Ultracold Neutron Sources and Experiments

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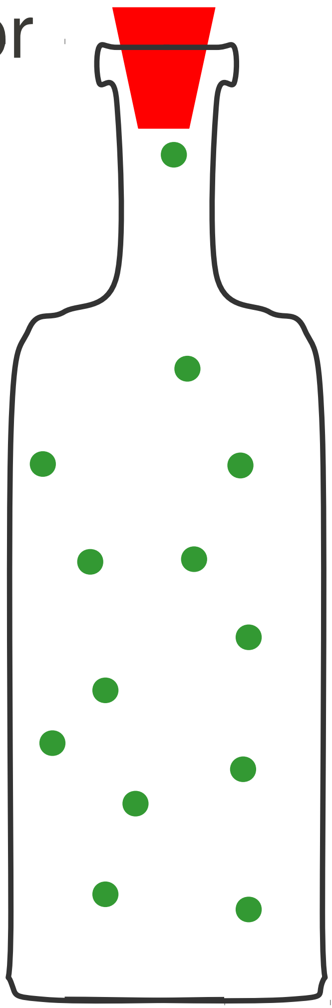
Ultracold Neutrons (UCN)

- 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

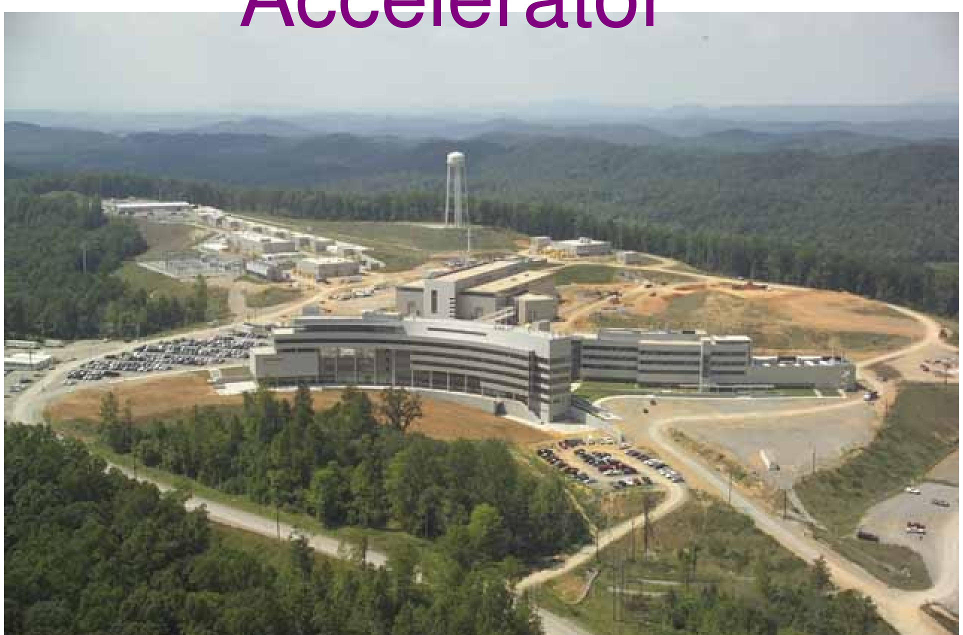


How to make lots of neutrons: Liberate them from nuclei!

1) In a nuclear reactor (fission).

2) At an accelerator (spallation).

Accelerator



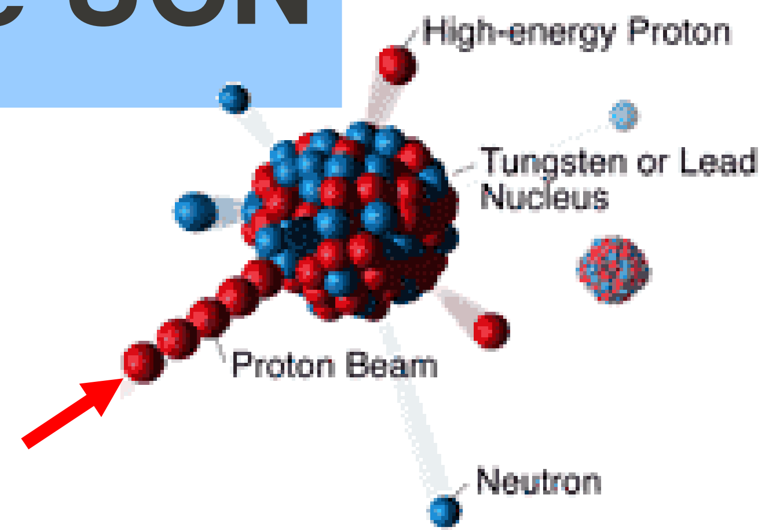
Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

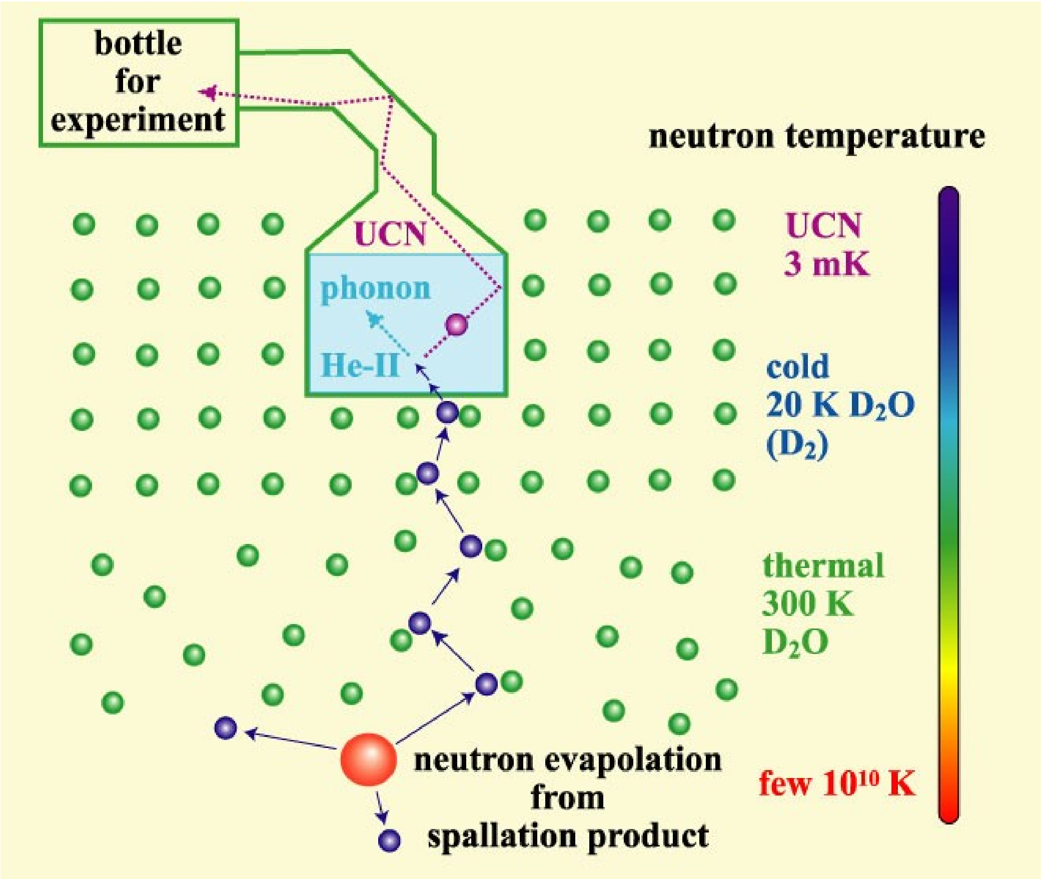
Reactor

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

New methods to make UCN

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

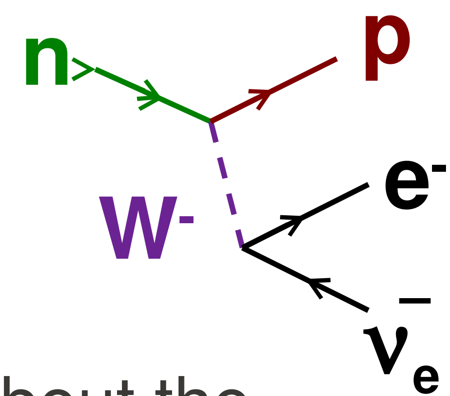




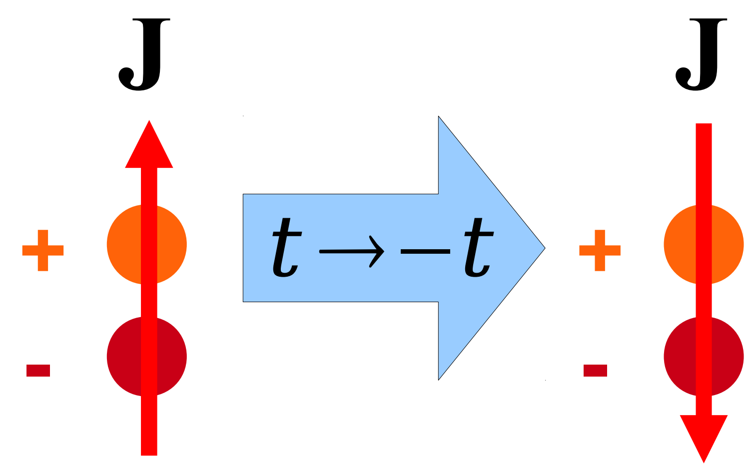
UCN Facilities

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

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.

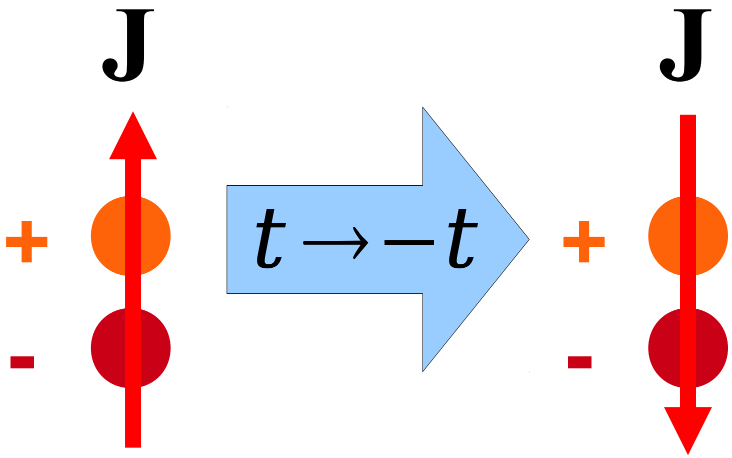


- Interactions of neutrons with gravity and are there extra dimensions?

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

Neutron Electric Dipole Moment (n-EDM, d_n)



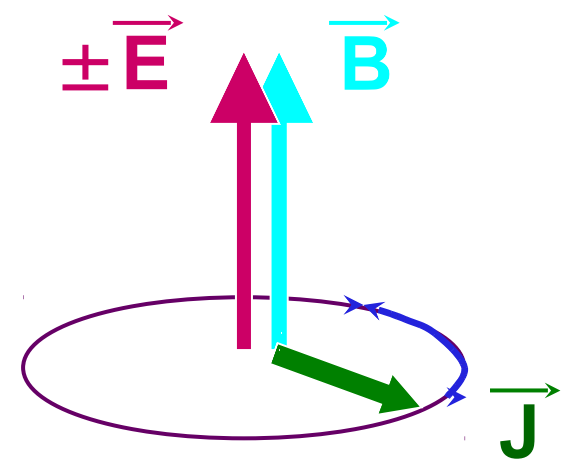
$$d_n \Rightarrow \not{T} \Rightarrow \not{CP}$$

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 (the Larmor frequency) upon *E* reversal.

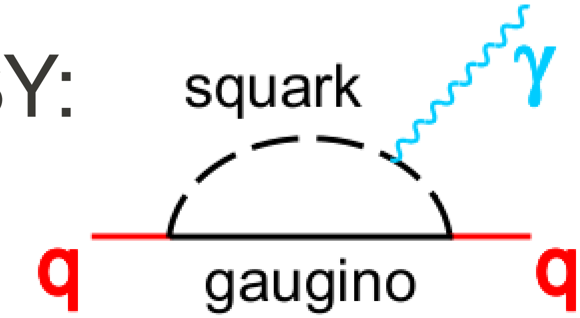


$$h\nu = 2\mu_n B \pm 2\mathrm{d}_e E$$

EDM's and Supersymmetry (SUSY)

- Scale of EDM's for quarks in SUSY:

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



from P. Harris, Sussex

- For “reasonable” values of new parameters:

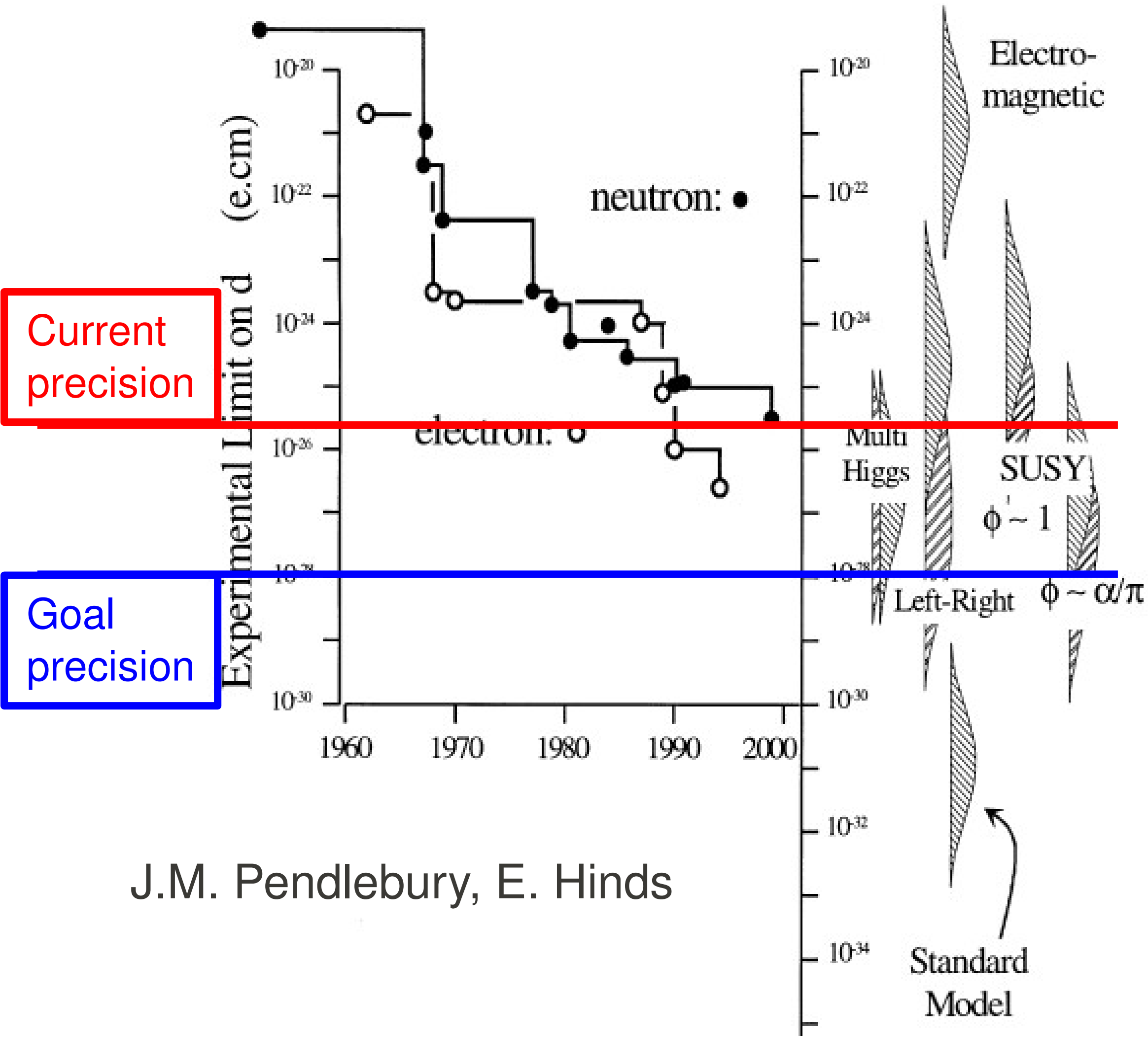
$$d_q \sim 3 \times 10^{-24} e \cdot cm$$

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

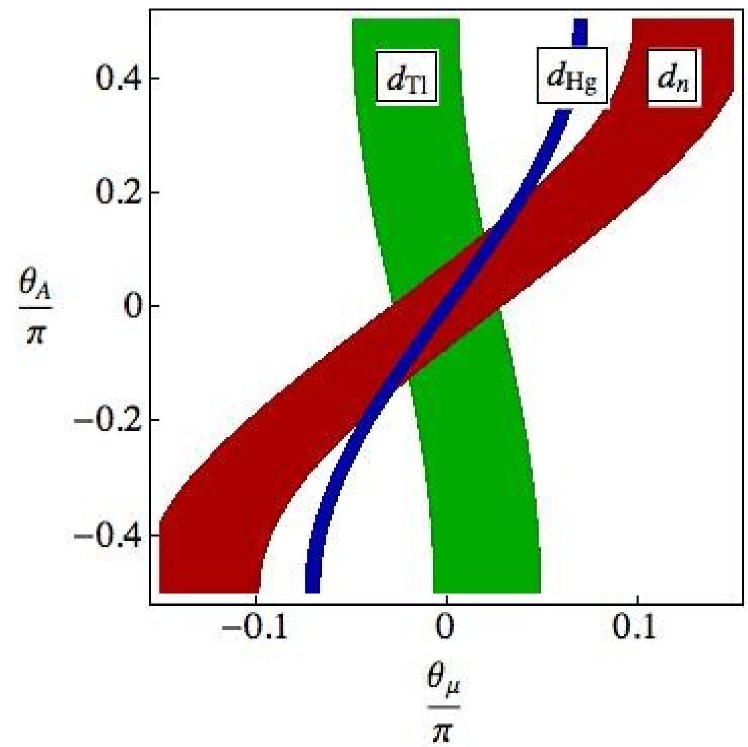
EDMs, the SM, and beyond



J.M. Pendlebury, E. Hinds

A. Ritz, M. Pospelov, et al

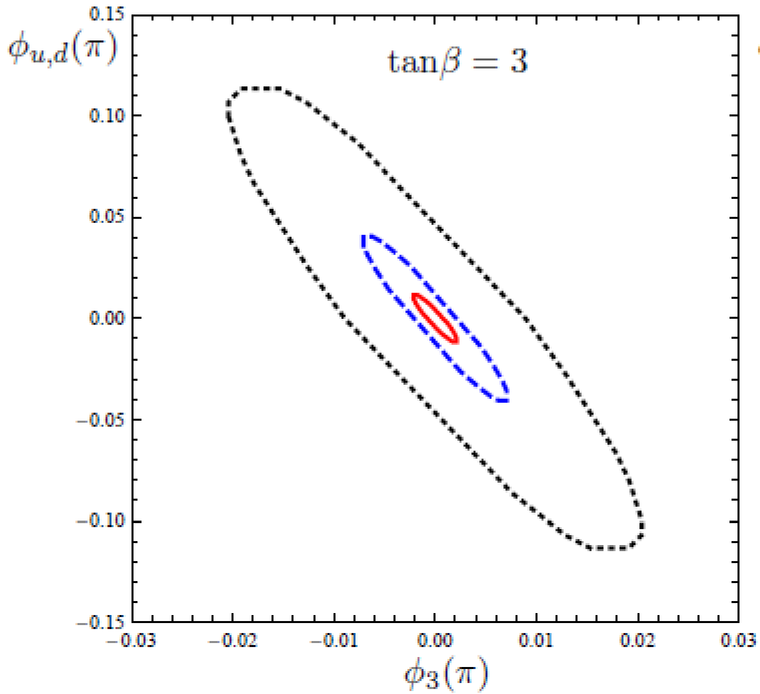
SUSY M = 1 TeV, tanβ = 3

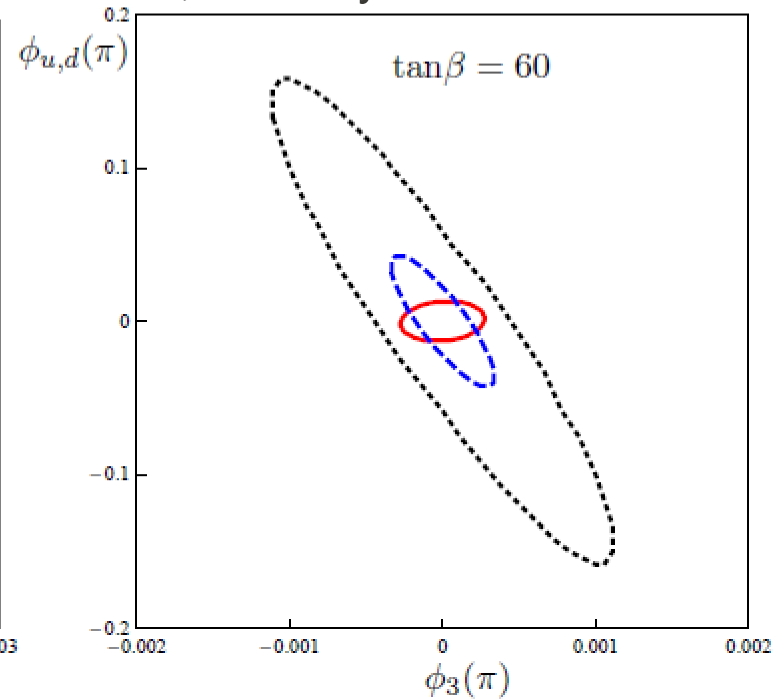


- “n-EDM has killed more theories than any other single experiment!”
- “More money has been spent testing theories inspired by the n-EDM than on n-EDM experiments themselves!” (referring to searches for dark matter axions)

Testing Universality in MSSM

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

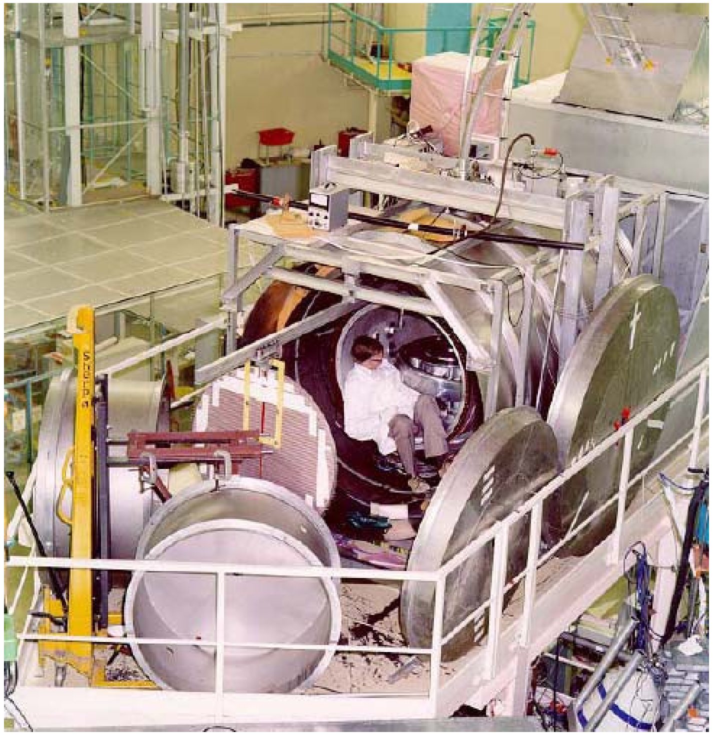




- Open up to full MSSM parameter space.
- Scan parameters obeying neutron, Tl, Hg limits.

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

The CryoEDM Experiment

RAL
- Neutron production
- Neutron detection
- Cryogenics

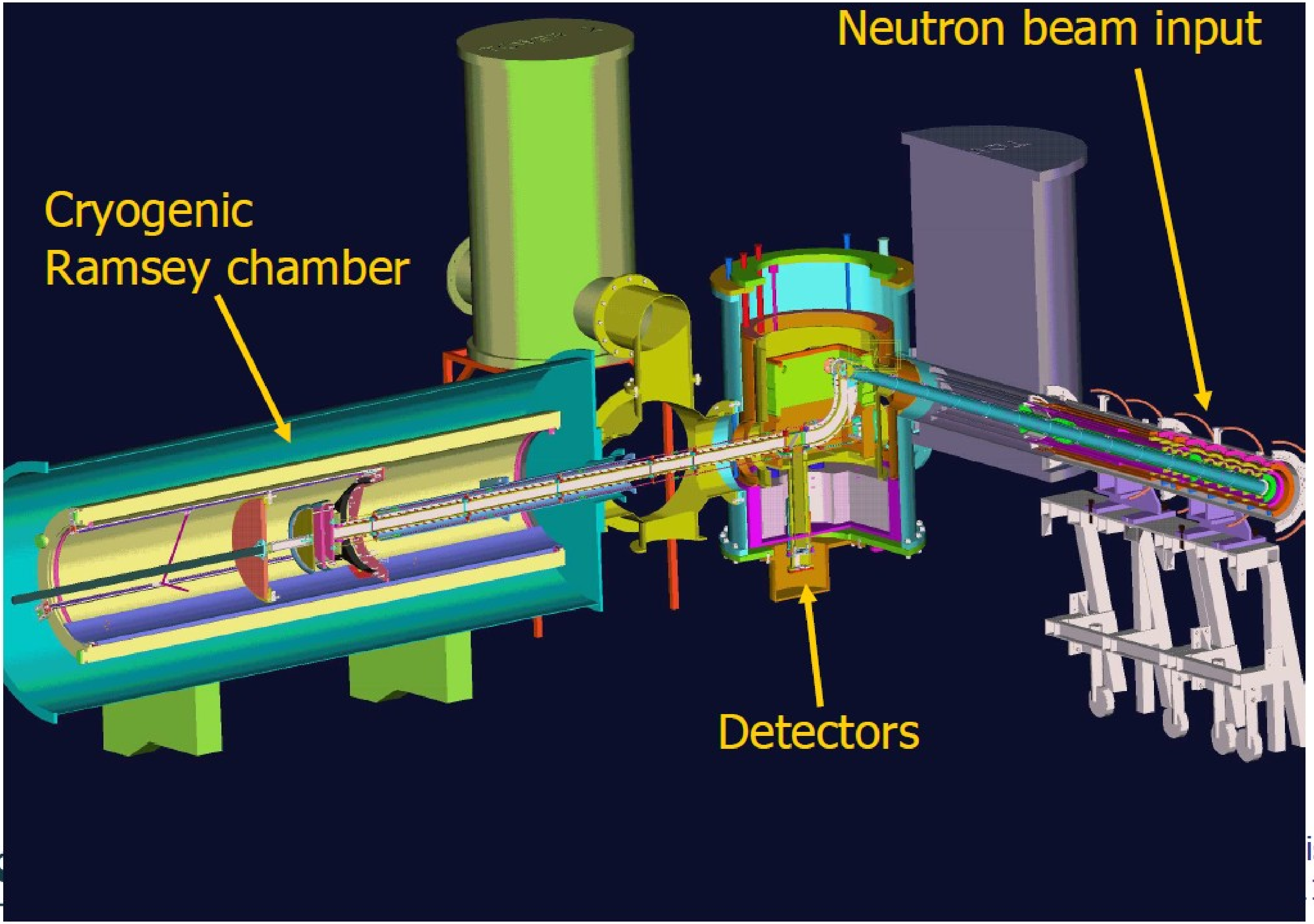
Sussex
- HV, inc. in liquid He
- Cryogenics
- DAQ
- B-field control
- Simulations, modelling & calculations
- Analysis

Oxford
- SQUID magnetometry

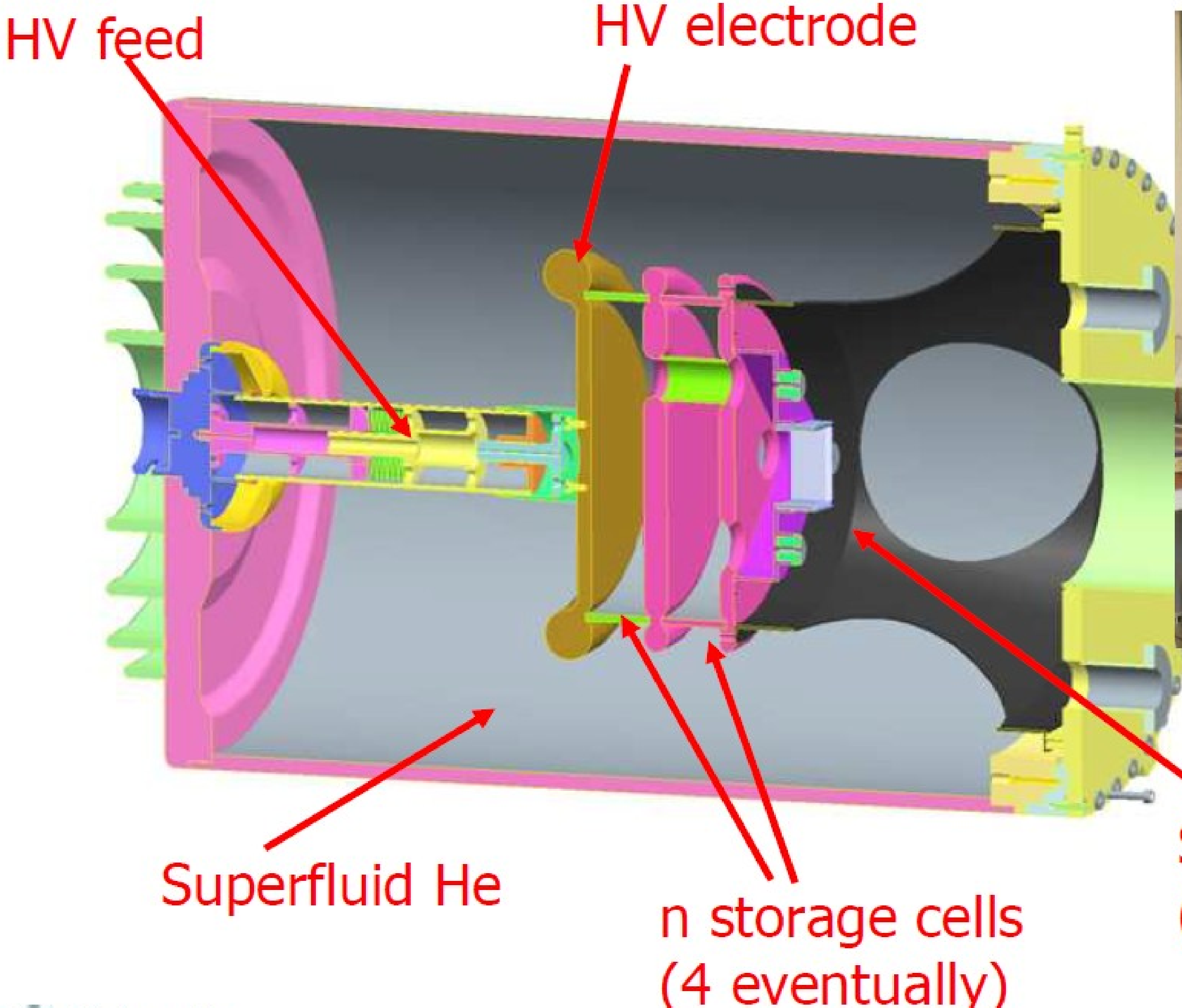
ILL
- Reactor neutrons

Kure
- Cryogenic equipment

CryoEDM overview



Cryogenic Ramsey chamber

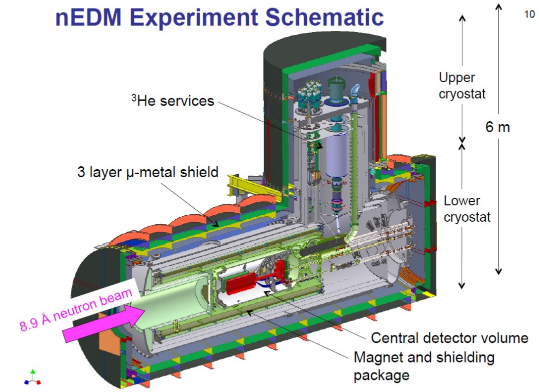


CryoEDM

Status:
- Successfully produced, transported, stored neutrons, but need to reduce losses
- Successfully applied 10 kV/cm HV; aiming for 20-30 kV/cm
- Polarisation observed, but must improve
- Detector efficiency set to improve significantly
- Magnetic field stability can improve factor 1000 – we know how to do this

Challenges remain, but we are on the way.

nEDM Experiment Schematic



The nEDM Collaboration

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The University of Virginia

S. Lamoreaux, D. McKinsey, A. Sushkov

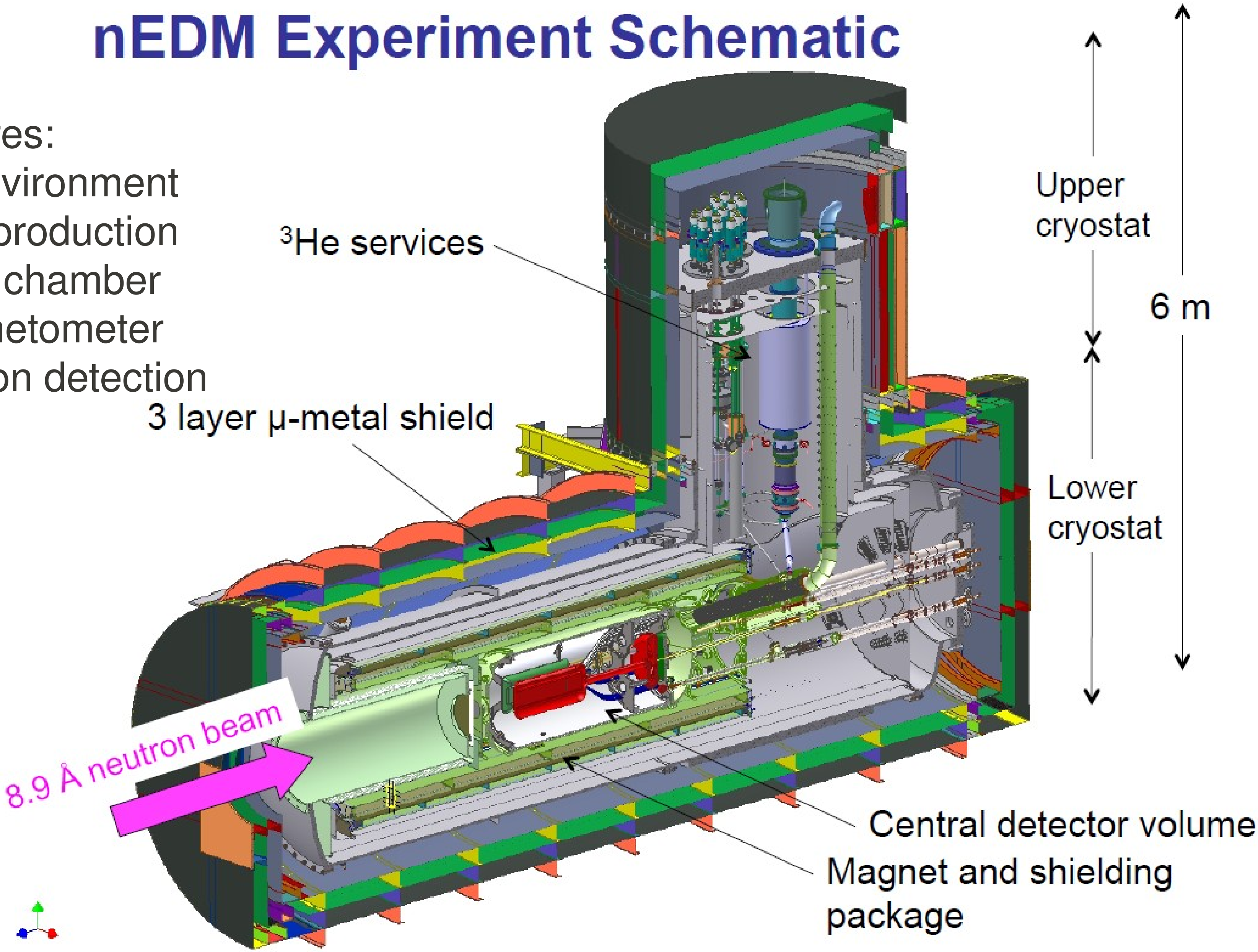
Yale University

courtesy: T. Ito

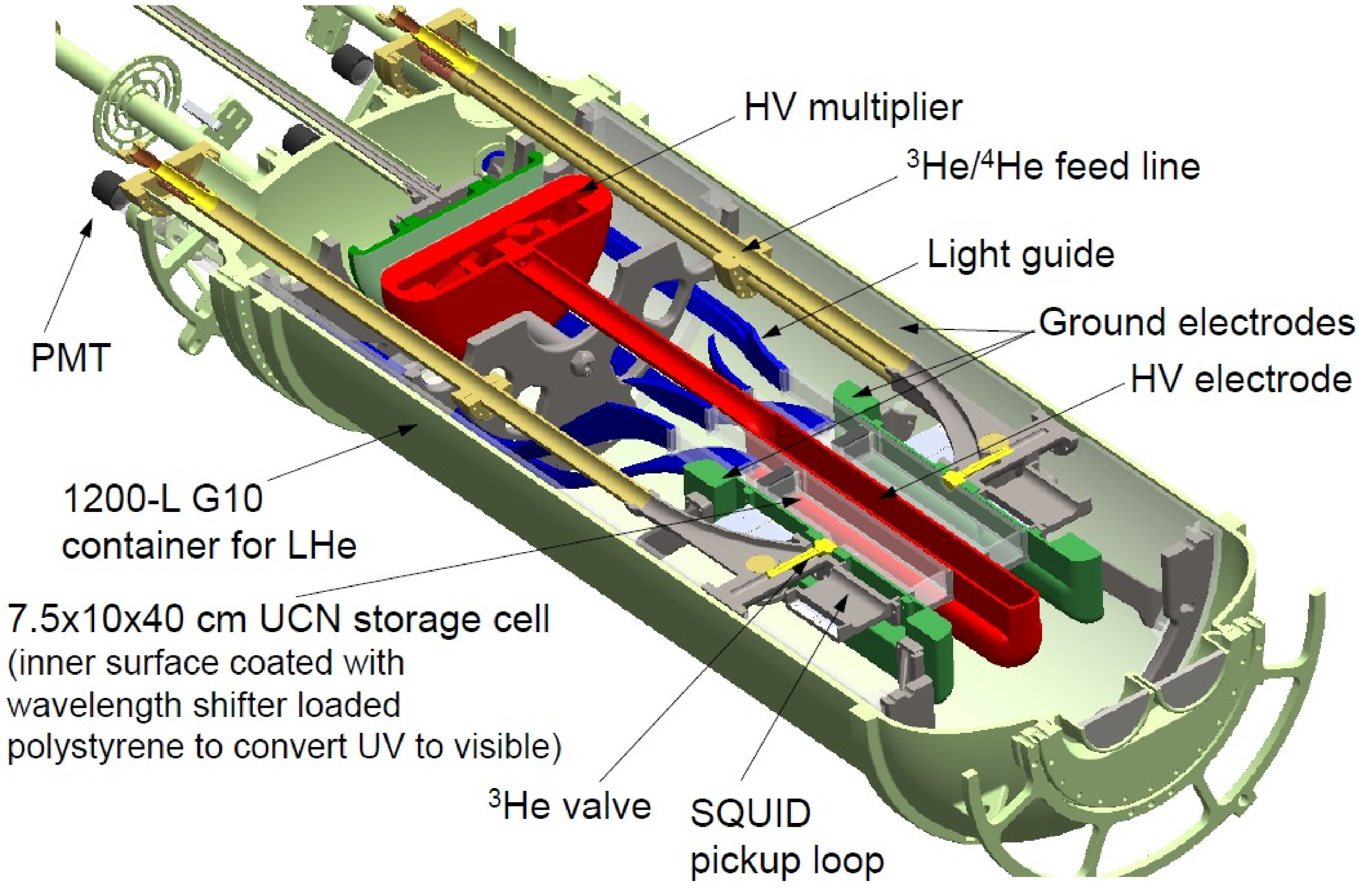
nEDM Experiment Schematic

special features:

- cryogenic environment
- in-situ UCN production
- double UCN chamber
- ^{3}He co-magnetometer
- He scintillation detection



Central Detector System



Projected sensitivity

- Projected statistical sensitivity (limited by the neutron density in the storage cells):

  90% CL $\sigma_d < 8 \times 10^{-28}$ e-cm in 300 live-days

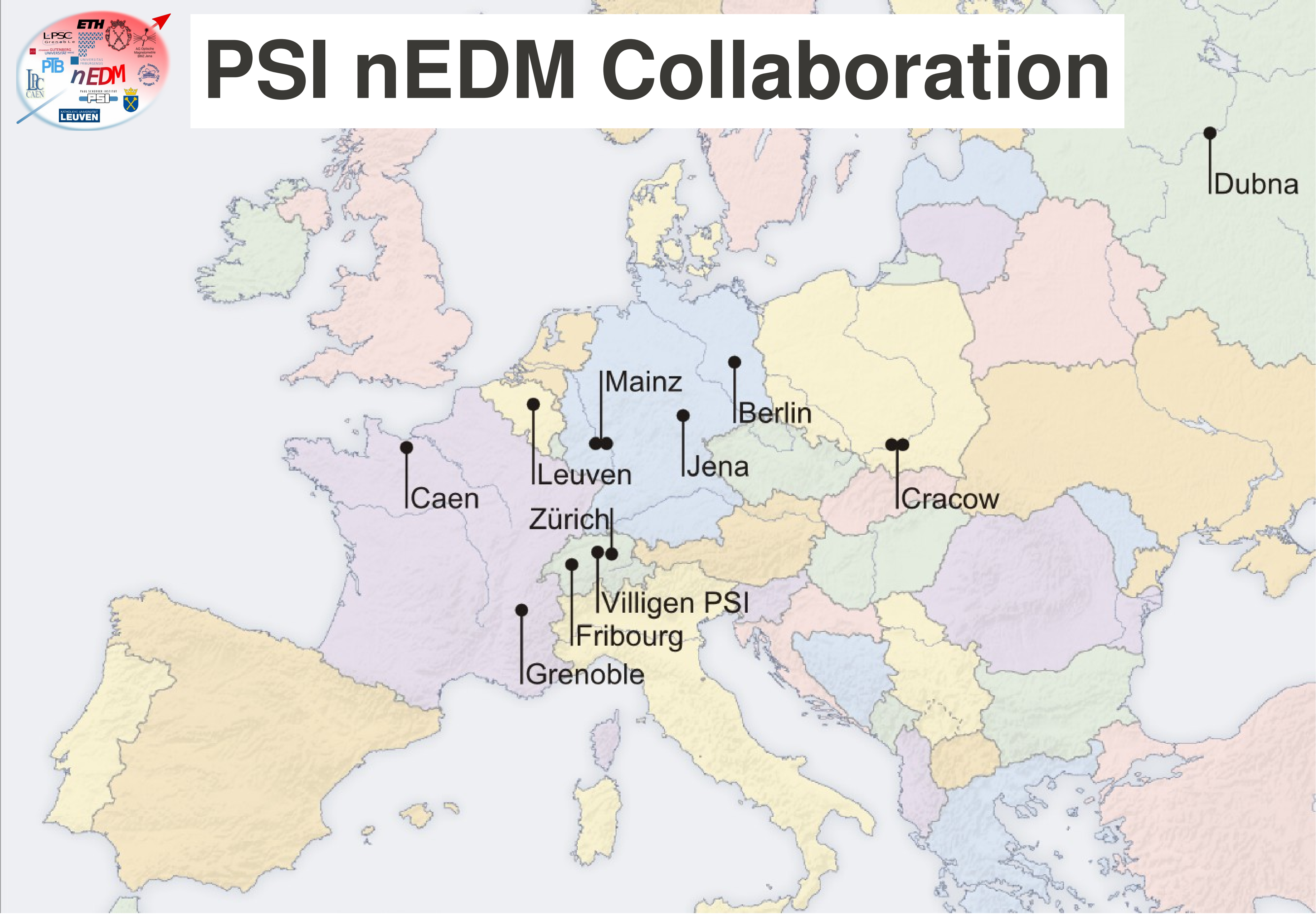
update: 3×10^{-28} e cm by using the FNPB and dressed spins

- Expected systematic effects:

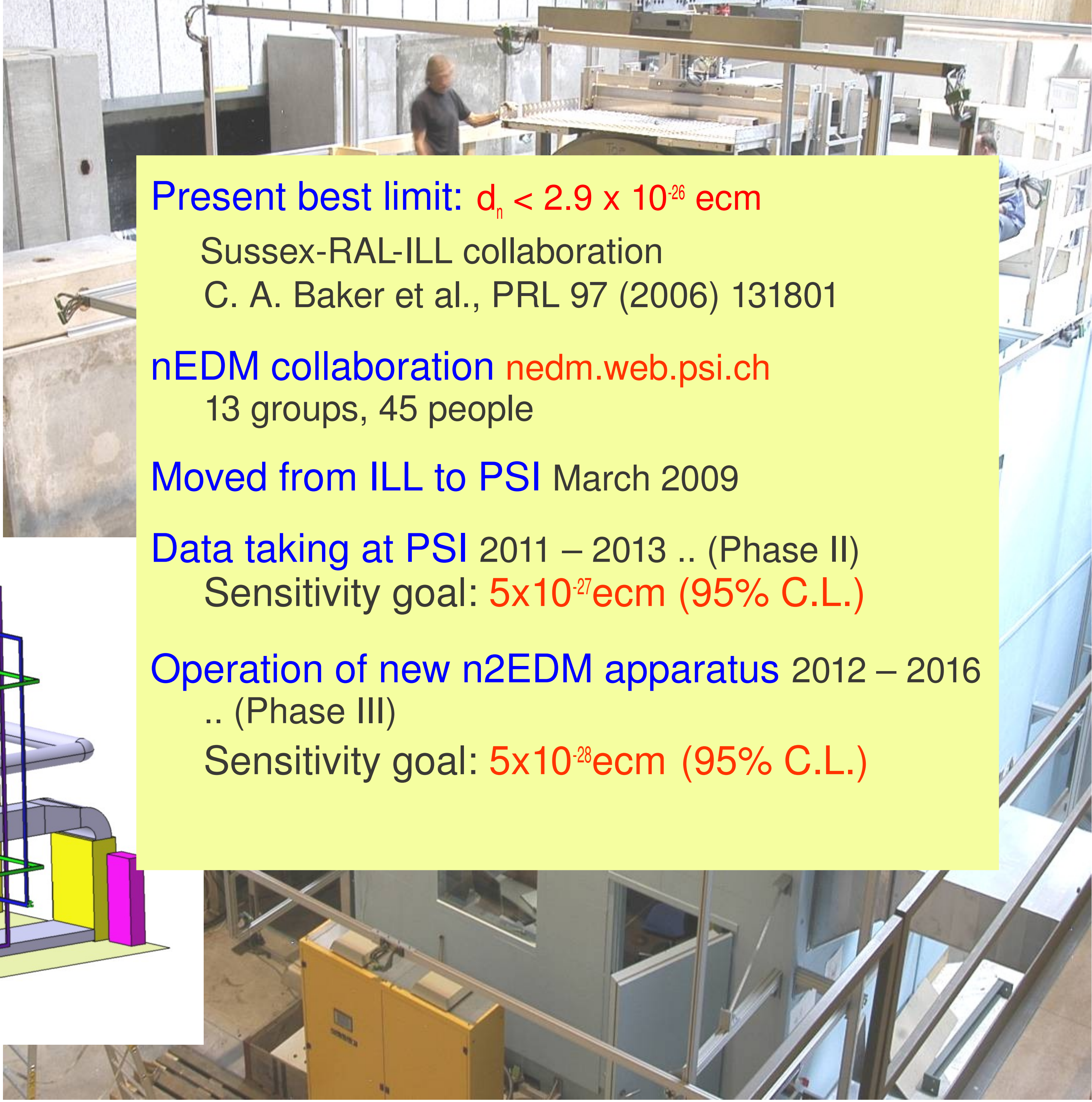
Source	δd_n (e cm)	Comments
Linear v×E (geometric phase effect)	$< 2 \times 10^{-28}$	Uniformity of B_0
Quadratic v×E	$< 0.5 \times 10^{-28}$	E-field reversal to 1%
Pseudomagnetic field effects	$< 1 \times 10^{-28}$	$\pi/2$ pulse, comparing two cells
Gravitational offsets	$< 0.1 \times 10^{-28}$	With 1 nA leakage currents
Leakage currents	$< 1 \times 10^{-28}$	< 1 nA
Miscellaneous	$< 1 \times 10^{-28}$	

  – Various means by which to tackle potential systematic effects: ^{3}He comagnetometer, dressed spin method, and characterization of geometric phase effect by variation of the temperature.

PSI nEDM Collaboration



Thank you, Klaus Kirch



Present best limit: $d_n < 2.9 \times 10^{-26}$ ecm

Sussex-RAL-ILL collaboration

C. A. Baker et al., PRL 97 (2006) 131801

nEDM collaboration nedm.web.psi.ch

13 groups, 45 people

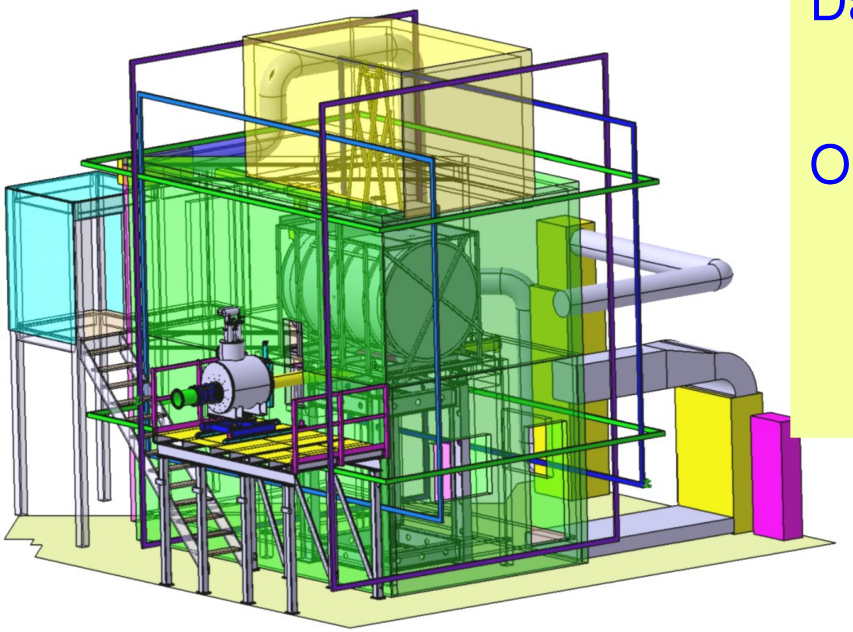
Moved from ILL to PSI March 2009

Data taking at PSI 2011 – 2013 .. (Phase II)

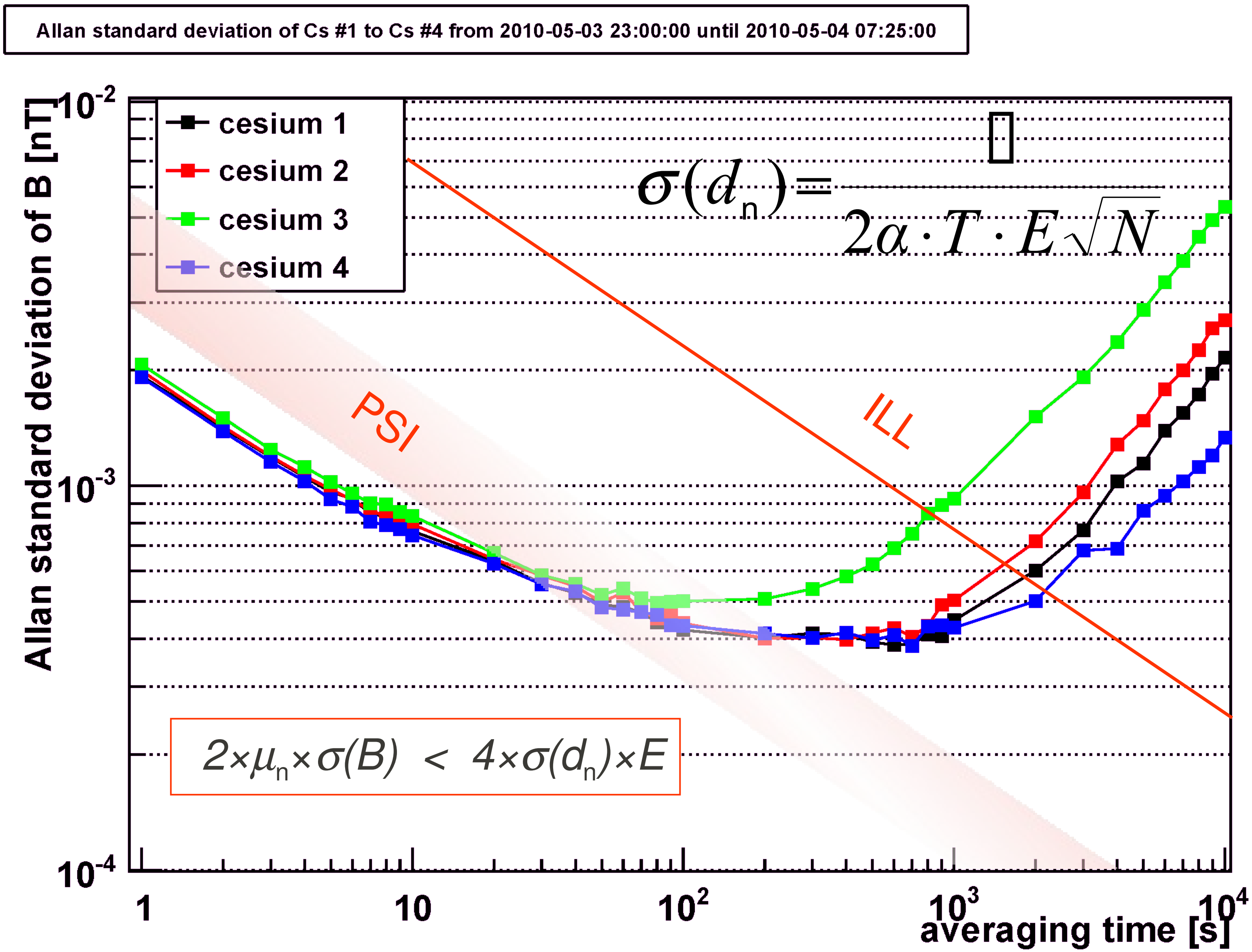
Sensitivity goal: 5×10^{-27}ecm (95% C.L.)

Operation of new n2EDM apparatus 2012 – 2016 .. (Phase III)

Sensitivity goal: 5×10^{-28}ecm (95% C.L.)



Magnetic field stability



Stability:

- Active compensation
- Night runs

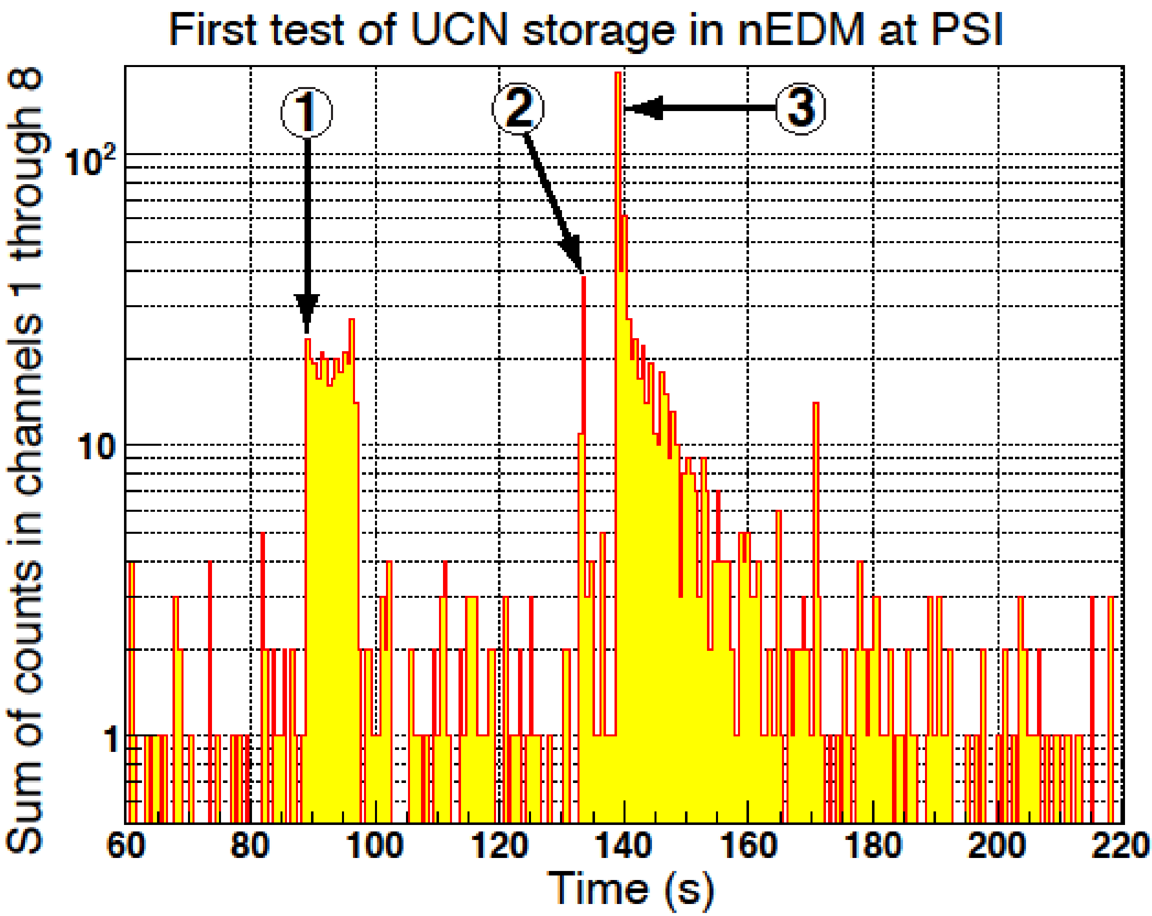
Magnetometers

- Hg co-magn.
- Cs gradiometer

UCN stored

First UCN stored in apparatus @ PSI: Wednesday, December 22nd, 2010

- 8s Pulse on target ②
- 40s filling
- Closing of UCN shutter
- Turning switch in emptying position ③
- Opening of shutter ④
- Emptying into detector



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

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

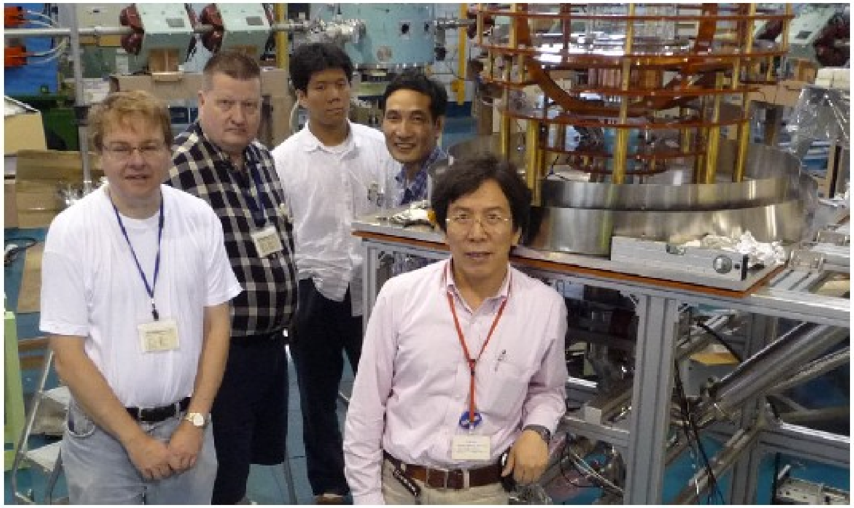
Collaborators: T. Adachi, K. Asahi, M. Barnes, C. Bidinosti, J. Birchall, L. Buchmann, C. Davis, T. Dawson, J. Doornbos, W. Falk, M. Gericke, R. Golub, K. Hatanaka, B. Jamieson, S. Jeong, S. Kawasaki, A. Konaka, E. Korkmaz, E. Korobkina, M. Lang, L. Lee, R. Mastumiya, K. Matsuta, M. Mihara, A. Miller,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

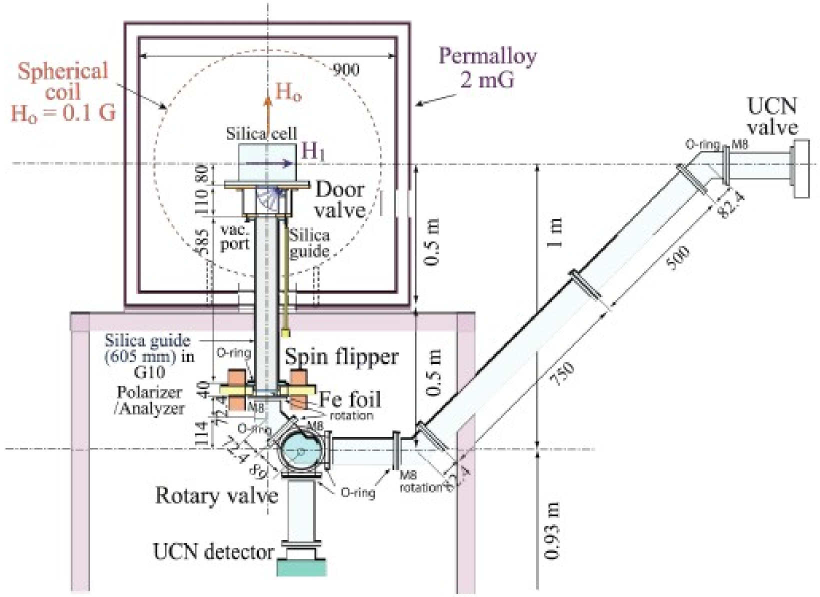
(KEK, Titech, Winnipeg, Manitoba, TRIUMF, NCSU, RCNP, UNBC, UBC, Osaka)

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

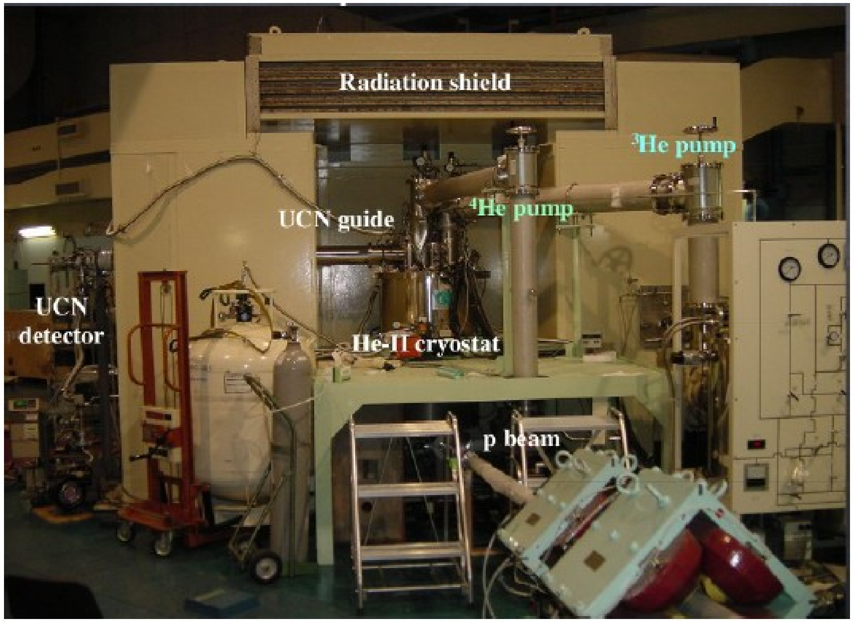
Japan-Canada nEDM experiment

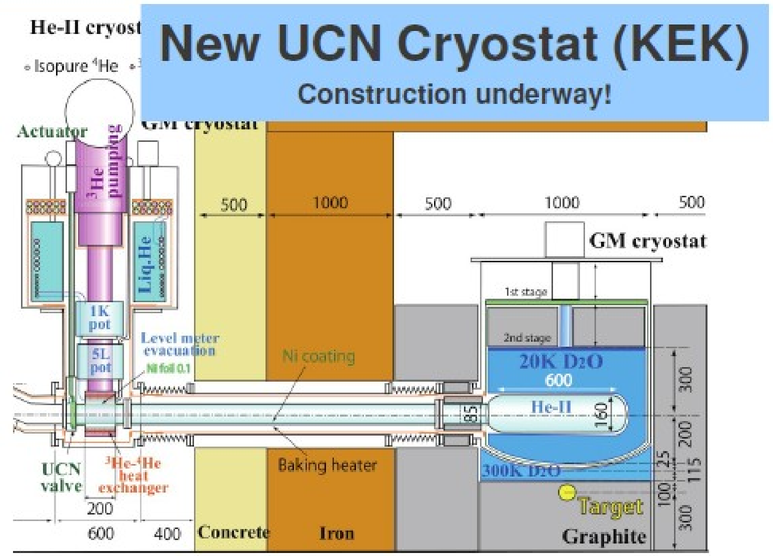
- Spherical coil for DC field
- Xe-129 nuclear-spin buffer-gas comagnetometer
- Room-temp experiment, keeping EDM cell size small, anticipating gains in UCN density
- Modern magnetic shielding, cost reduced with cell size
- Superfluid He-4 UCN source
- Basic prototype in operation

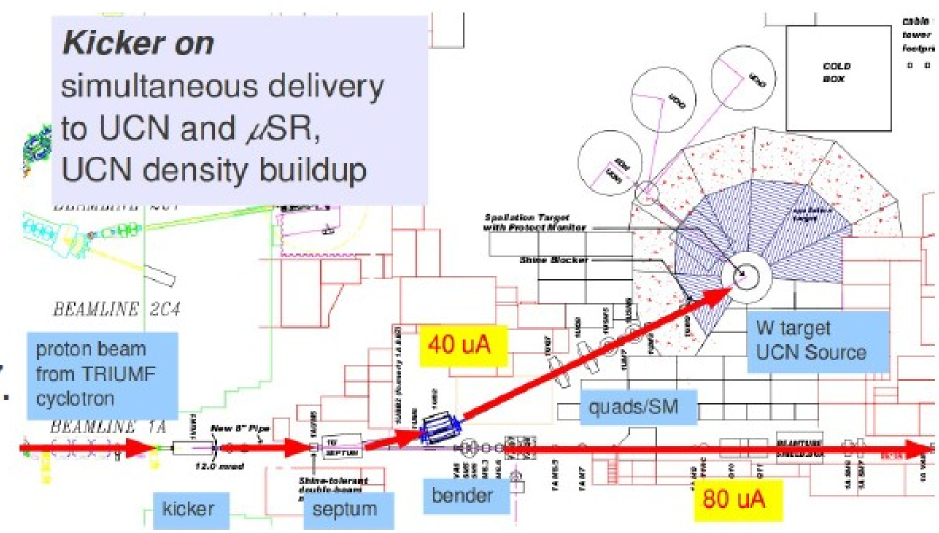




Schedule and Goals







RCNP Phase (-2014)

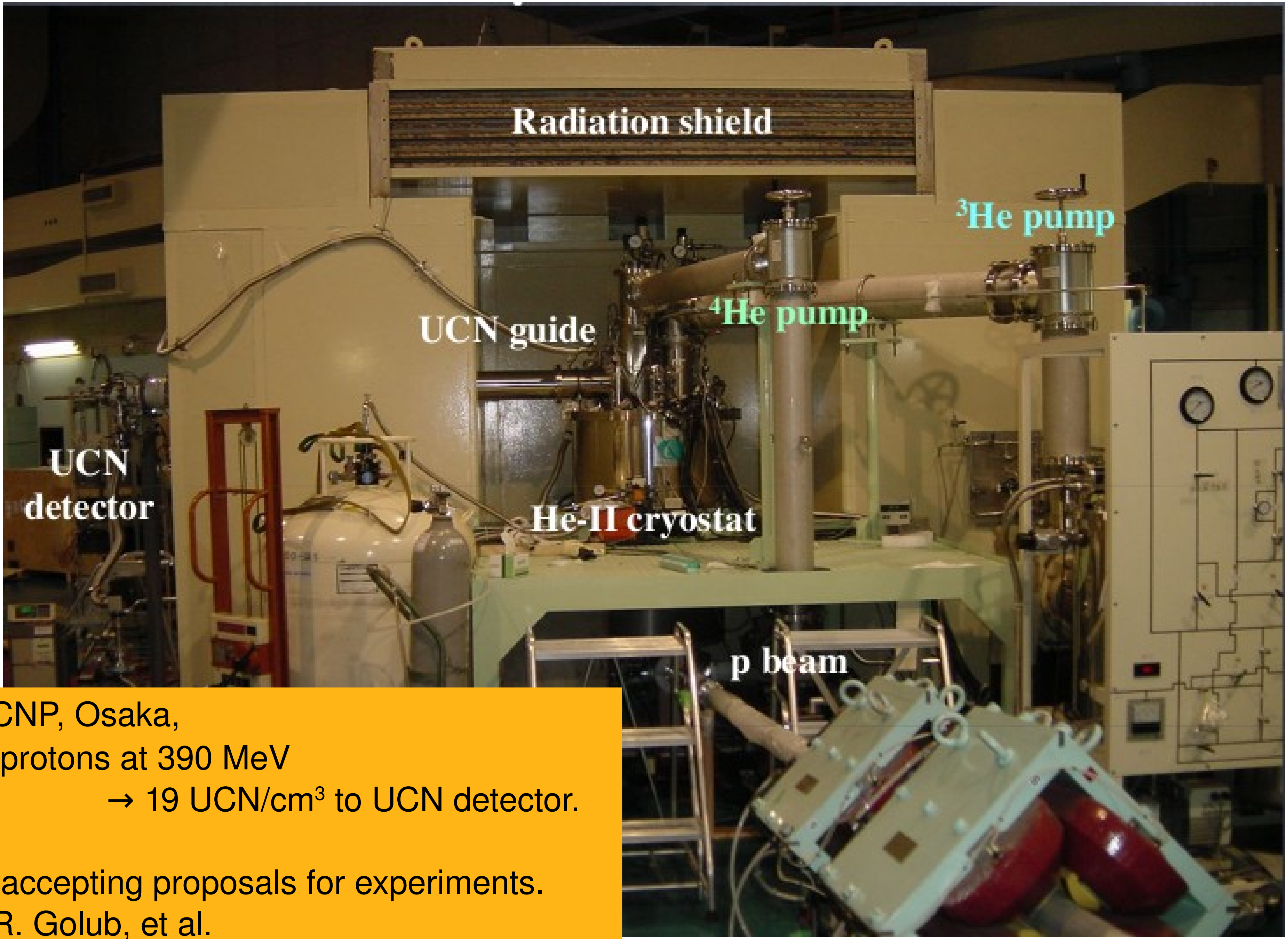
- Goal $d_n < 1 \times 10^{-26}$ e-cm

TRIUMF Phase (2015-)

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

courtesy: J.W. Martin

KEK-RCNP UCN Source

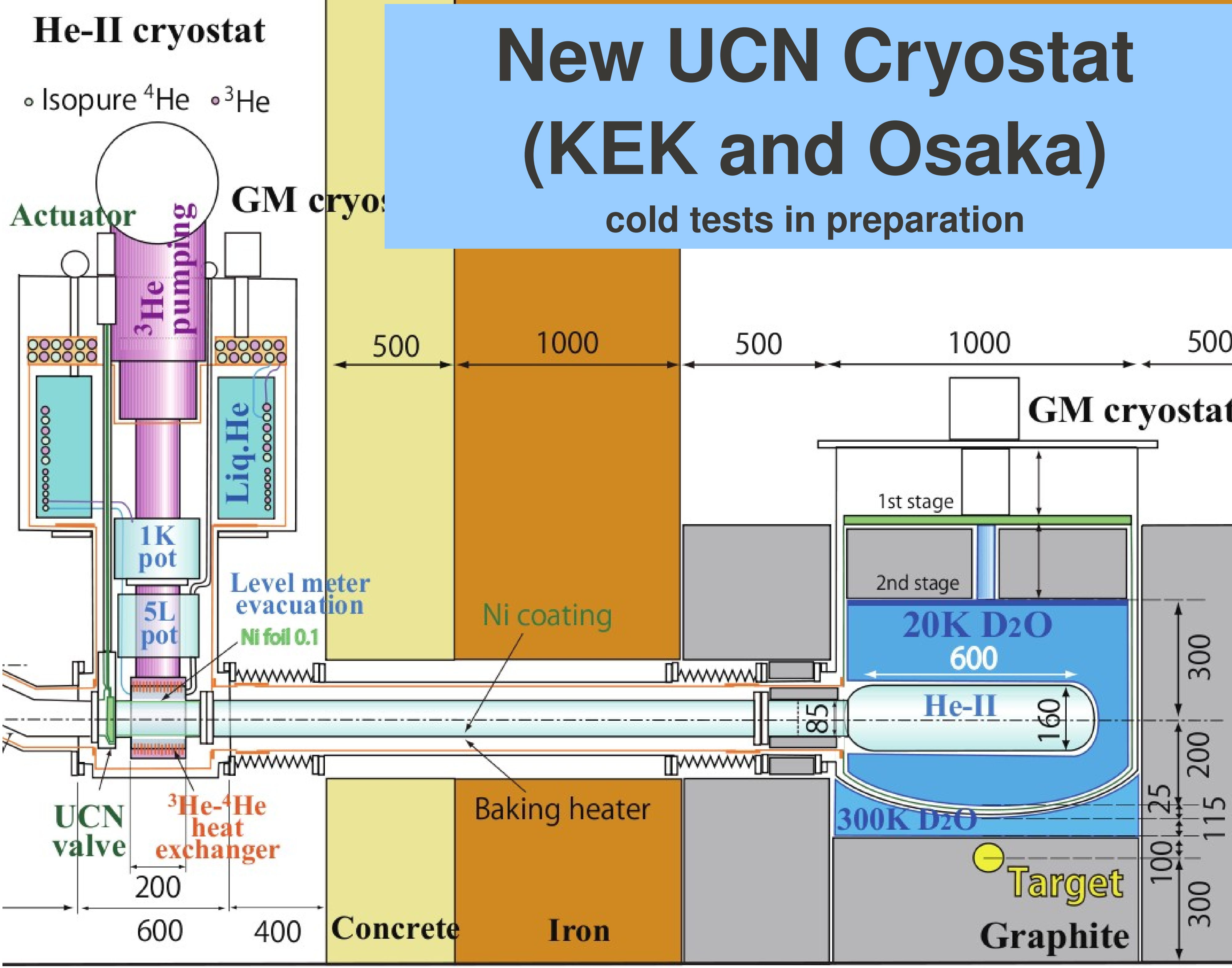


At RCNP, Osaka,
1 μa protons at 390 MeV
→ 19 UCN/cm^3 to UCN detector.

Now accepting proposals for experiments.
e.g. R. Golub, et al.

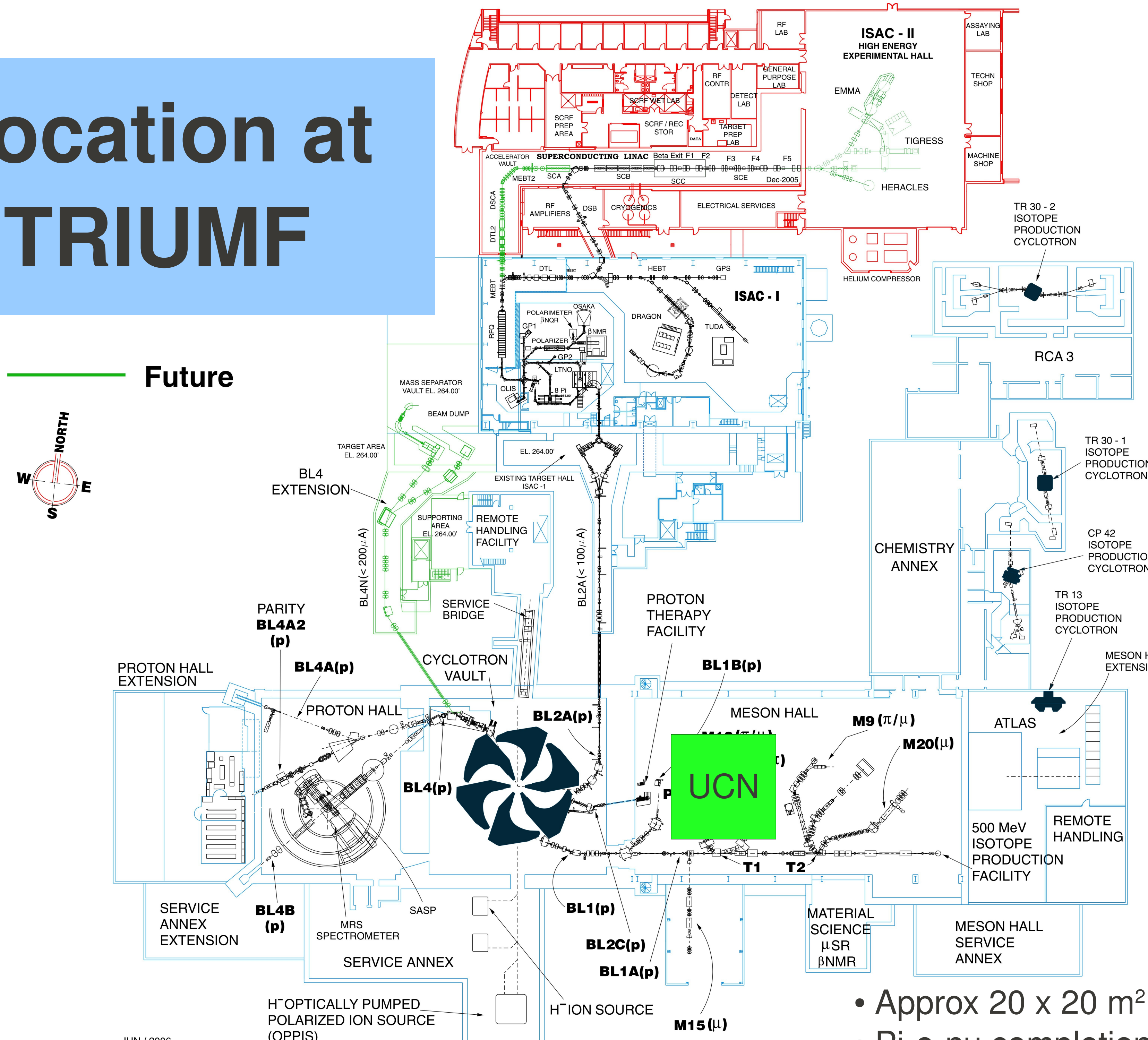
New UCN Cryostat (KEK and Osaka)

cold tests in preparation



- 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 summer 2014.
- Longer running time at TRIUMF (8 months/yr vs few weeks)

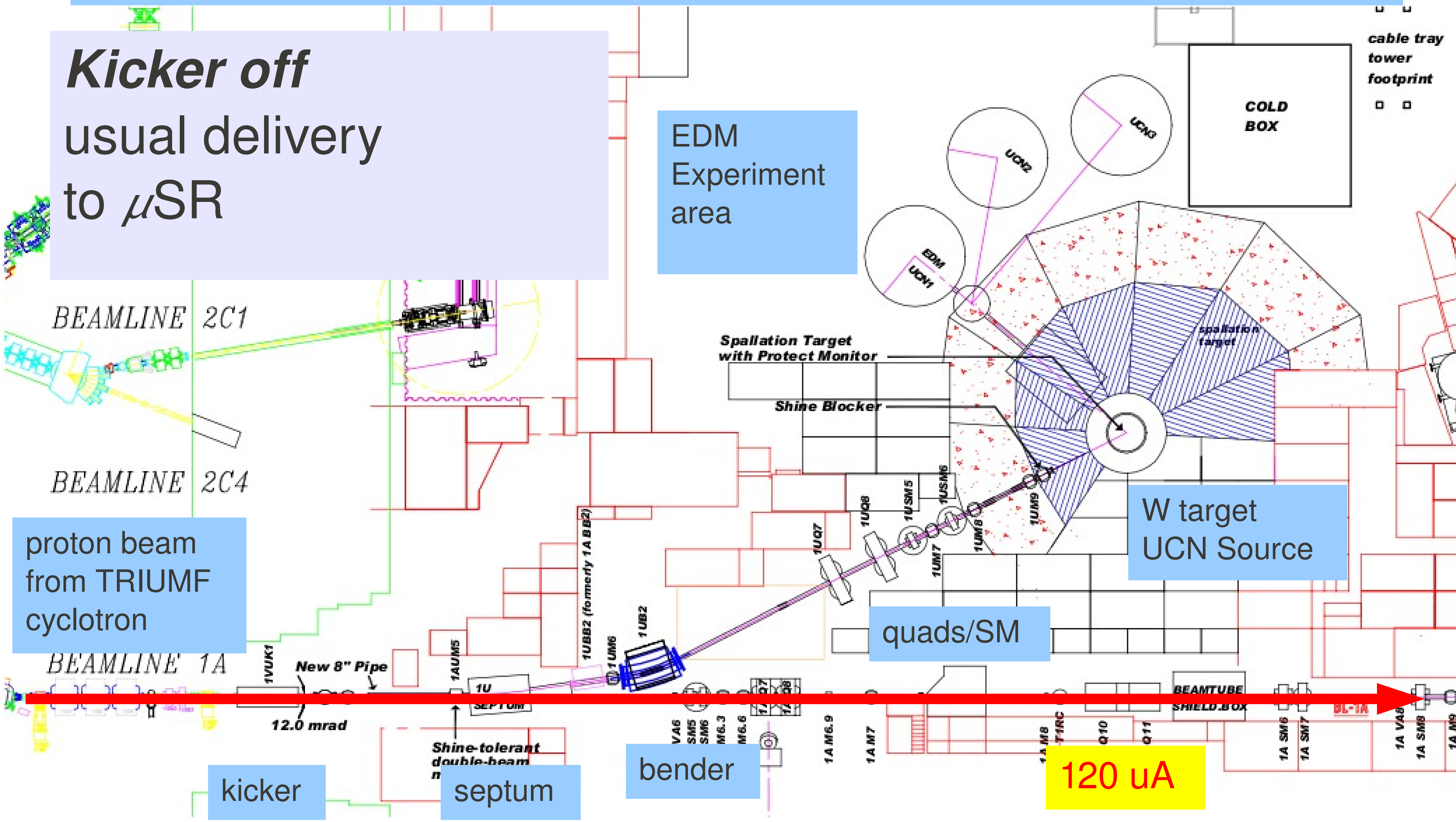
Location at TRIUMF



- Approx 20 x 20 m^2 box
- Pi-e-nu completion 2011

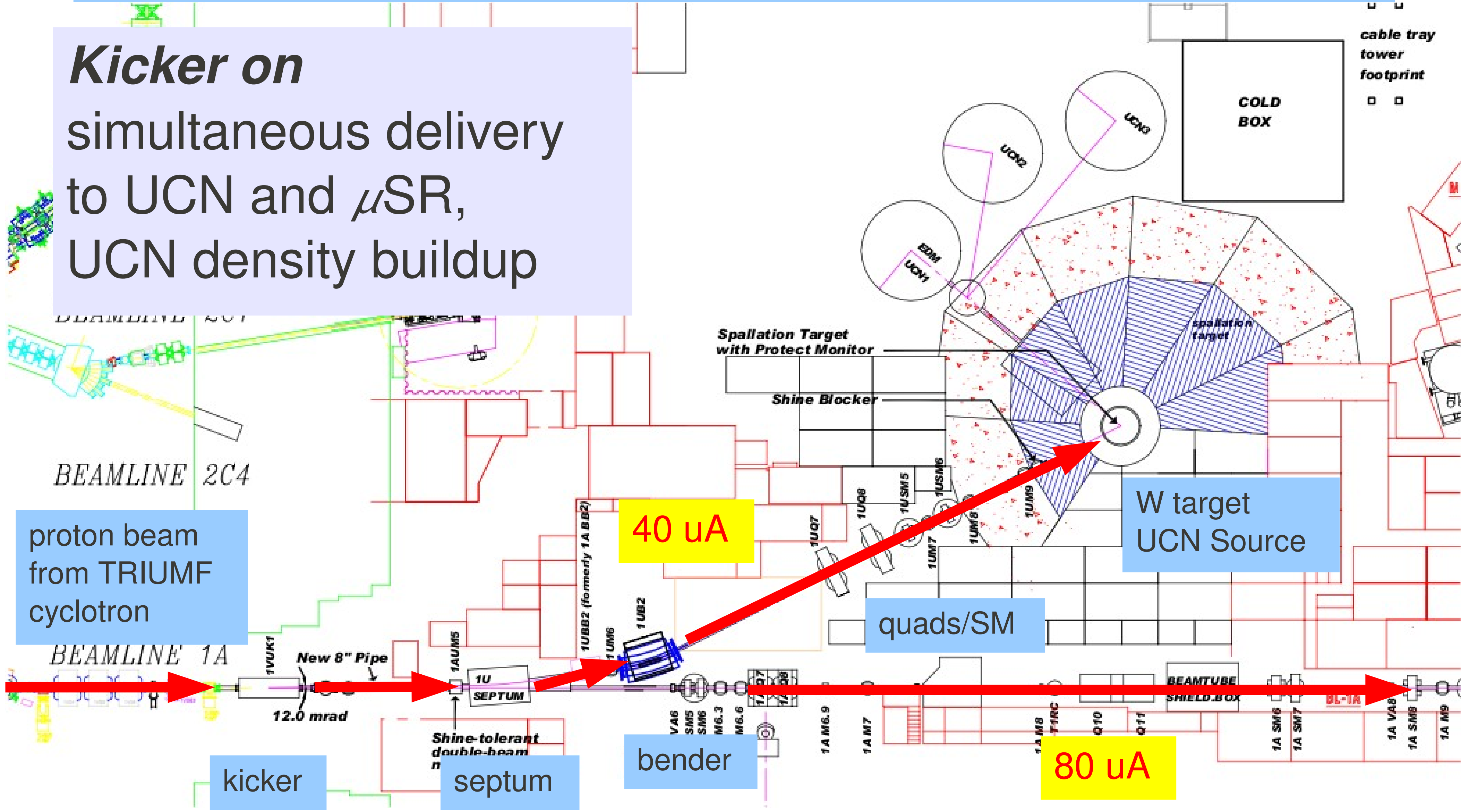
Layout and Overview

Kicker off
usual delivery
to μSR



Layout and Overview

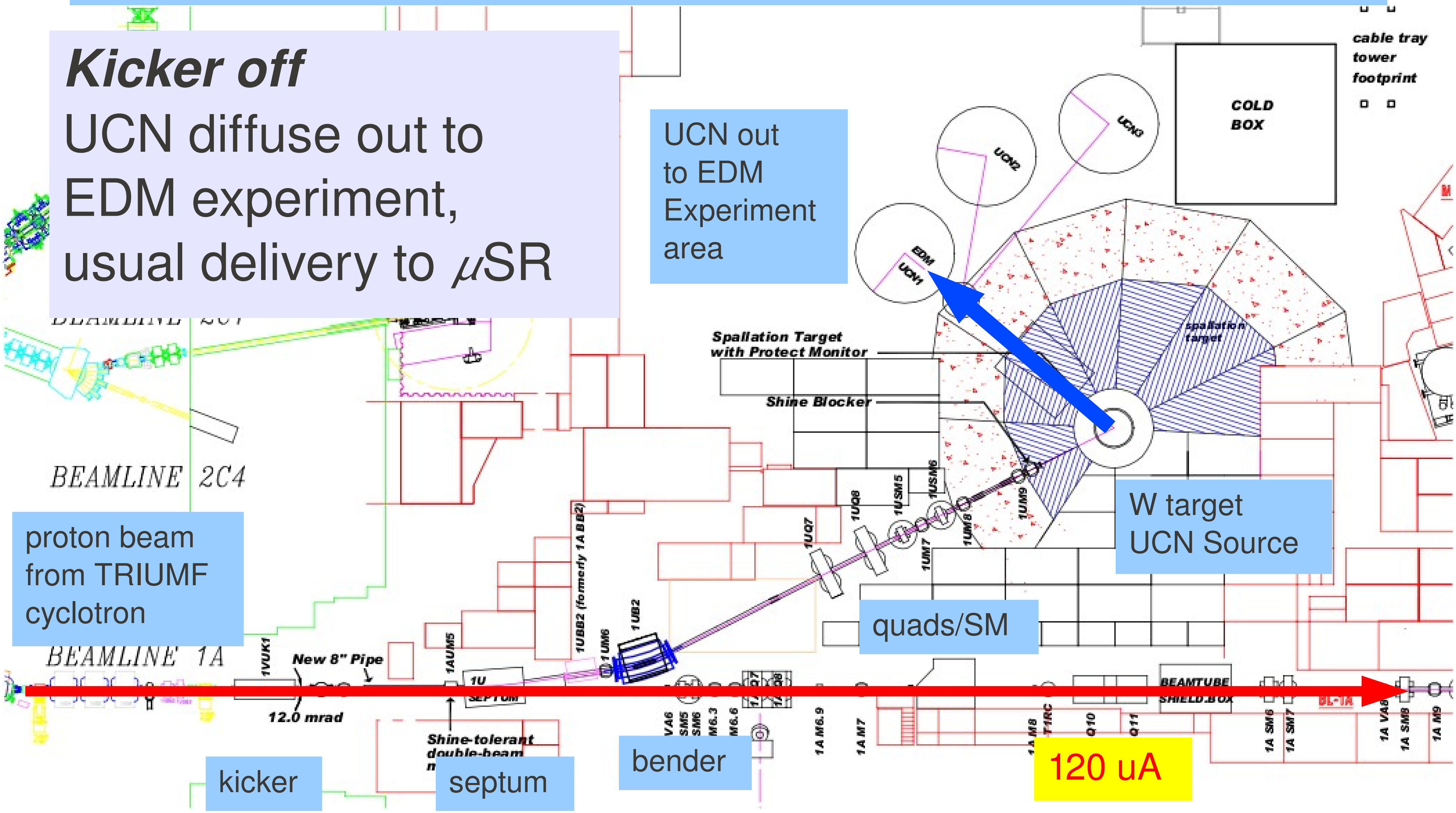
Kicker on
simultaneous delivery to UCN and μSR,
UCN density buildup



Layout and Overview

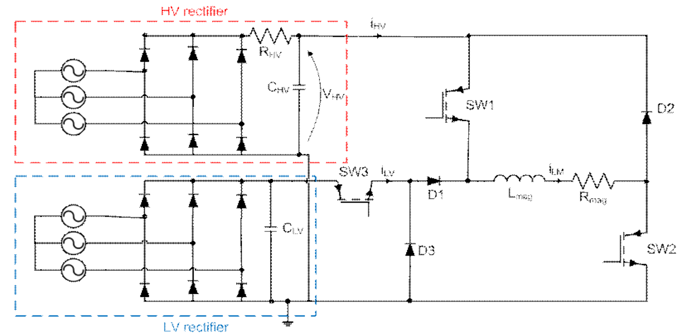
Kicker off

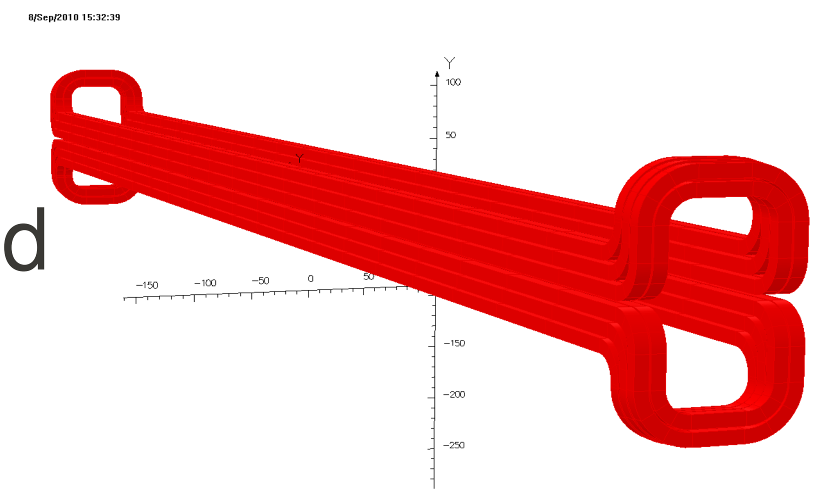
UCN diffuse out to EDM experiment, usual delivery to μSR



Kicker

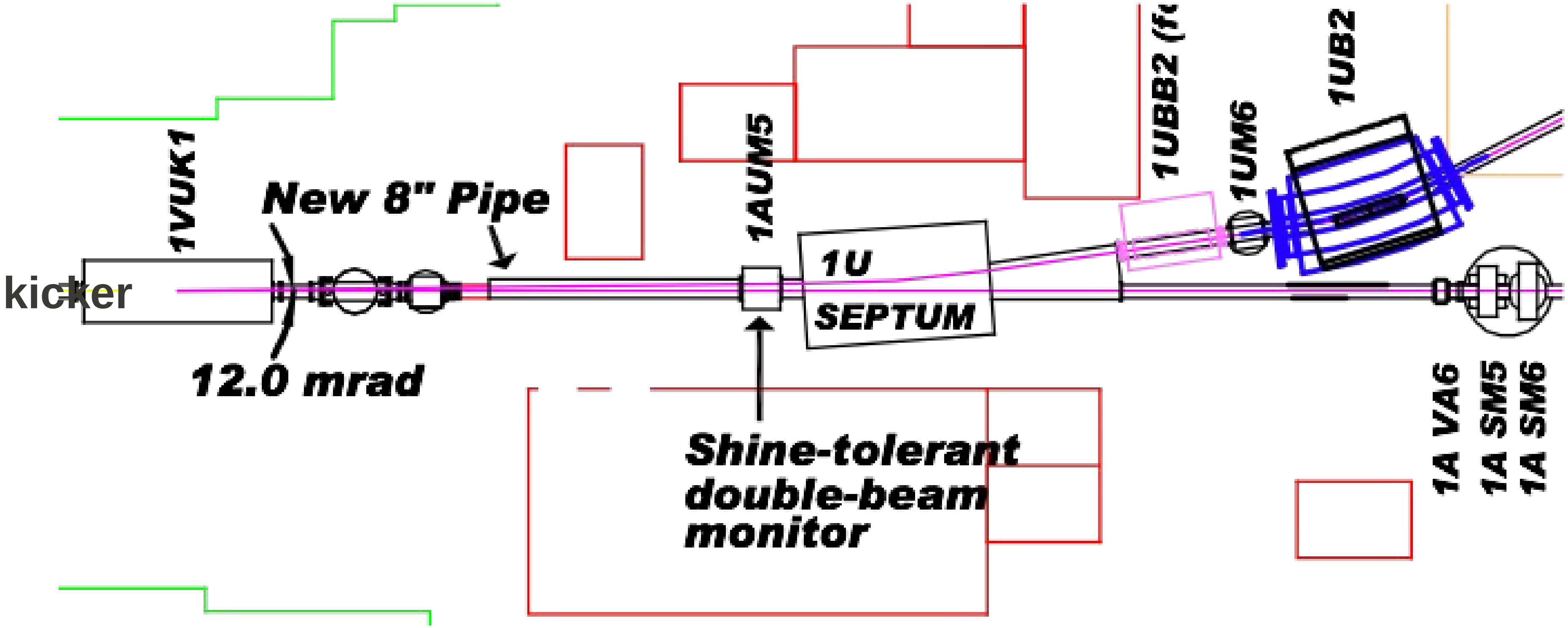
- Redirect 1A beam into UCN line on kHz timescale using existing TRIUMF beam structure.
- TRIUMF/CERN design
  - HV SS switches
  - Fast dipole magnet
- Magnet coil design completed summer 2011.





M. Barnes, M. Hahn

UCN beam line magnets



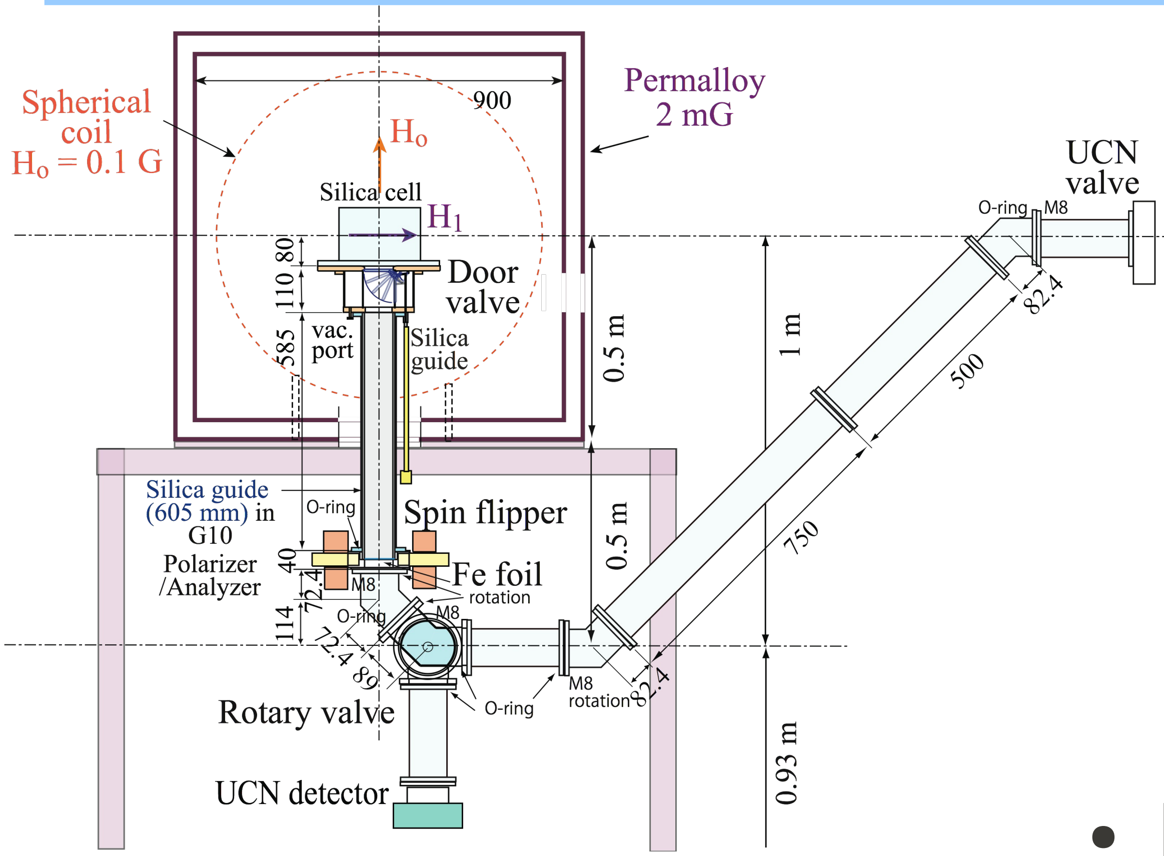
- Septum/bender magnets built by KEK
  - Lambertson design considered for septum
  - Sector design for bender (under construction this FY)

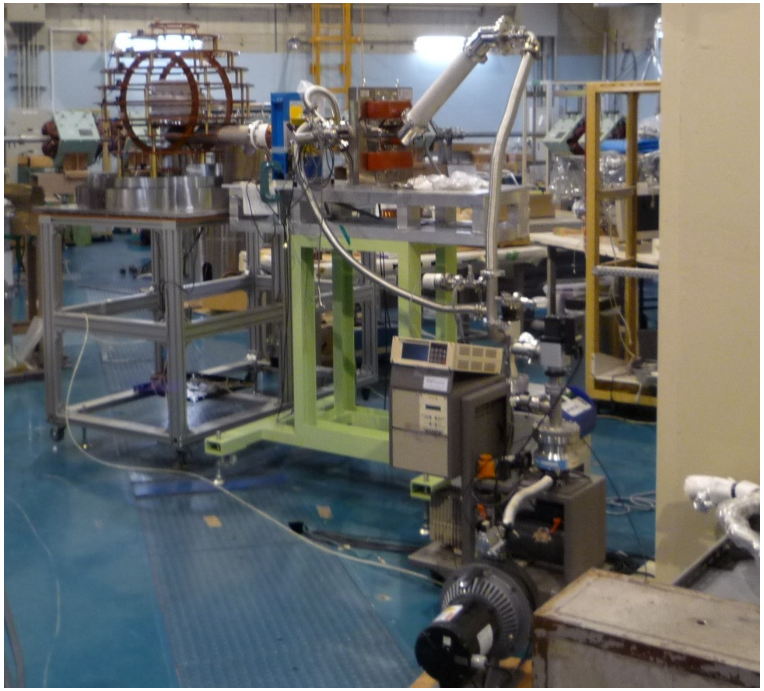
H. Tanaka, A. Miller

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.

n-EDM development in Japan

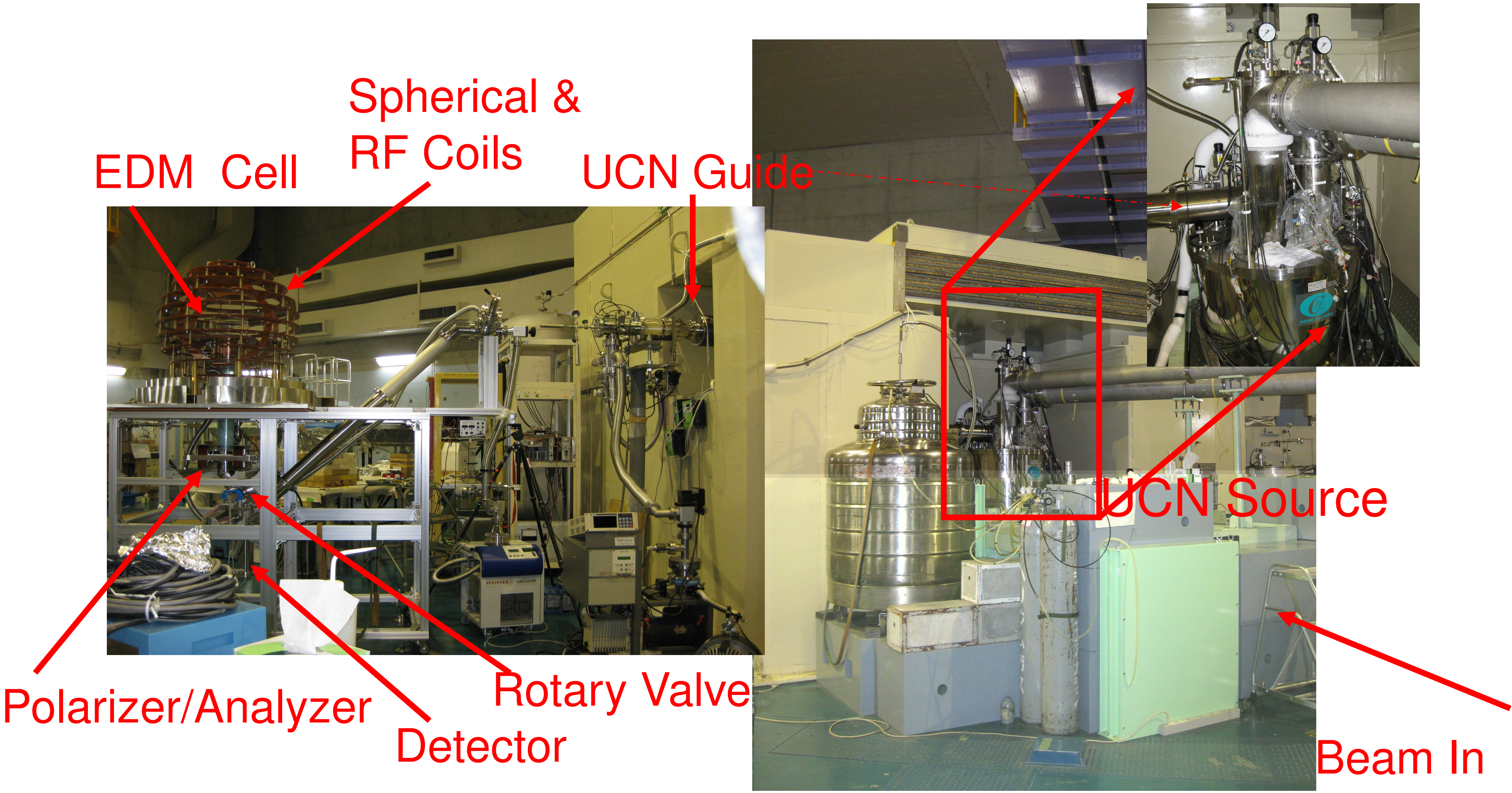




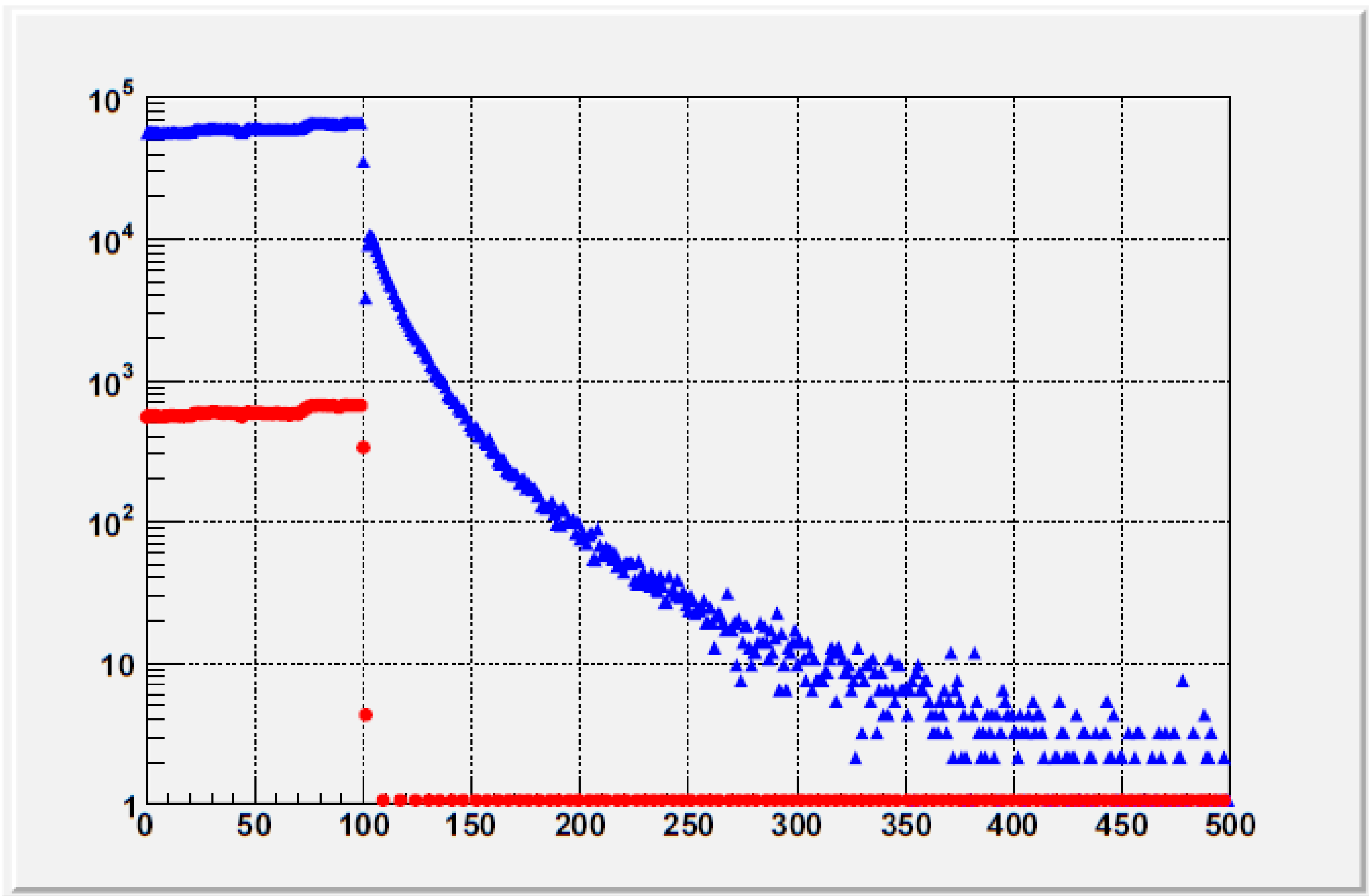
Masuda, et al. Beam tests July, December 2009, April 2010, February 2011, October 2011.

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

Experimental Setup



Proton Beam 1μA x 100 s

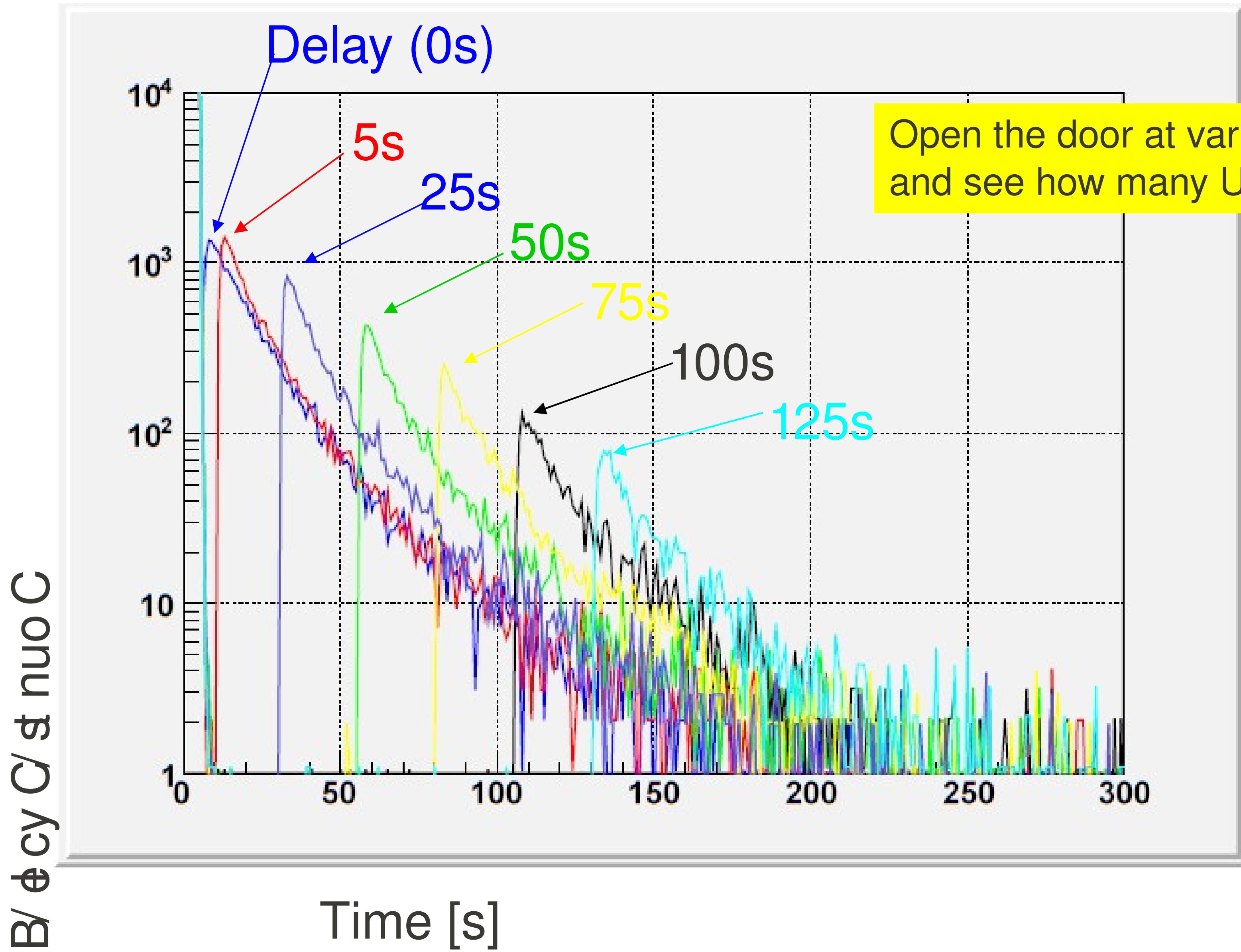


UCN count

Time [s]

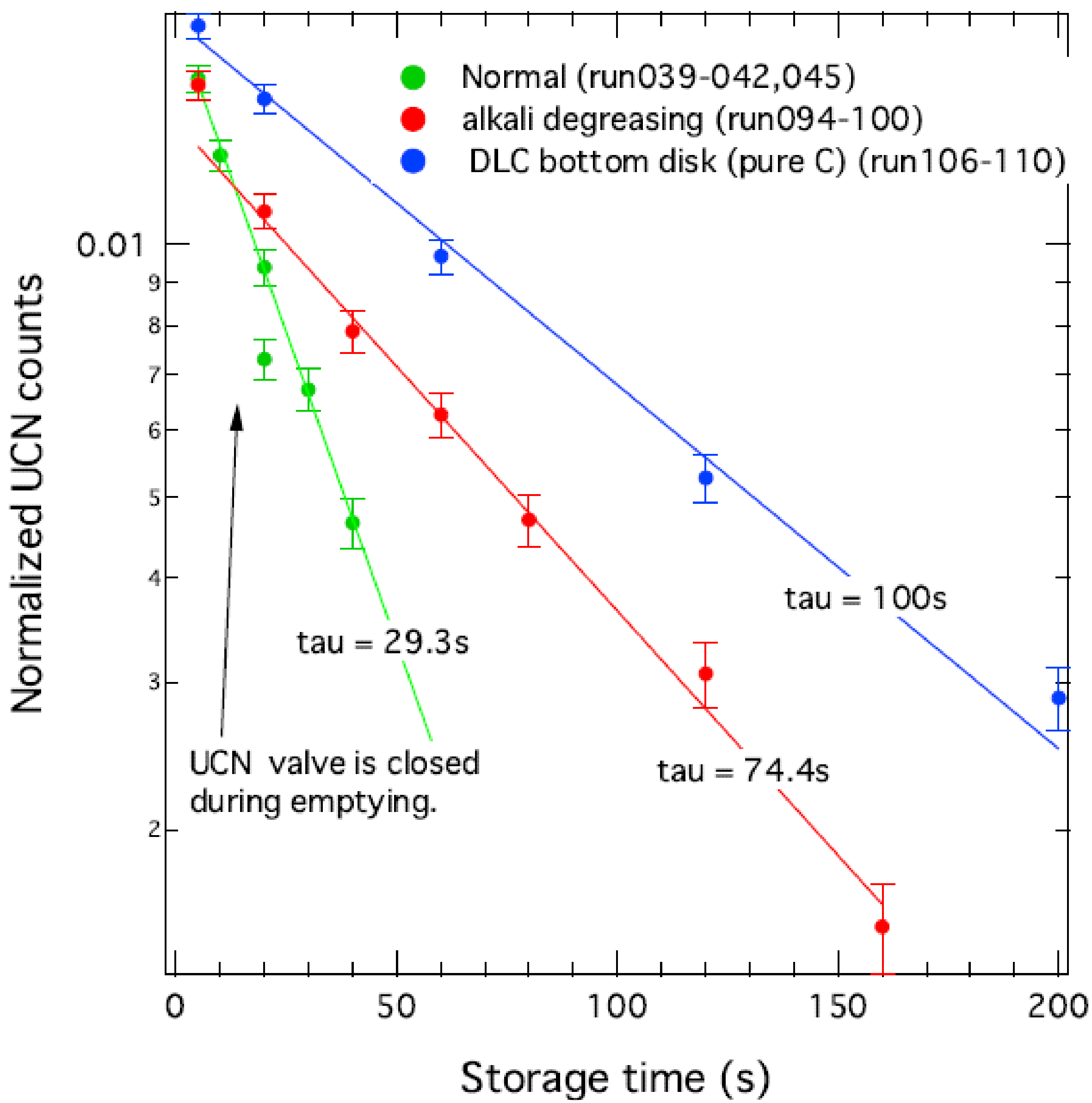
~15 UCN/cc in region just outside shield wall.
a remarkably reliable source of UCN!

Upstream UCN Storage Time



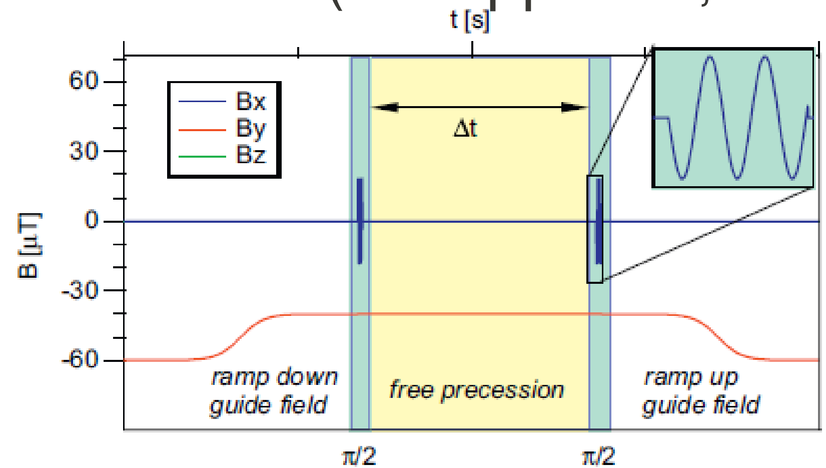
Open the door at various times and see how many UCN come out!

Storage Time in EDM Cell



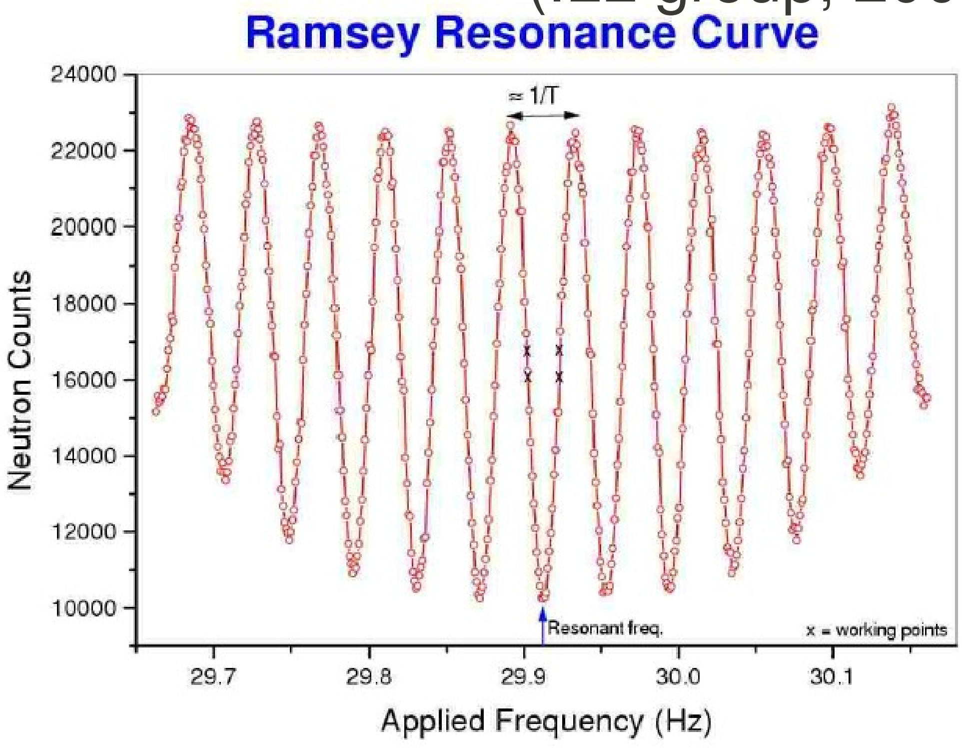
Ramsey Resonance

(S.Filipp et al, 2009)

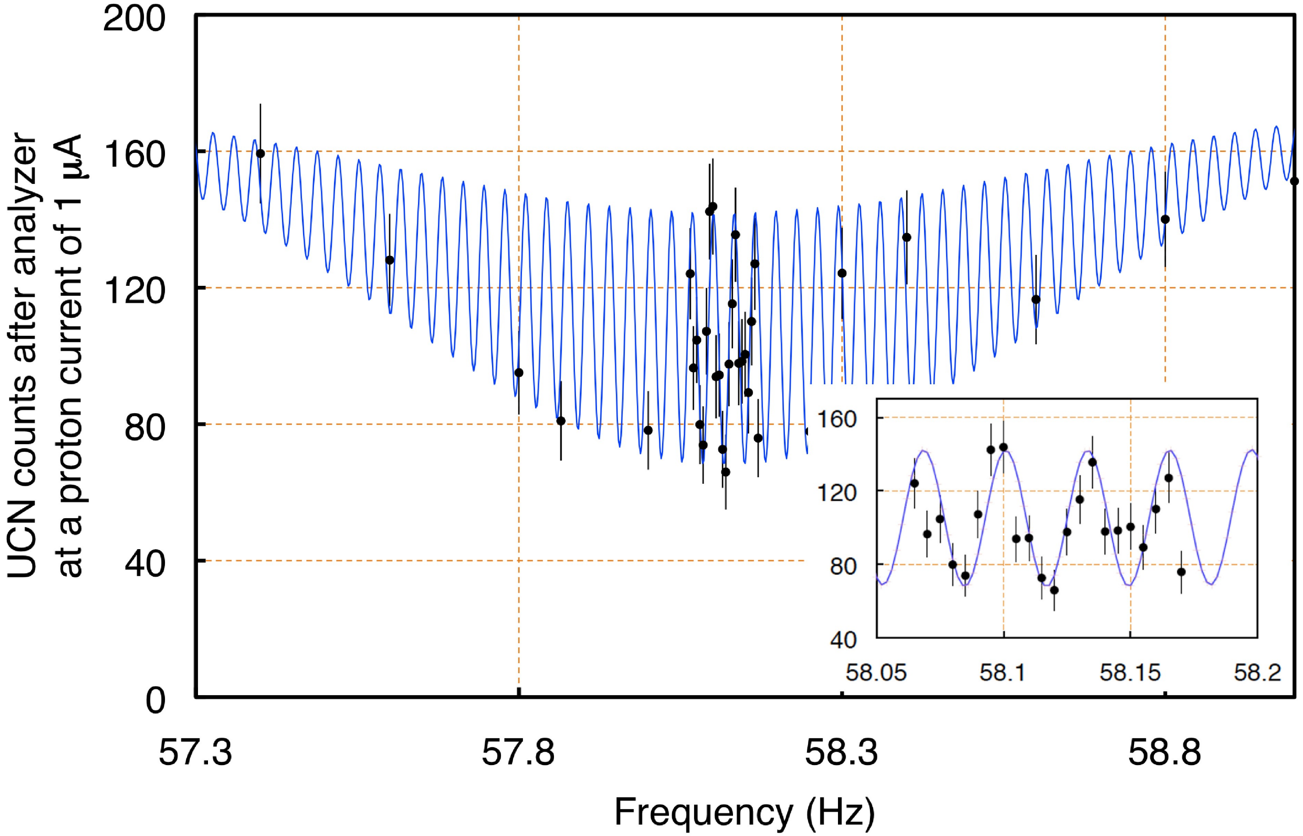


- π/2 pulse
- free precession time τ
- π/2 pulse
- For $\omega=\omega_0$, no UCN.
- Vary ω and narrow "Ramsey fringes" are observed.
- Width of fringe ~ $1/\tau$

(ILL group, 2003)



Ramsey Resonance Results



Dec. 2009, achieved:
T_2 ~ 300 ms

April 2010, achieved:
T_2 > 30 s

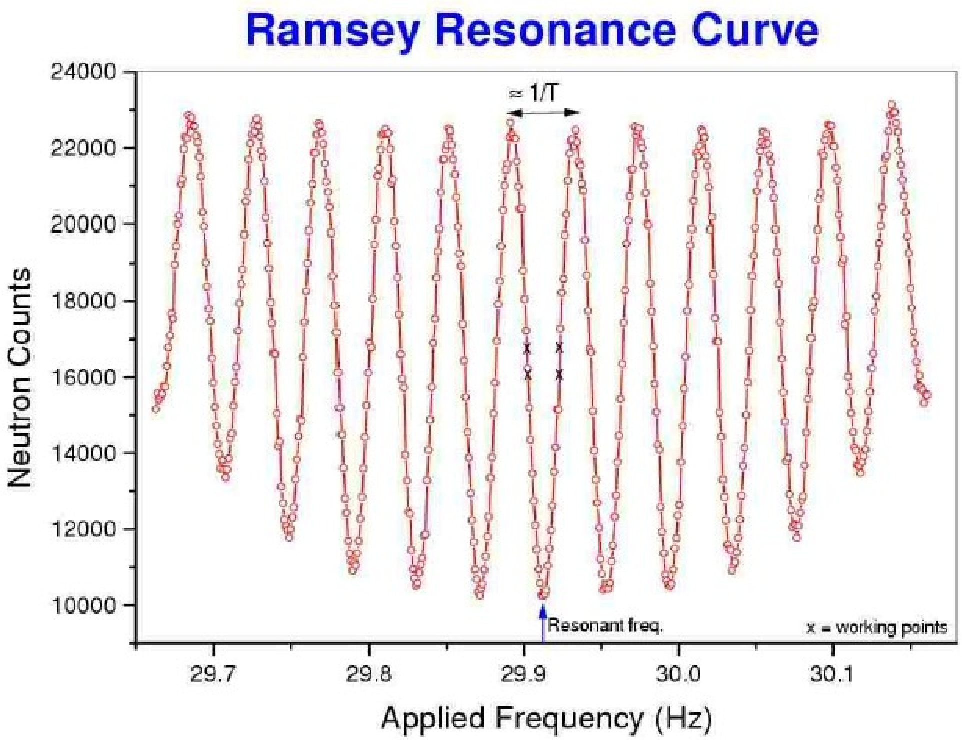
becoming competitive with ILL, where T_2 = 120 s (typ.)

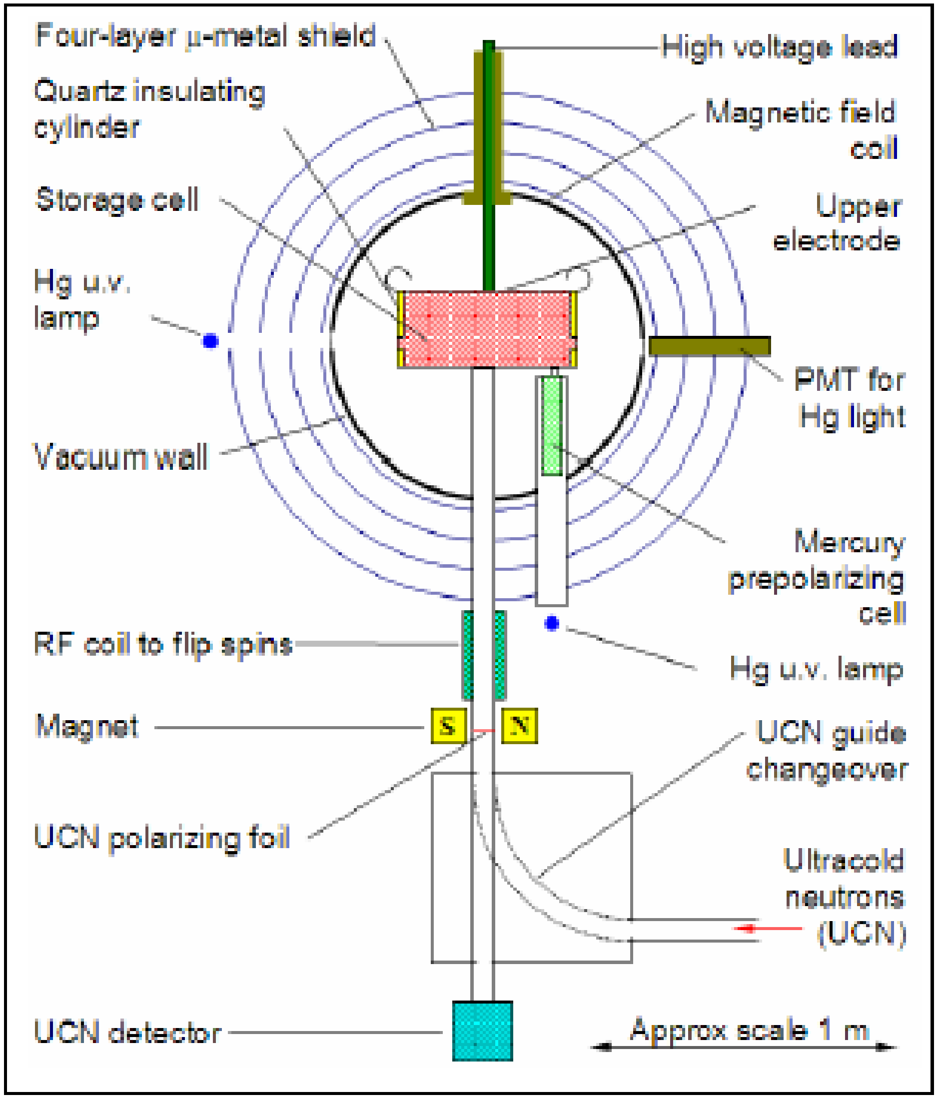
$$\sigma\left(d_n\right) = \frac{\hbar}{2\alpha E T \sqrt{N}} \quad \text{(stat)}$$

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

EDM Method





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

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

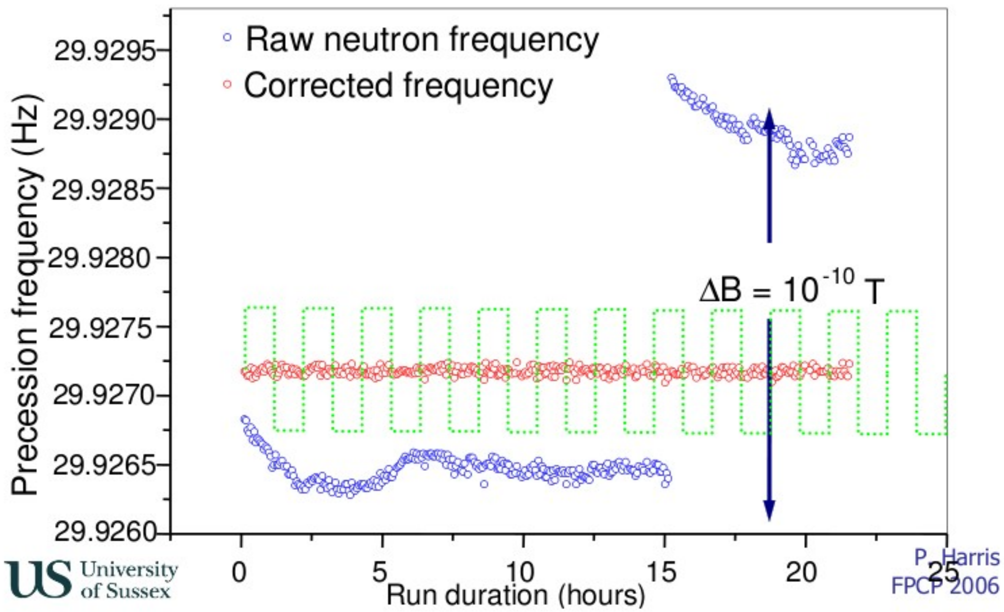
Photo from February Run

RCNP-Osaka, Feb. 2011

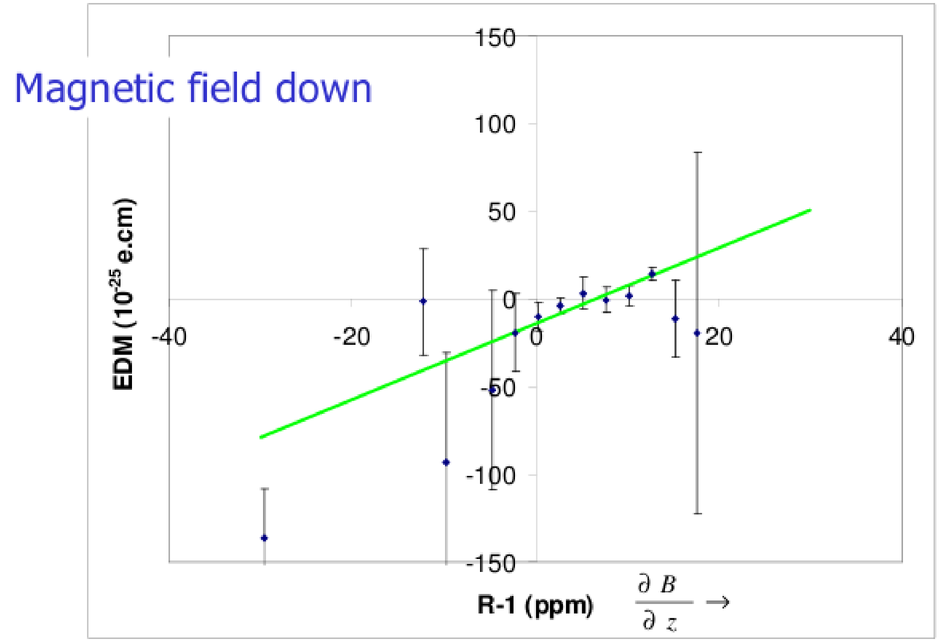
n-EDM Systematics

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

(co)magnetometry



comagnetometry



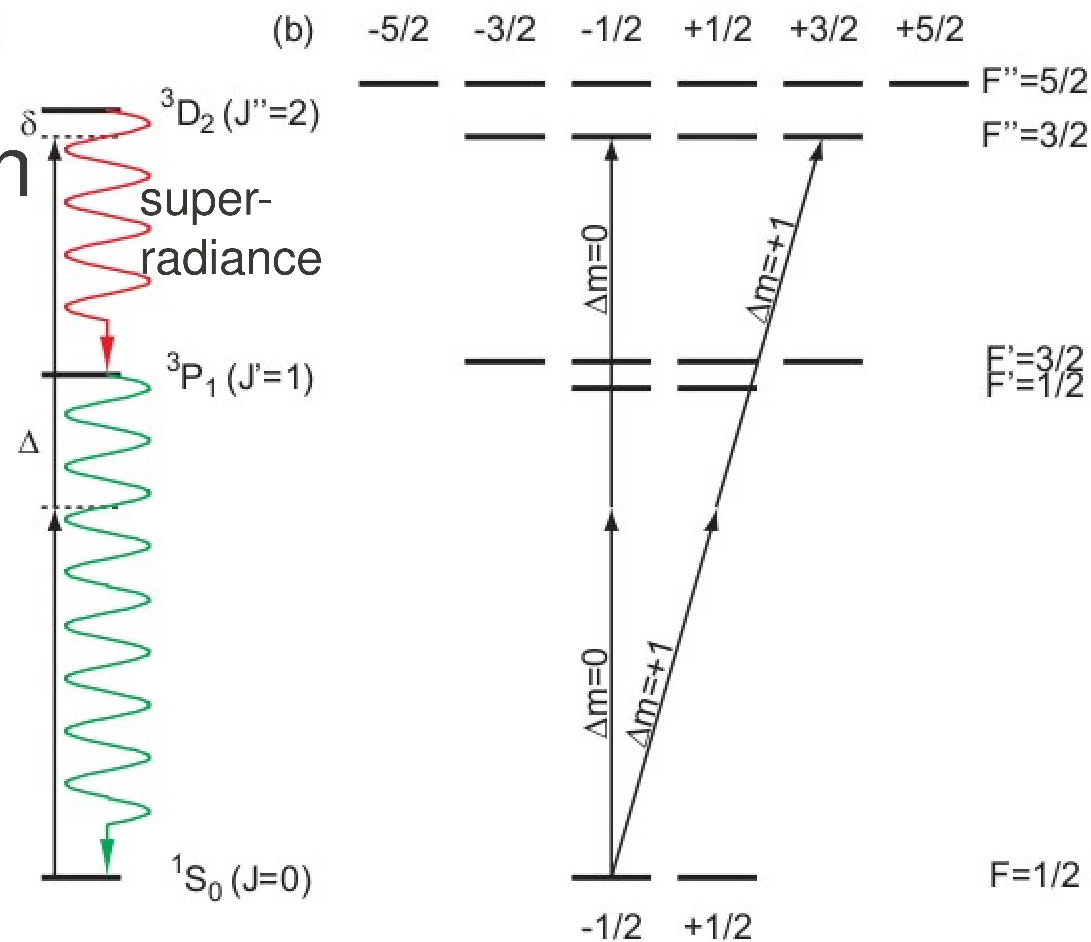
false EDM (GP) effect

Xe-129 buffer-gas nuclear spin comagnetometer

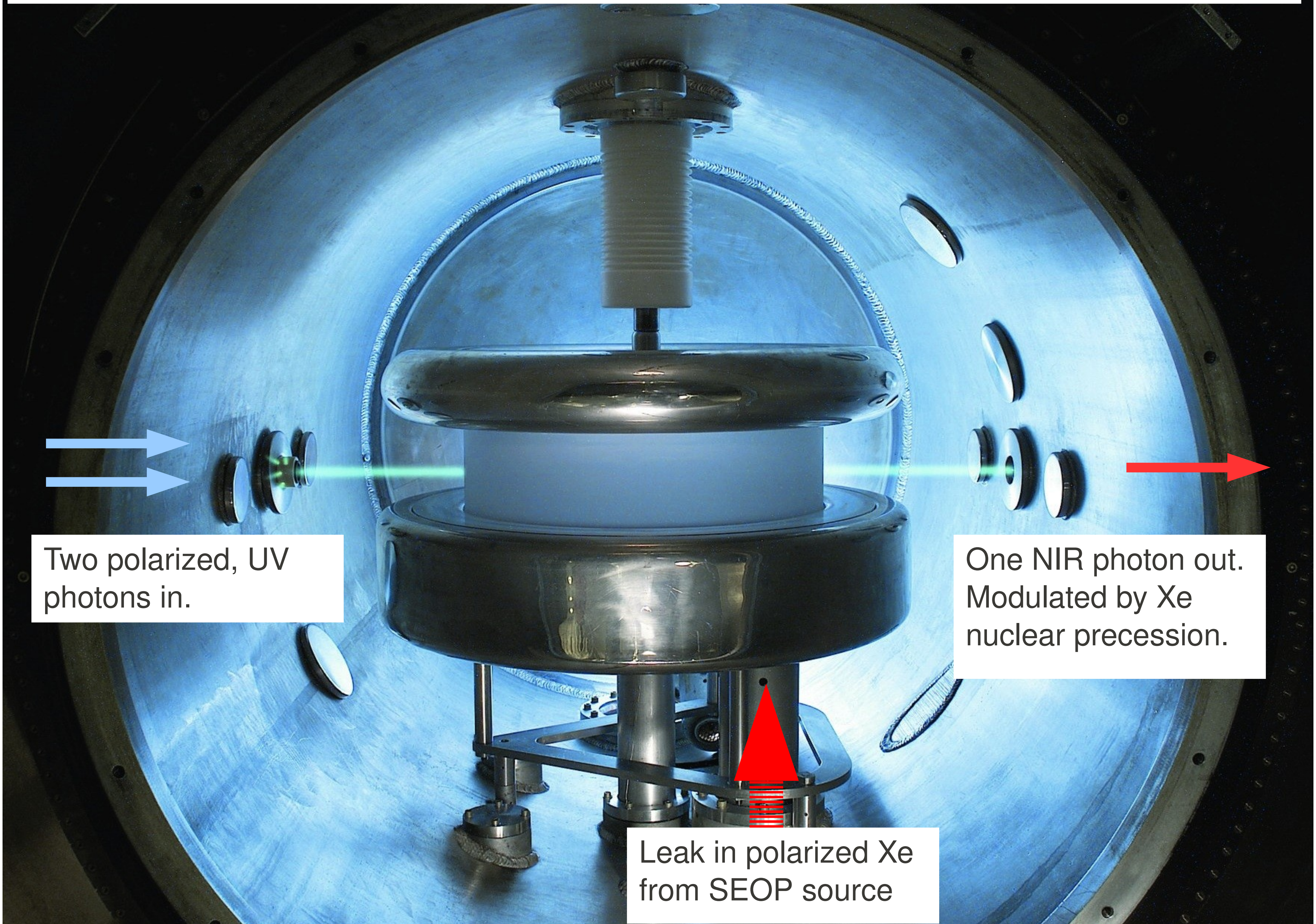
- Masuda-san's idea: leak polarized Xe-129 into the EDM cell with the neutrons and watch spins precess.
- Xe-129 pressure must be large
  - Xe-Xe Collisions -> small MFP -> small GPE.
  - Ring-down signal picked up by SQUID.
- Xe-129 pressure must be small
  - Electrical breakdown at higher pressures.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

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



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.

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.