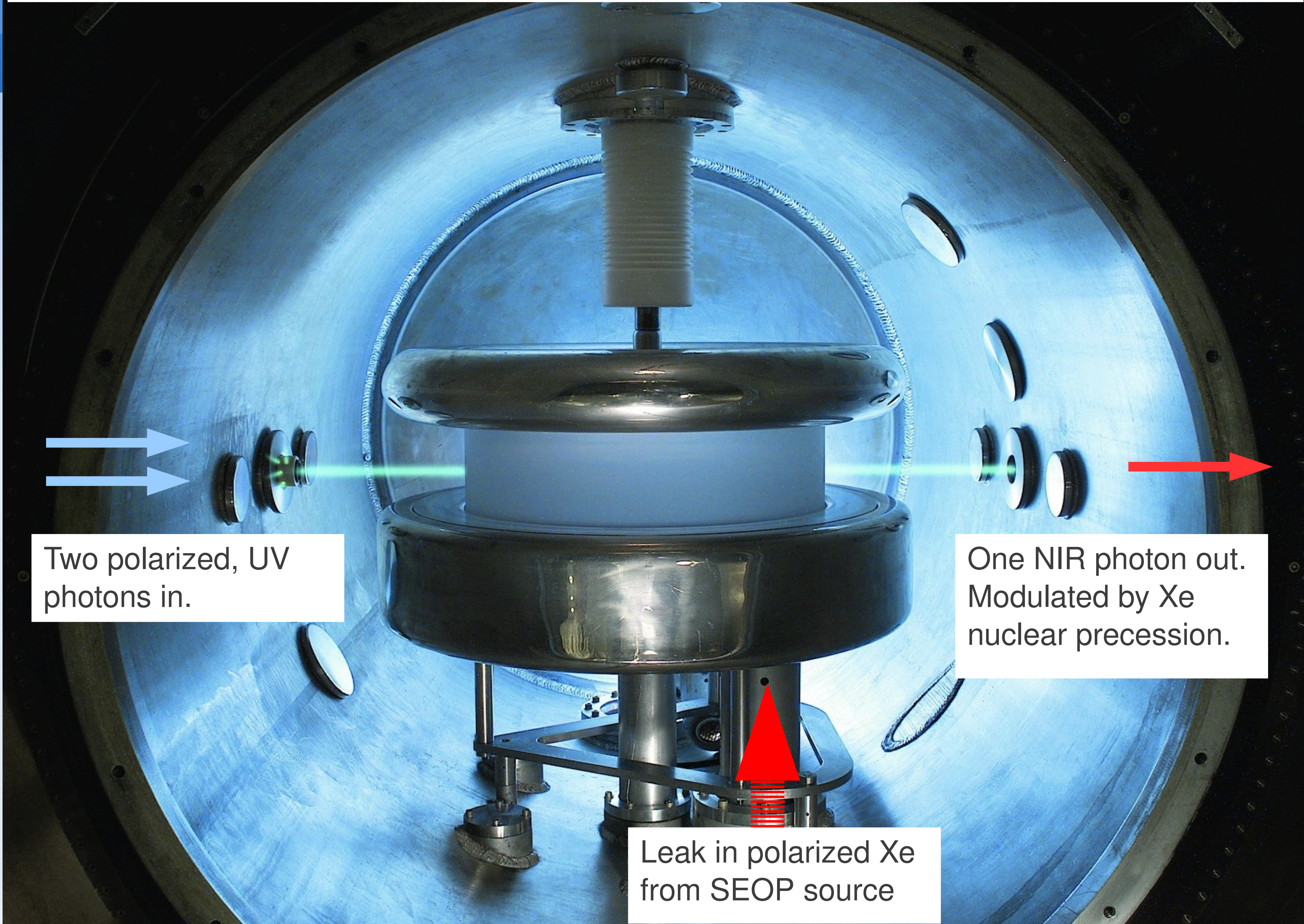
Similar to how the Sussex-RAL-ILL (PSI) EDM experiment uses their Hg-199 comagnetometer.



Schedule and Goals

Phase	Goals	Year
RCNP	T_2 to 130 s, HV	2011
	New source, improved UCN density	2011-12
	Horizontal EDM experiment, improvement of UCN density in EDM cell to 900 UCN/cm^3, SC polarizer, precision Xe comagnetometry	2012-13
	In 20 days production running, $d_n < 1 \times 10^{-26}$ e-cm	2013-14
TRIUMF	Commissioning and first experiment with same setup.	2015-16
	Further improvements to magnetic shielding, (co)magnetometry, EDM cell, detectors, $d_n < 1 \times 10^{-27}$ e-cm	2016-17
	Improvements to cold moderator, magnetic shielding, beam current, targetry, remote handling, cryogenics, (co)magnetometry, $d_n < 1 \times 10^{-28}$ e-cm	2018-

Complementarity

Project	H_0 field	magnetometer	EDM cell	magnetic shielding
KEK / RCNP / TRIUMF	***spherical coil***	***^{129}Xe buffer gas co-magnetometer***	***small*** **T = 300 K**	***finemet/ superconductor***
Sussex / RAL / ILL	solenoid	n at E = 0 magnetometer	large T ~ 0.5 K	μ metal superconductor
SNS	cosθ coil	^{3}He co-magnetometer	large T ~ 0.5 K	μ metal superconductor
PSI	cosθ coil	Cs multi-Magnetometer Hg-199	large T = 300 K	μ metal

UCN sources are *totally* different.

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UCN Summary

- Neutron EDM experiments are being prepared, ultimately to improve precision to the 10^{-28} e-cm level.
- UCN sources are popping up all over the world, with vibrant fundamental physics programs: Neutron lifetime, Neutron Gravity levels experiment, Neutron beta-decay, $n\bar{n}$ oscillation search, neutron-ion interactions.
- UCN can also be used for material studies (not covered in today's talk)

Acknowlegements: Special thanks to J. Martin, and L. Lee from whom I have borrowed many of these slides.

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Fin.

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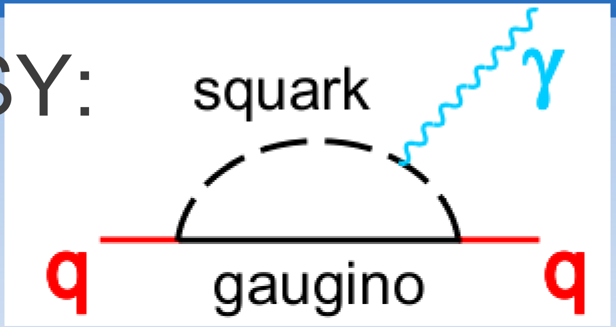
UCN Facilities

- Reactor sources:
  - ILL, Mainz, Munich, NCSU, PNPI
- Spallation sources:
  - LANL, KEK-RCNP-TRIUMF, PSI, J-PARC
- And dedicated UCN experiments installed in Cold Neutron beamlines:
  - ILL, NIST, SNS

EDM's and Supersymmetry (SUSY)

- Scale of EDM's for quarks in SUSY:



from P. Harris, Sussex

$$d_q \sim \frac{\alpha}{\pi} \times \frac{m_q}{\Lambda_{SUSY}^2} \times \sin\theta_{CP}$$

- For “reasonable” values of new parameters:

$$d_q \sim 3 \times 10^{-24}\, e \cdot cm$$

- According to neutron EDM measurements:

$$d_u < 2 \times 10^{-25}\, e \cdot cm \qquad d_d < 5 \times 10^{-26}\, e \cdot cm$$

- Unattractive solution (“SUSY CP problem”):
  - Λ_{SUSY} > 2 TeV and/or θ_{CP} < 0.01

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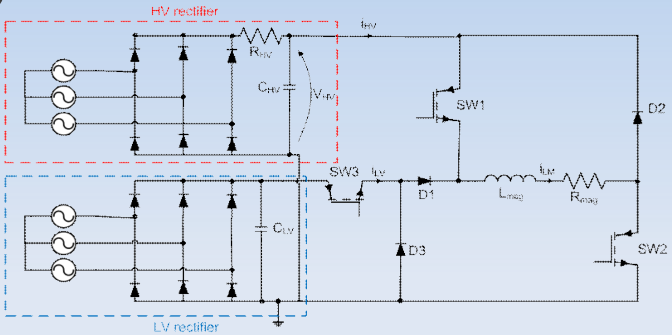
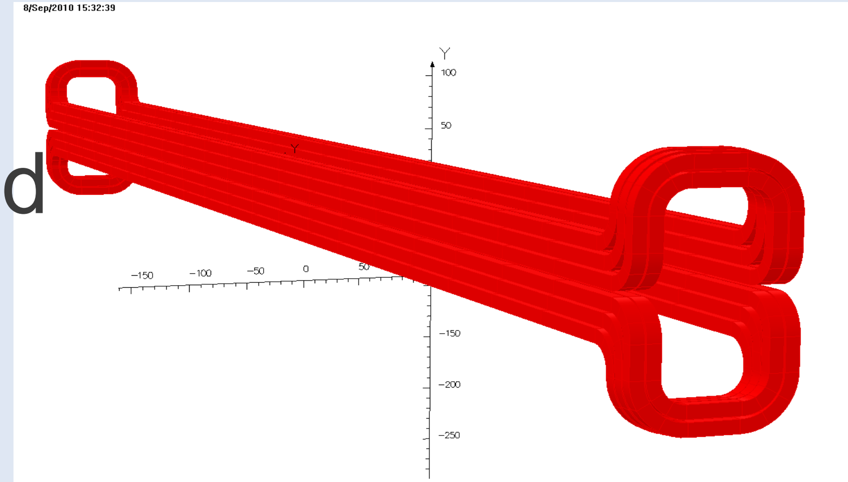
Kicker

- Redirect "1A" beam into UCN line on kHz timescale using existing TRIUMF beam structure.
- TRIUMF/CERN design
  - HV SS switches
  - Fast dipole magnet
- Magnet coil design completed summer 2011.





M. Barnes, M. Hahn

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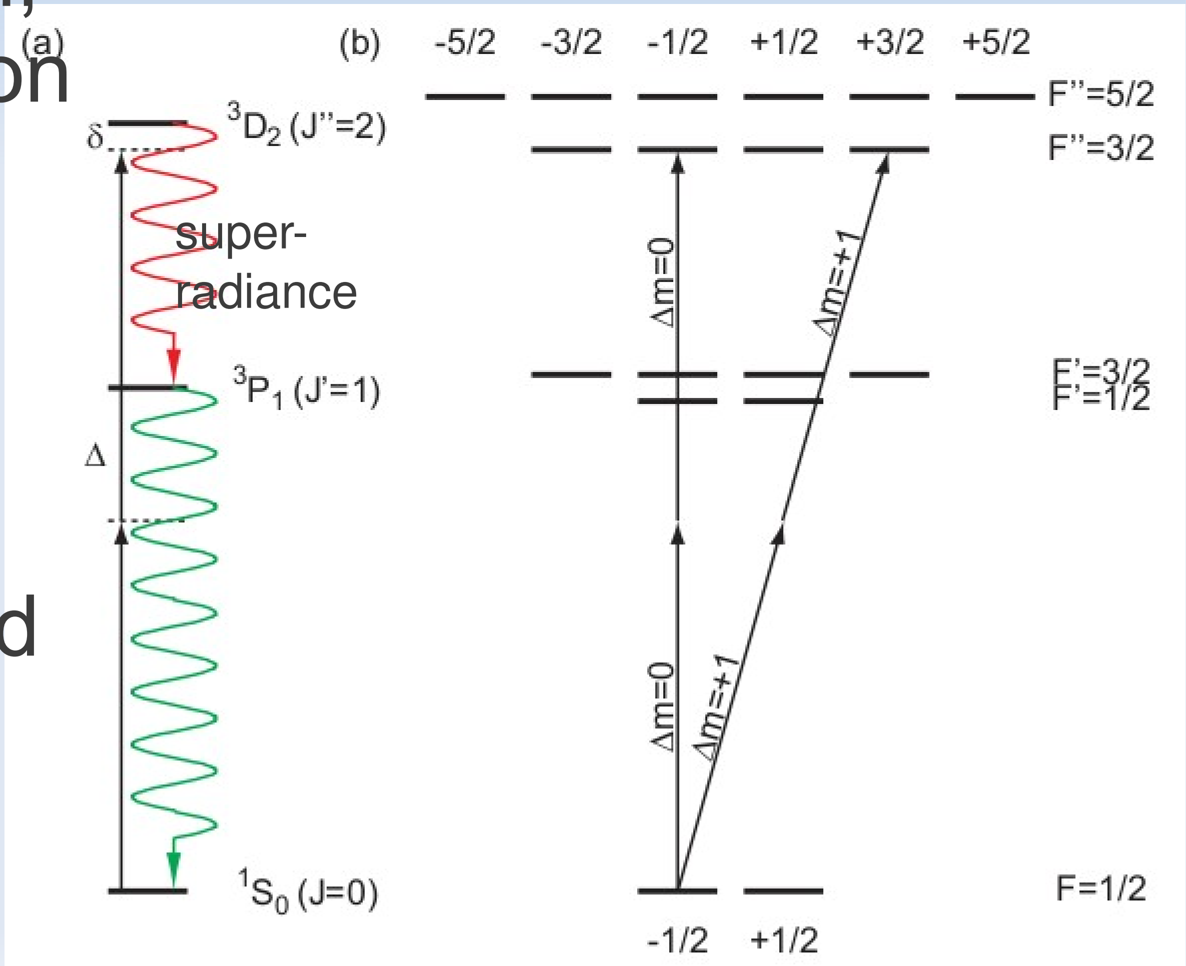
New ideas: Optical readout of Xe-129 spins

- Polarized two-photon transition Δm=2 selection rule occurs for nuclear spin aligned (T. Chupp)
- Chupp: absorption, or index of refraction
- New idea: use superradiance (T. Momose)
- Level structure being characterized @UBC



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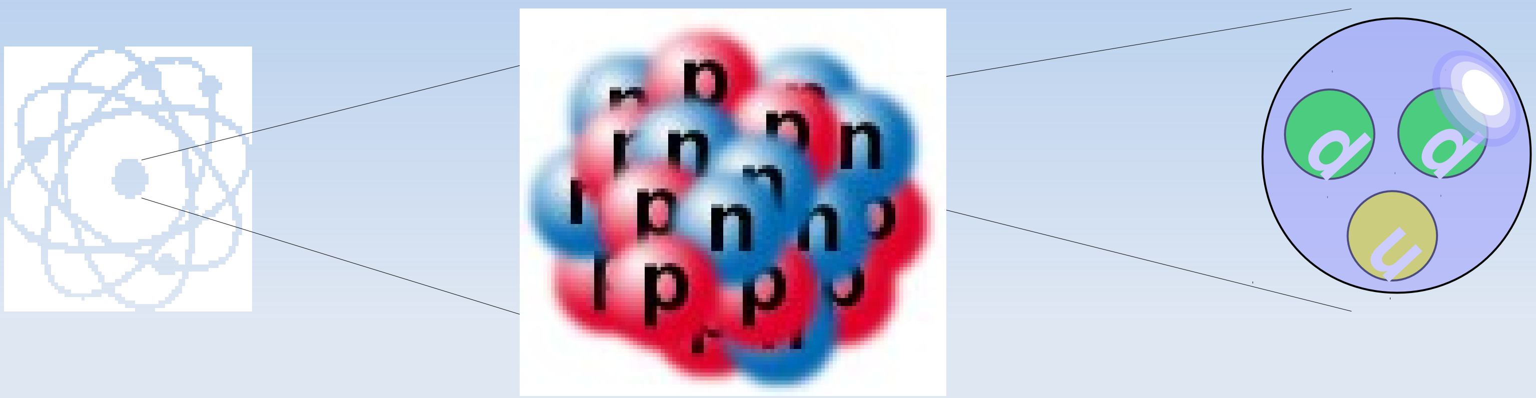
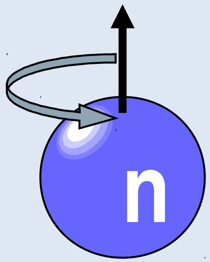
What are Neutrons?

The atomic nucleus is made of protons & neutrons



- The neutron:
  - has no charge
  - contains quarks
  - carries spin and has a magnetic moment



Think of a spinning top

Think of a bar magnet

- Free neutrons decay ($\tau = 885.7 \pm 0.8$ s)
  - Neutron in nucleus is stable

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Why are Neutrons Important?

- They keep the nucleus together (without them, only H)
- Free neutrons were one of the first things present in the early universe. Their decay half-life is intimately related to the amount of (D, He, Li) in the universe.
- Important in many reactions going on in our sun (nuclear fusion), and in nuclear reactors (nuclear fission).
- We're made of them
- Neutrons are used to:
  - Study many Fundamental Physics questions
  - Probe the structure of materials

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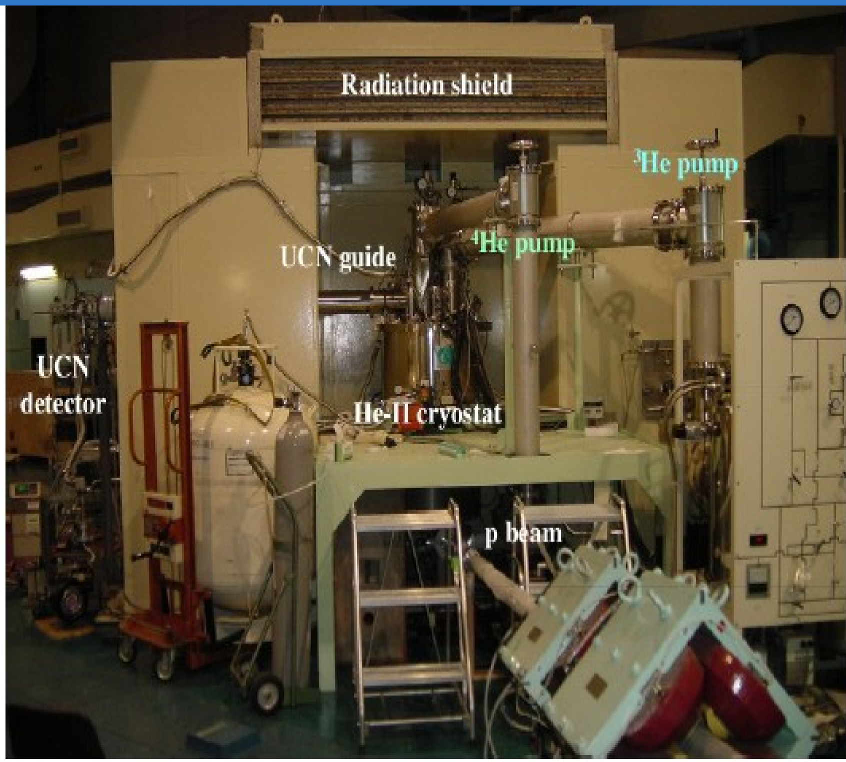
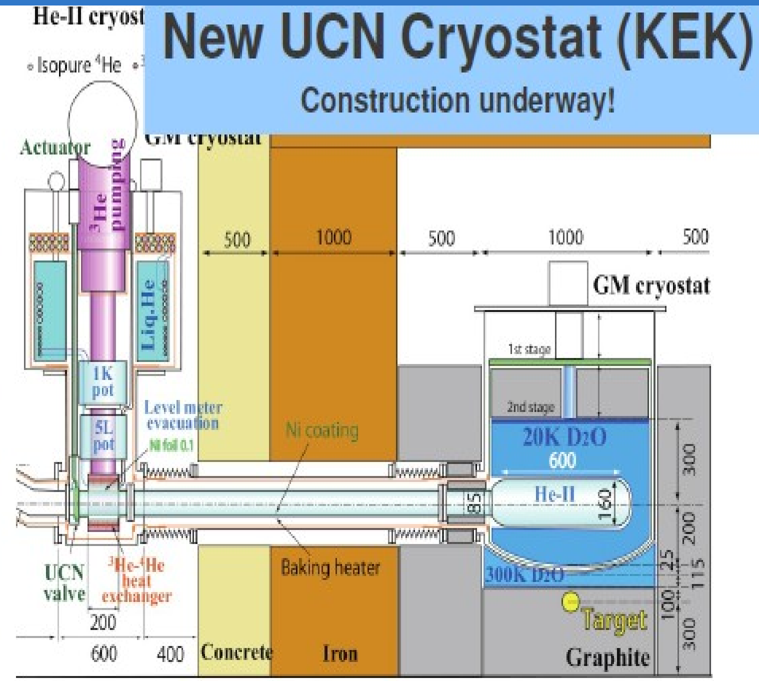
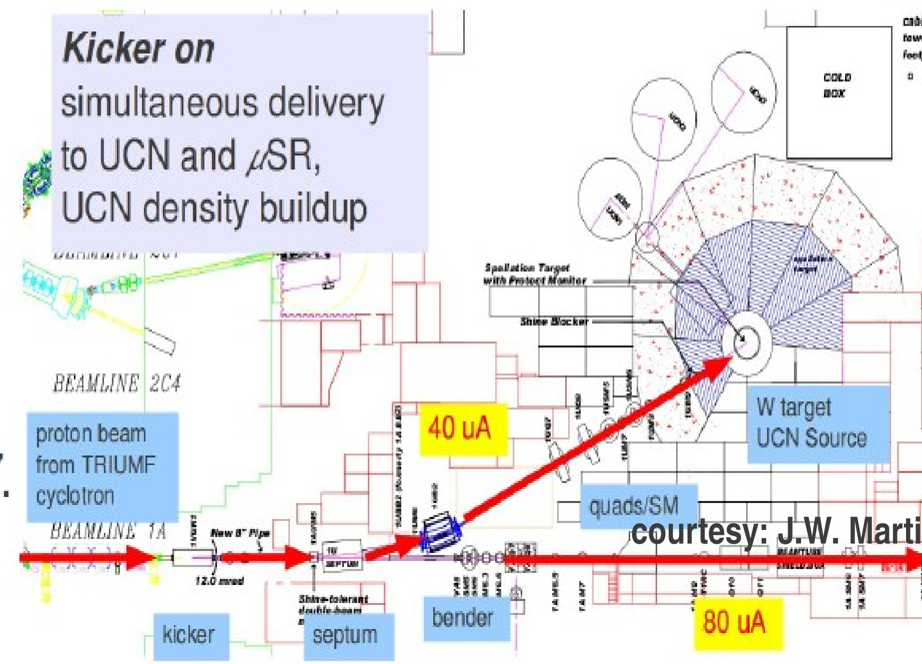
Basic Timeline for TRIUMF n-EDM







RCNP Phase (-2014)

- Goal $d_n < 1 \times 10^{-26}$ e-cm

TRIUMF Phase (2015-)

- Goal $d_n < 1 \times 10^{-27}$ e-cm by 2017.
- Improve to $d_n < 1 \times 10^{-28}$ e-cm.

Physics Experiments with UCN

- neutron electric dipole moment
- neutron lifetime
- gravitational levels of UCN confined above a mirror
- beta-asymmetry measurements
- $n\bar{n}$-oscillations
- free n target

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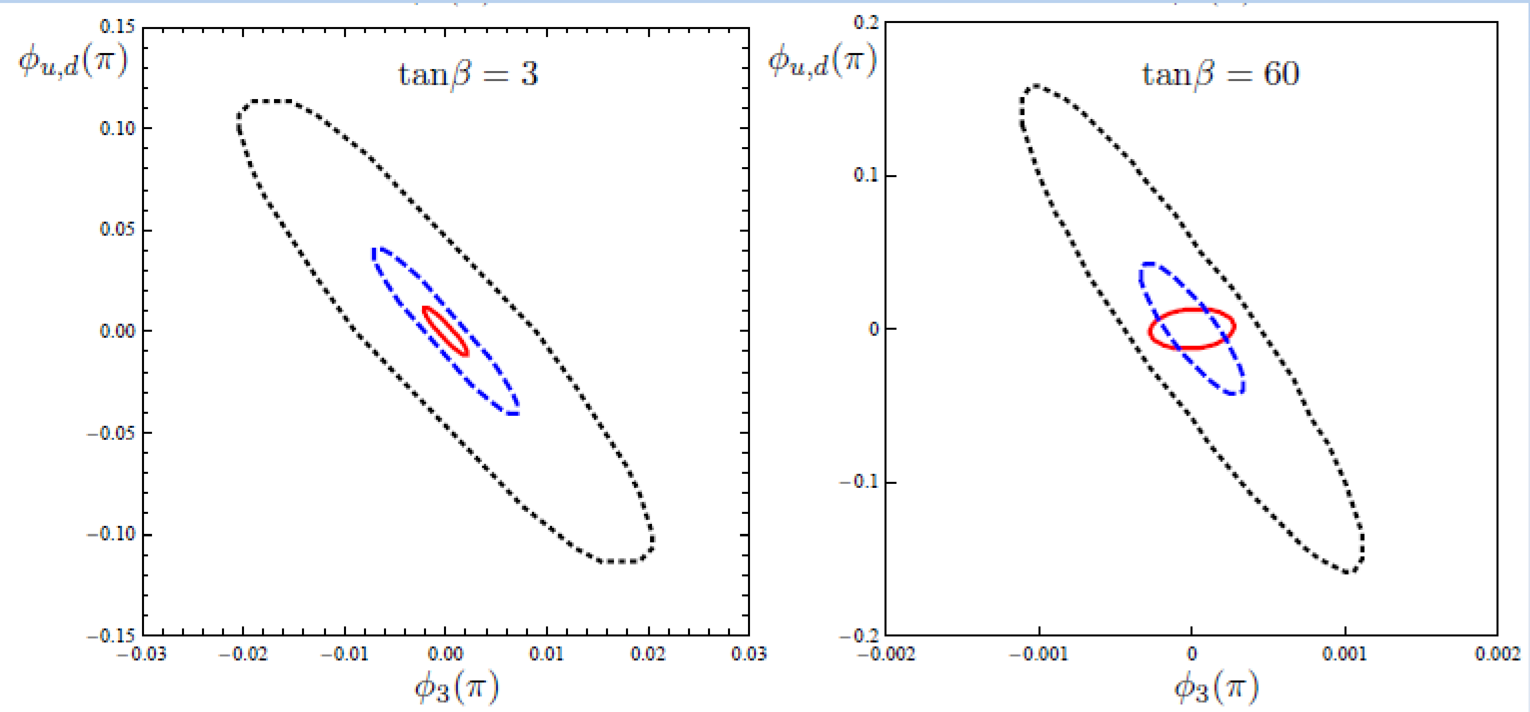
Other Technical Progress at TRIUMF

- Target and Remote Handling
  - Target workshop with PSI experts at TRIUMF (Aug. 2011).
  - RCNP / TRIUMF / Acsion collaboration.
- Radiation Shielding conceptual design, cost
- Cryo Plant design specifications
- Project Management, Cost, Schedule, Human resources, Gantt charts, MOU's, etc.

Testing Universality in MSSM

Li, Profumo, Ramsey-Musolf JHEP 1008, 062 (2010)



- Open up to full MSSM parameter space.
- Scan parameters obeying neutron, Tl, Hg limits.

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