Spin Control for Ultracold Neutrons

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The University of Winnipeg
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CRSNG

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TRIUMF

International Spallation Ultracold Neutron Source

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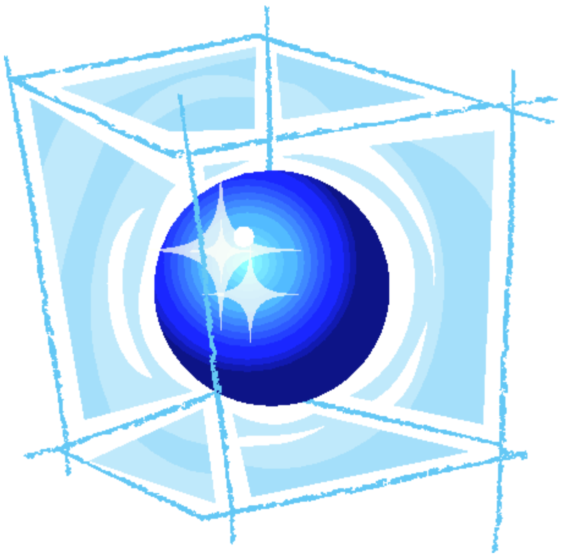
(KEK, Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, Tokyo, UNBC, Osaka, Kentucky)

We propose to construct the world's highest density source of ultracold neutrons and use it to conduct fundamental and applied physics research using neutrons.

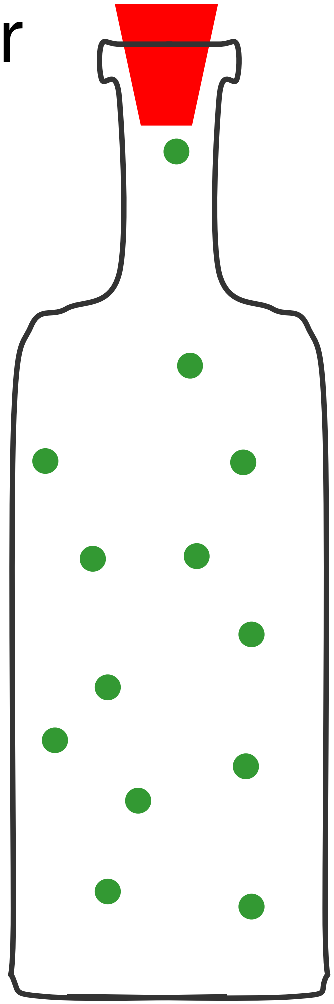
Ultracold Neutrons (UCN)



- What are UCN?
- How to make UCN
- Plans for UCN at TRIUMF
- Neutron electric dipole moment
- Prototyping for a neutron electric dipole moment experiment that we did this summer in Japan

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

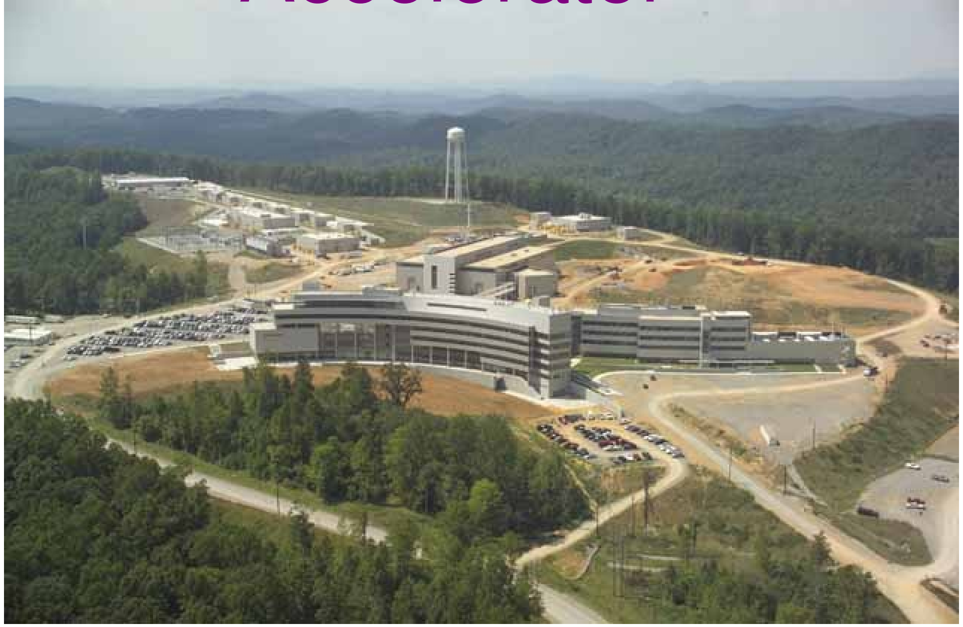


How to make lots of neutrons: Liberate them from nuclei!

1) In a nuclear reactor (fission).

2) At an accelerator (spallation).

Accelerator



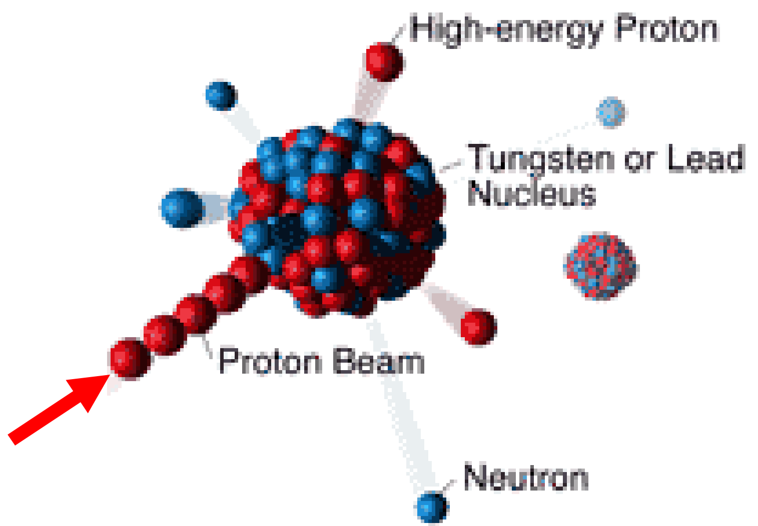
Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

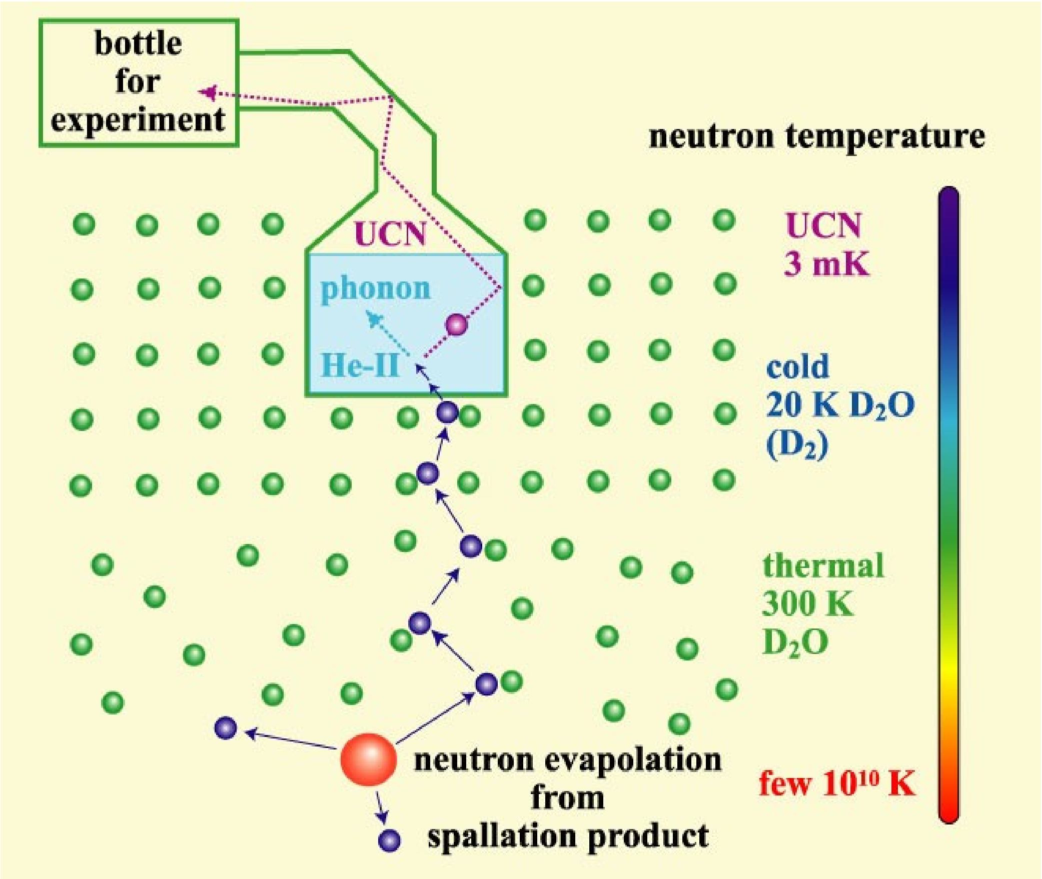
Reactor

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

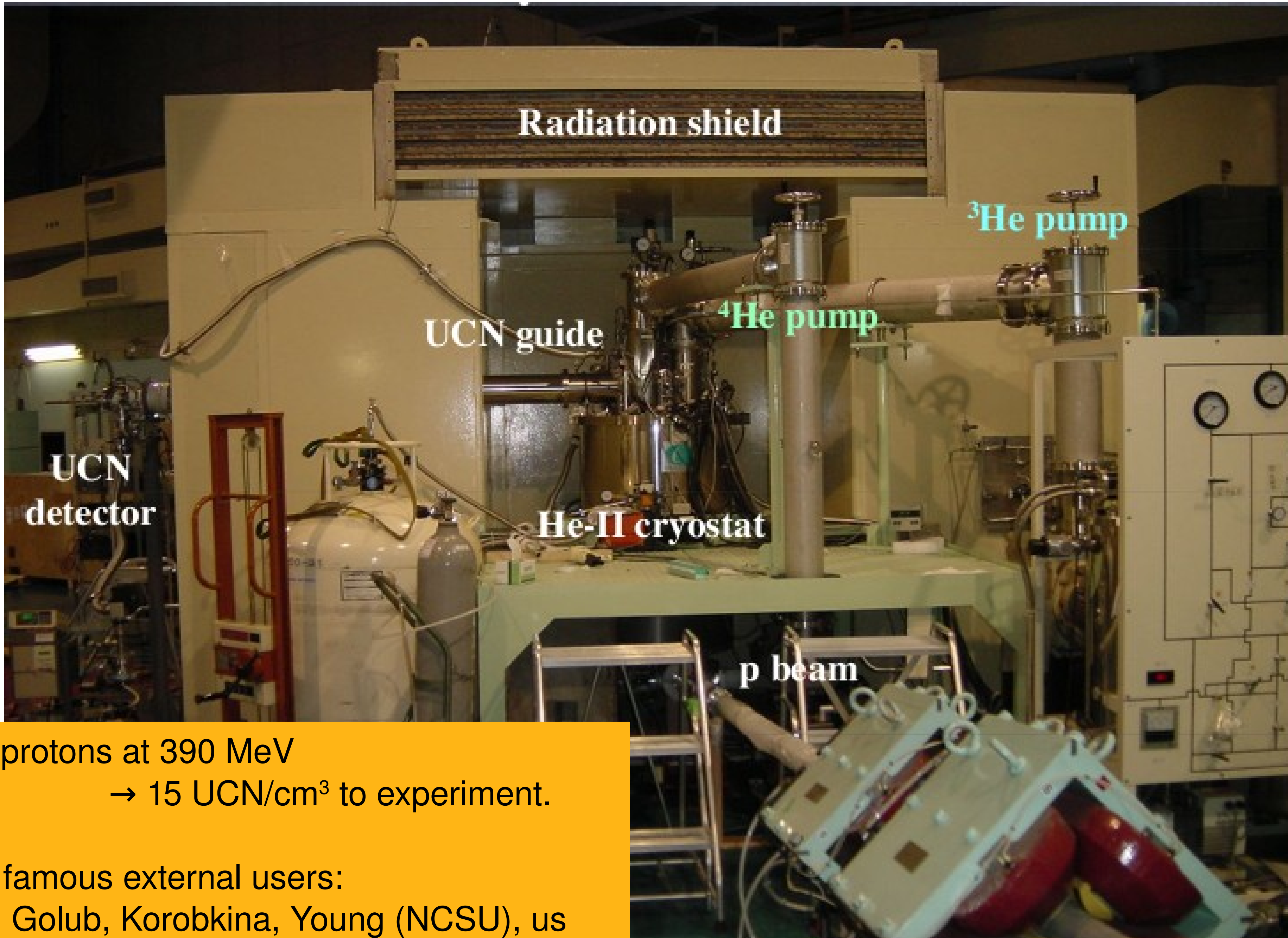
How to make UCN

- 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.





Japan UCN Source (Masuda, et al)



1 μa protons at 390 MeV
→ 15 UCN/cm^3 to experiment.

Very famous external users:
- e.g. Golub, Korobkina, Young (NCSU), us

- Proposed beam parameters for TRIUMF UCN source:
  - 500 MeV protons at 40 uA
- Recall RCNP, Osaka:
  - 390 MeV protons at 1 μA
- A fifty-fold increase in beam power.
- Cyclotron operates ~ 8 months/yr.

Japanese Section: UCN cryostat

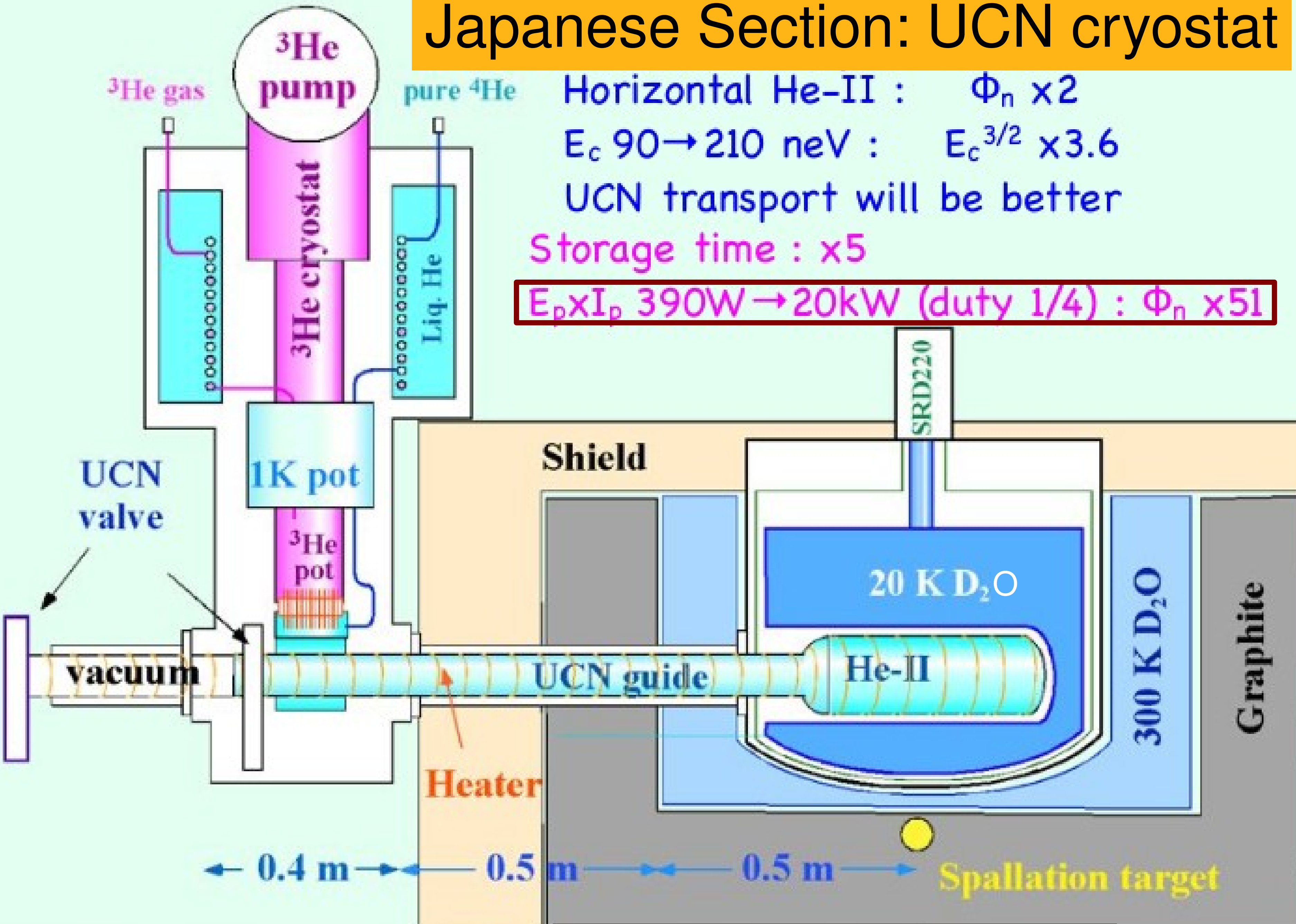
Horizontal He-II : Φ_n x2

E_c 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better

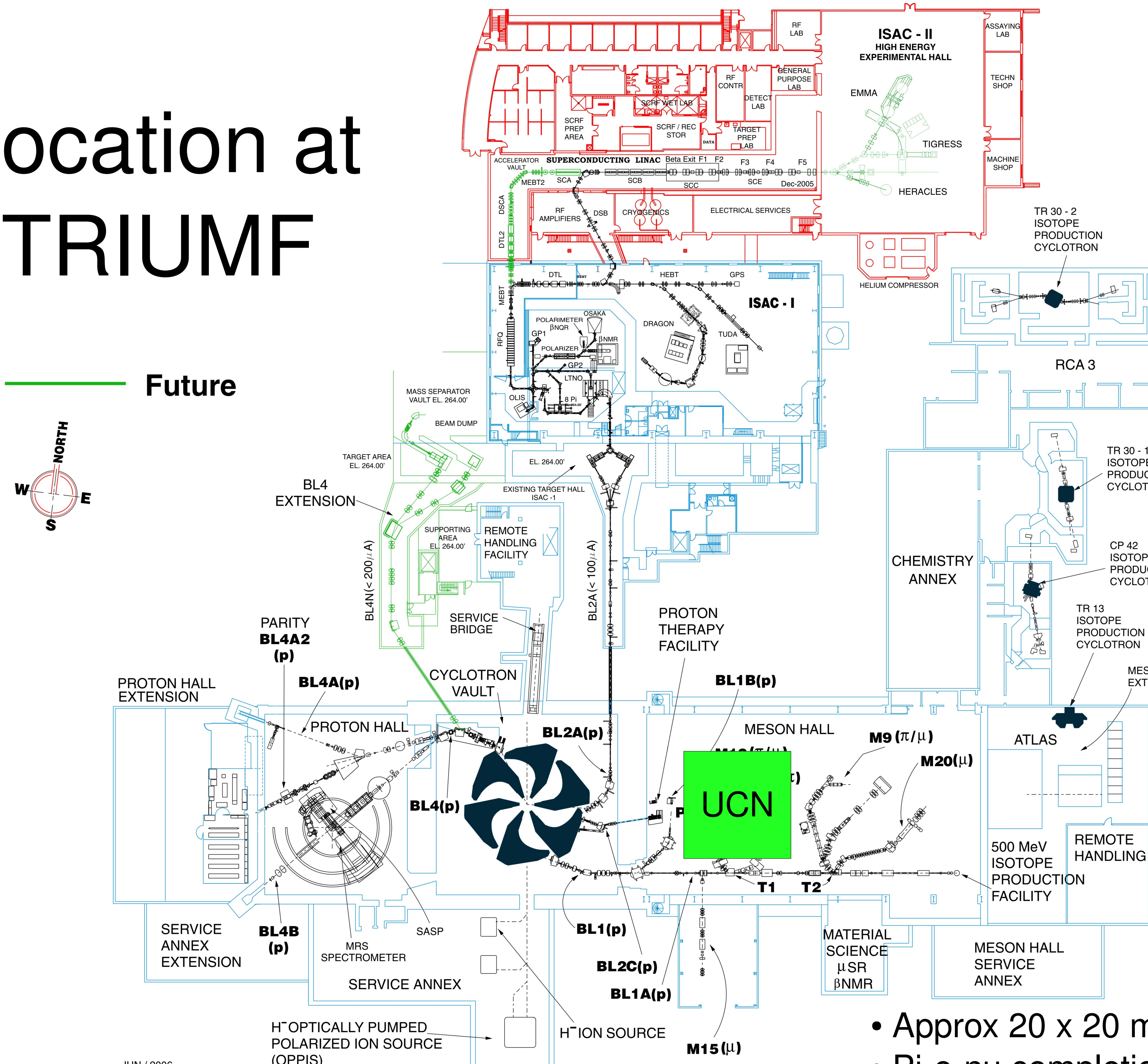
Storage time : x5

$E_p x I_p$ 390W→20kW (duty 1/4) : Φ_n x51



Future Upgrade: D_2O ice → LD_2 : x5

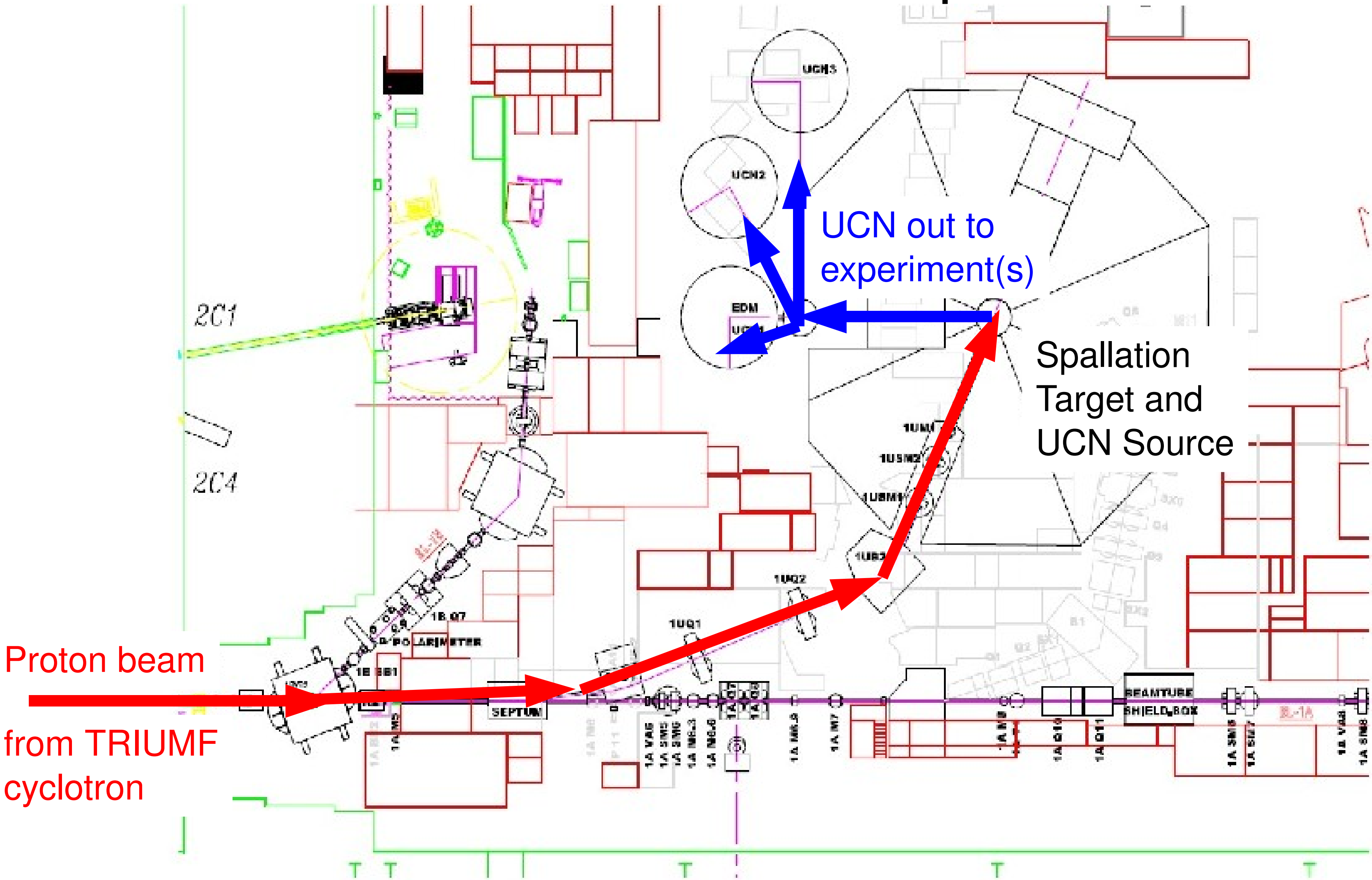
Location at TRIUMF



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

UCN Implementation at TRIUMF

Meson Hall concept



Challenges in Implementation

- For counting-mode physics experiments, it can be highly advantageous to switch the beam off.
- E.g. At RCNP:
  - 1 min beam on, 3 mins beam off.
- At TRIUMF, we will use a fast kicker to achieve this pulsing.
- Constraints of beam structure from cyclotron.
- We must also be careful to not affect downstream users (muSR CMMS facility)

Technical Progress

- Beamline design (J. Doornbos, G. Clark)
- Kicker feasibility, design (M. Barnes)
- Shielding estimates (A. Trudel)
- Layout (S. Austen, C. Davis)
- Cost/Sched/Manpower (V. Verma, W.D. Ramsay, C. Davis)
- All are being revisited prior to CFI resubmission.

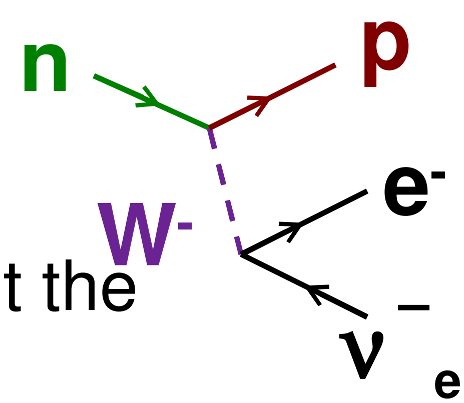
World's UCN projects

	source type	E_c neV	P_{UCN} /cm³/s	T_s s	ε_{ext}	ρ_{UCN} /cm³ source/exp.
TRIUMF	spallation He-II	210	0.4×10^4 (10L)	150	~1	3×10^5 (20L) 1-5 x 10^4
ILL	n beam He-II	250	10	150	~1	**/1000
SNS	n beam He-II	134	0.3 (7L)	500	1	**/150
LANL *	spallation SD2	250	4.4×10^4 (240cm³)	1.6	1.3×10^3/ 4.4×10^4	**/120
PSI	spallation SD2	250	2.9×10^5 (27L*)	6	0.1	2000 (2m³) /1000
NCSU	reactor SD2	335	2.7×10^4 (1L)	**	**	1300/**
Munich	reactor SD2	250	**	**	**	1×10^4/**

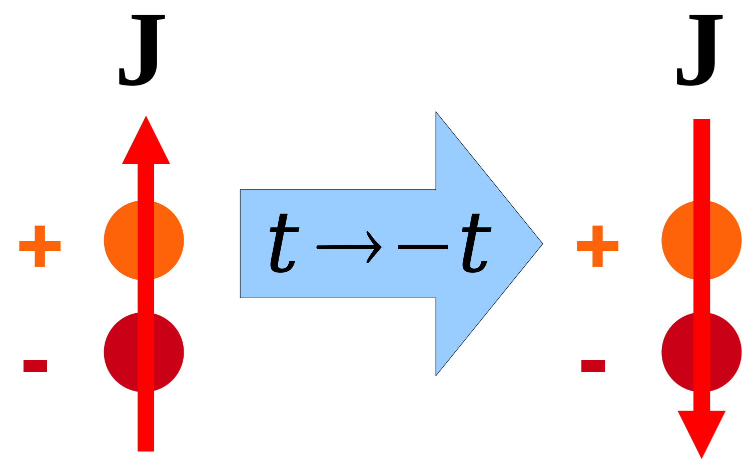
Physics Experiments with UCN

Fundamental Physics and Neutrons

- Neutrons and their interactions are a hot topic in particle physics.
  - 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 for i-SUN

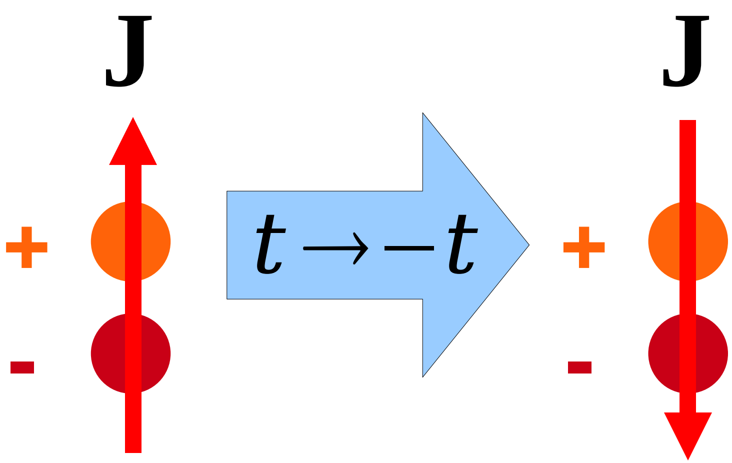
- neutron lifetime
- gravity levels
- n-EDM

near term

- $n\bar{n}$-oscillations
- Free n target

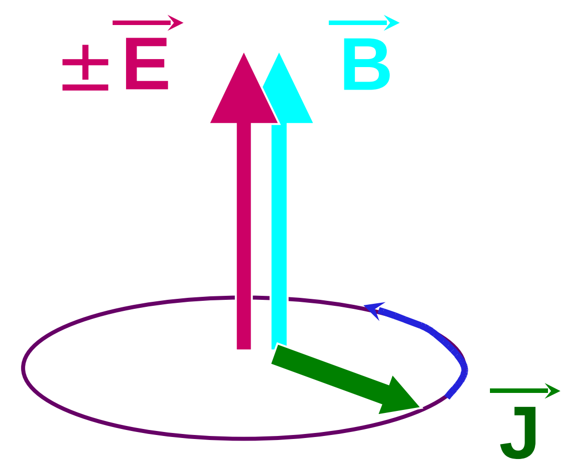
longer term

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.



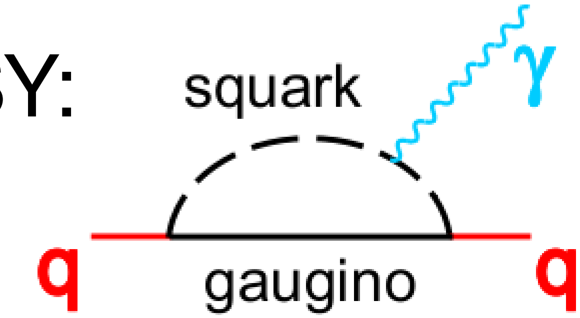
$$h\nu = 2\mu_n B \pm 2\mathrm{d}_e E$$

Experimental technique:
- put UCN in a bottle with *E*-, *B*-fields
- search for a change in spin precession frequency upon *E* reversal.

EDM's and 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:

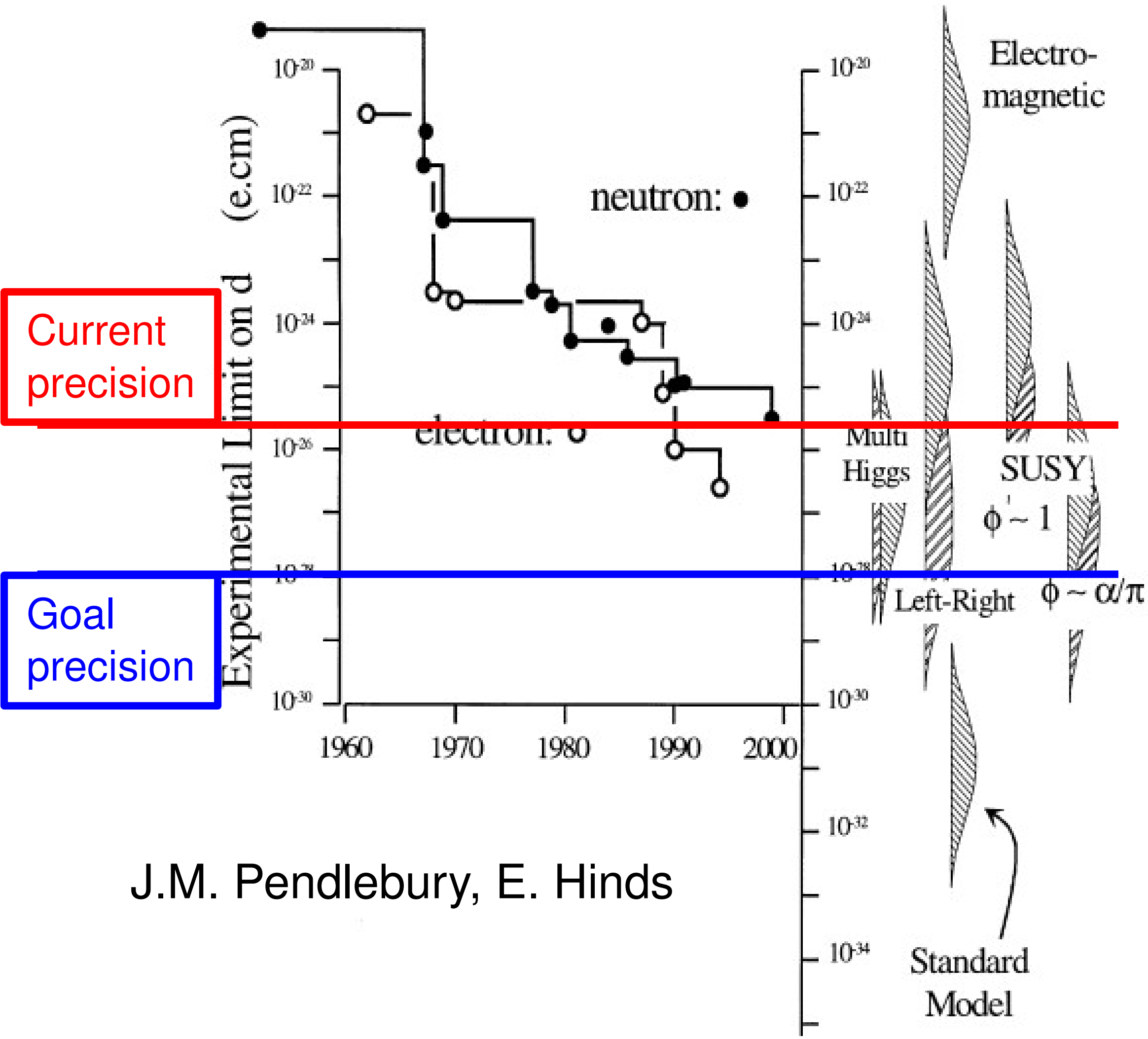
$$d_q \sim 3 \times 10^{-24} e \cdot cm$$

- 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"

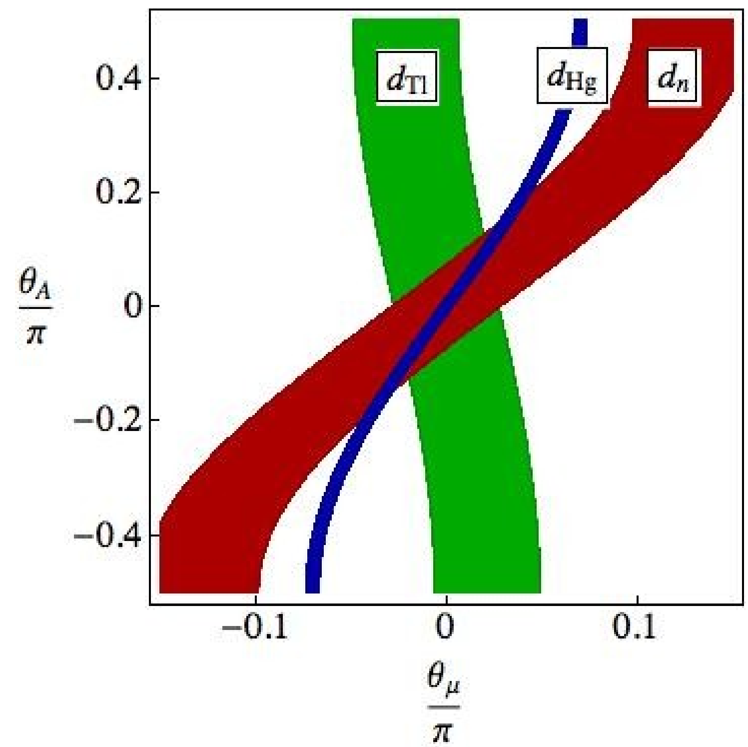
EDMs, the SM, and beyond



J.M. Pendlebury, E. Hinds

M. Romalis, MO-A4-2
A. Ritz, M. Pospelov, et al

SUSY M = 1 TeV, tanβ = 3

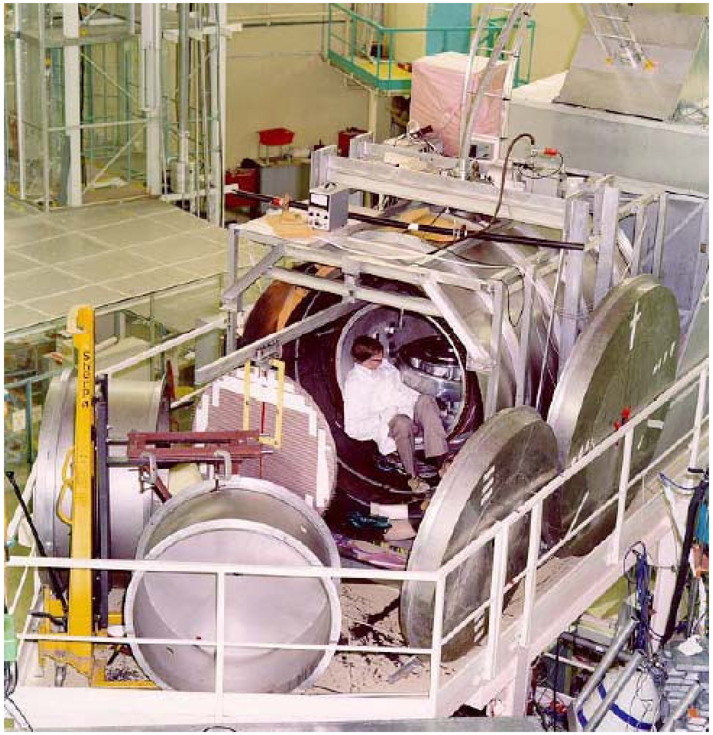


Note: universality assumptions are now even being tested
M. Ramsey-Musolf, TU-A10-3
A. Ritz, ...

- Ultimate goal: reach the SM limit

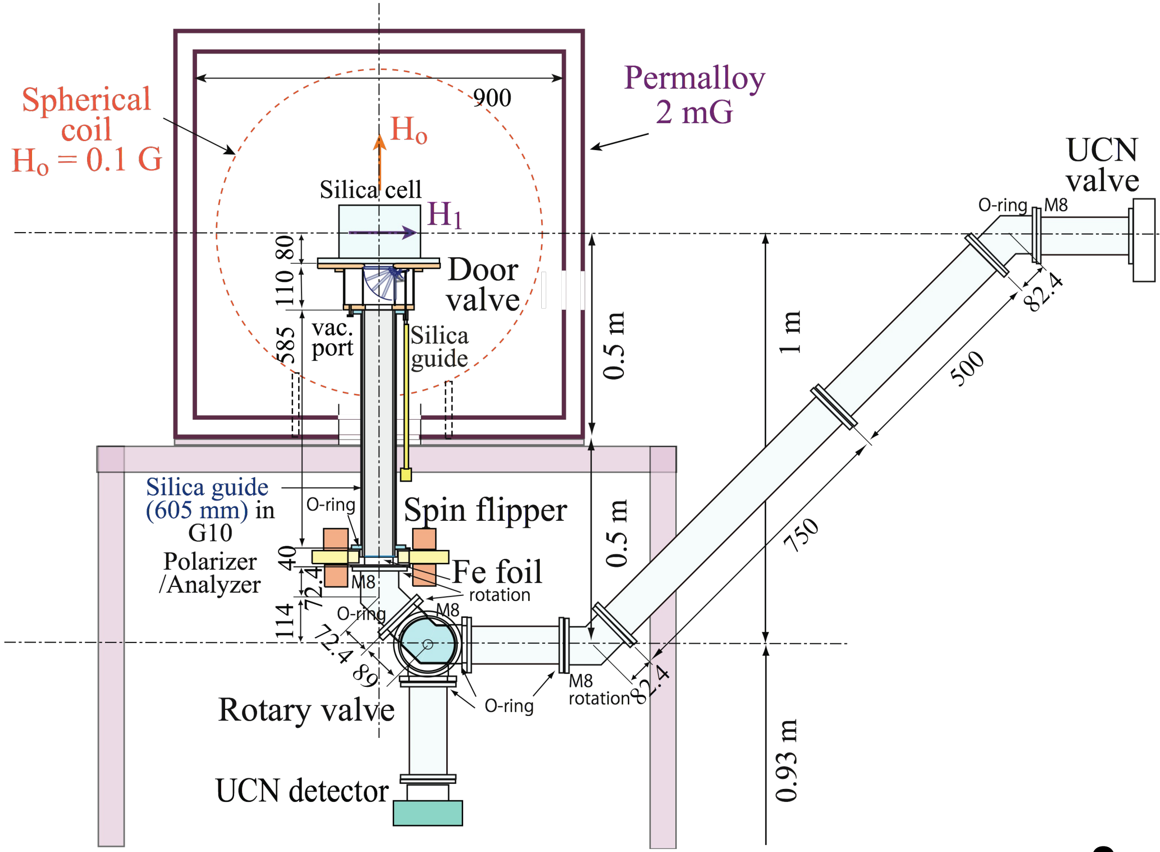
Past and Future n-EDM efforts

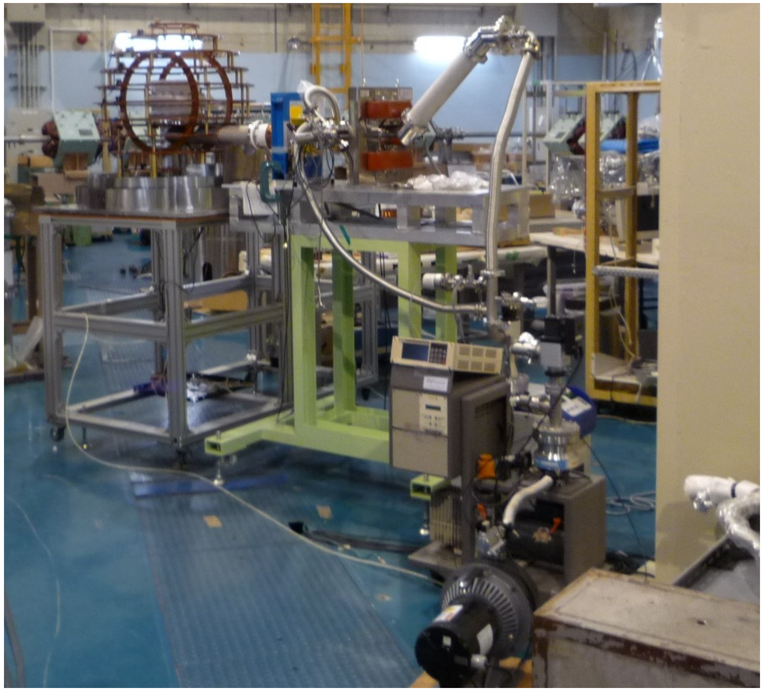
- Sussex-RAL-ILL expt. ($d_n < 3\times10^{-26}$ e-cm)
  - 0.7 UCN/cc, room temp, in vacuo
- CryoEDM (Sussex-RAL-ILL)
  - 1000 UCN/cc, in superfluid 4He
- SNS
  - 430 UCN/cc, in superfluid 4He
- PSI
  - 1000 UCN/cc, in vacuo
- TRIUMF: 1-5 x 10^4 UCN/cc



Sussex-RAL-ILL experiment

n-EDM development in Japan





- Development of:
  - Comagnetometers
  - Ramsey resonance
  - New B-field geometry

- Masuda, et al. First experiments July 7-16 at RCNP, Osaka.

What I did on my summer vacation

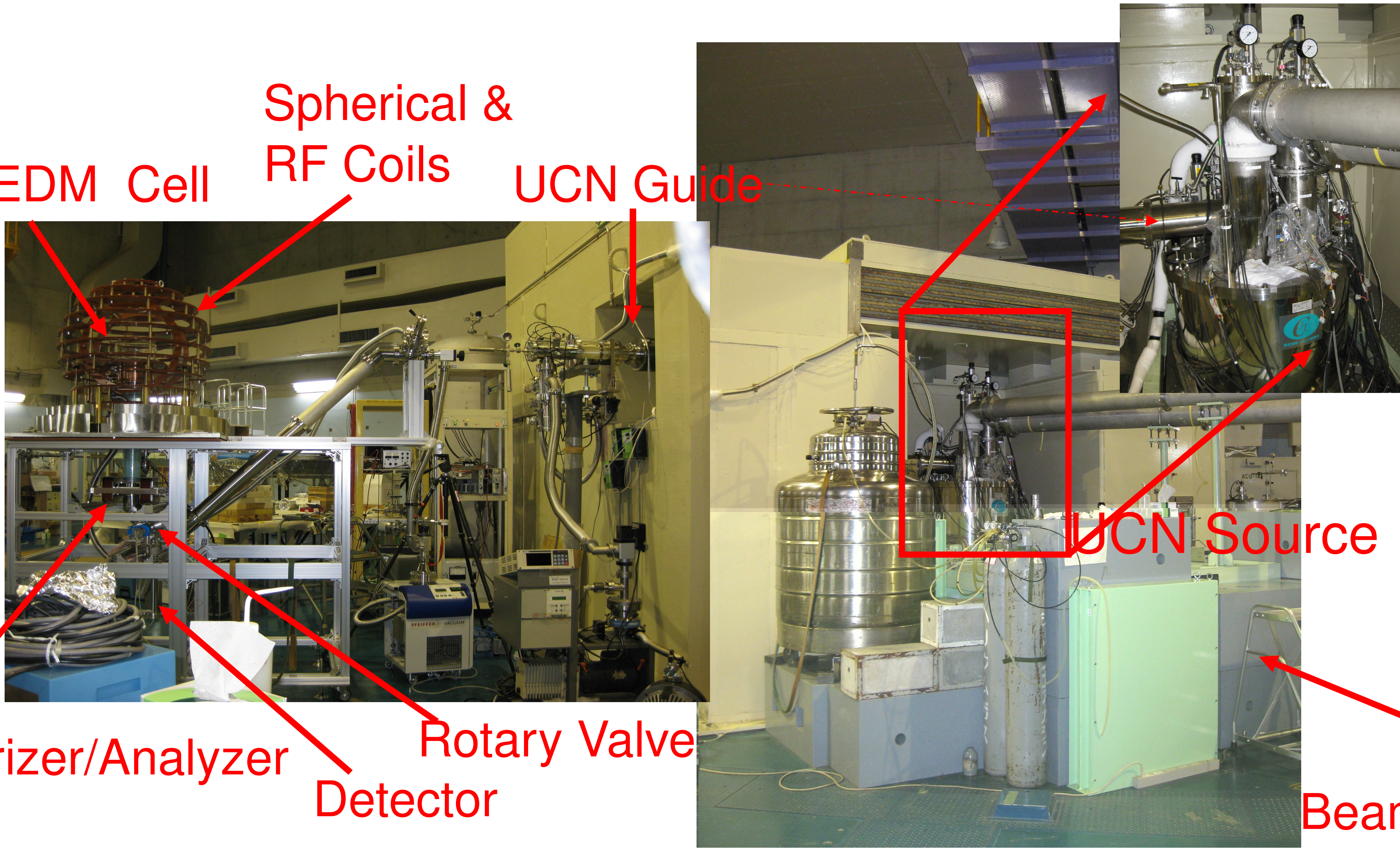
By Troy Dawson, MSc candidate.
(thank you for the slides, Troy!)

In one week of data-taking in July in Japan, we did:

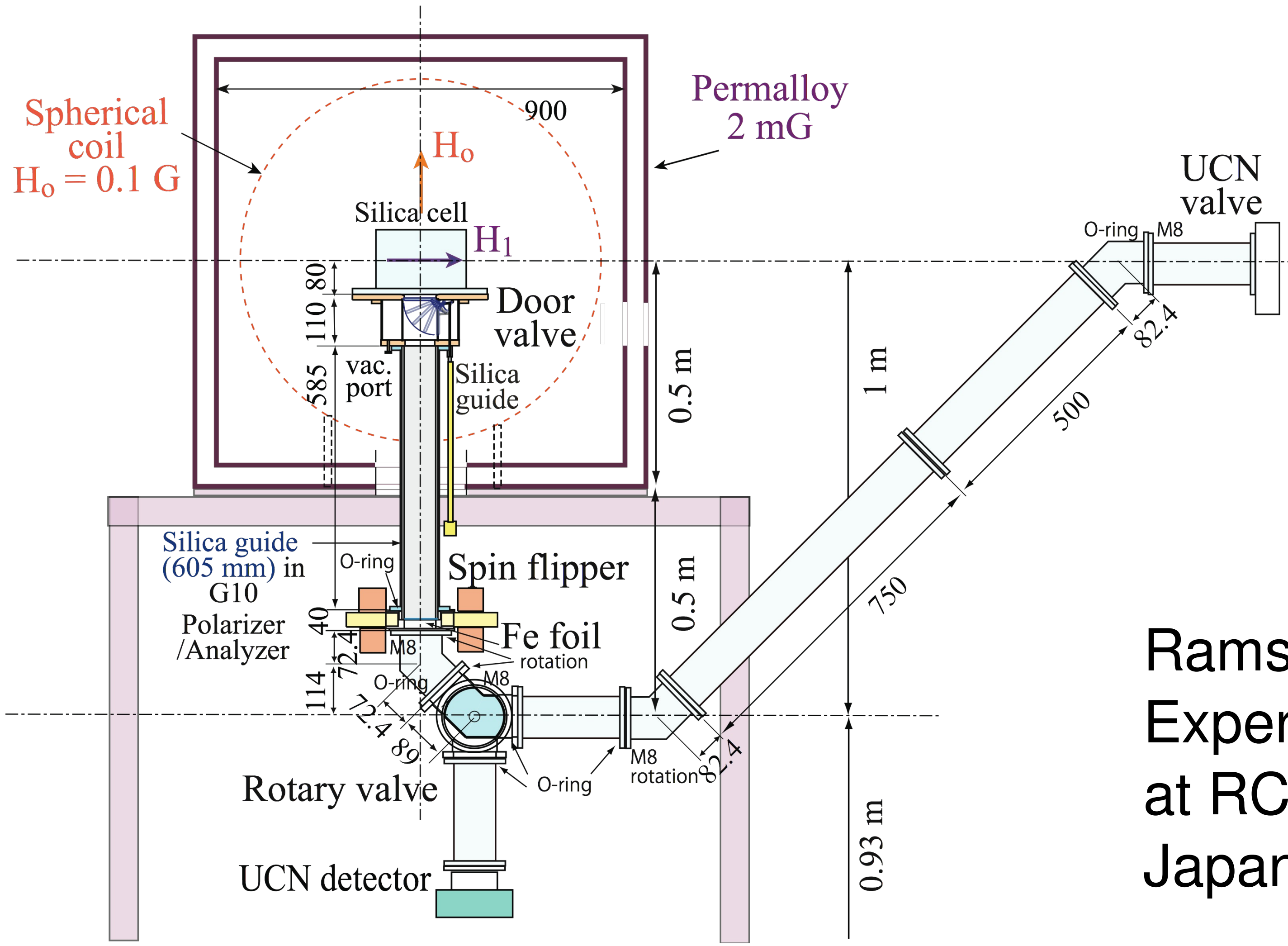
- UCN density optimization
- UCN transport & storage optimization
- UCN polarization
- Spin-flipping of UCN
- UCN polarization lifetime
- pi and pi/2 RF-pulses applied to UCN spins in a new spherical coil
- Ramsey resonance!!!

We did everything except apply the electric field!

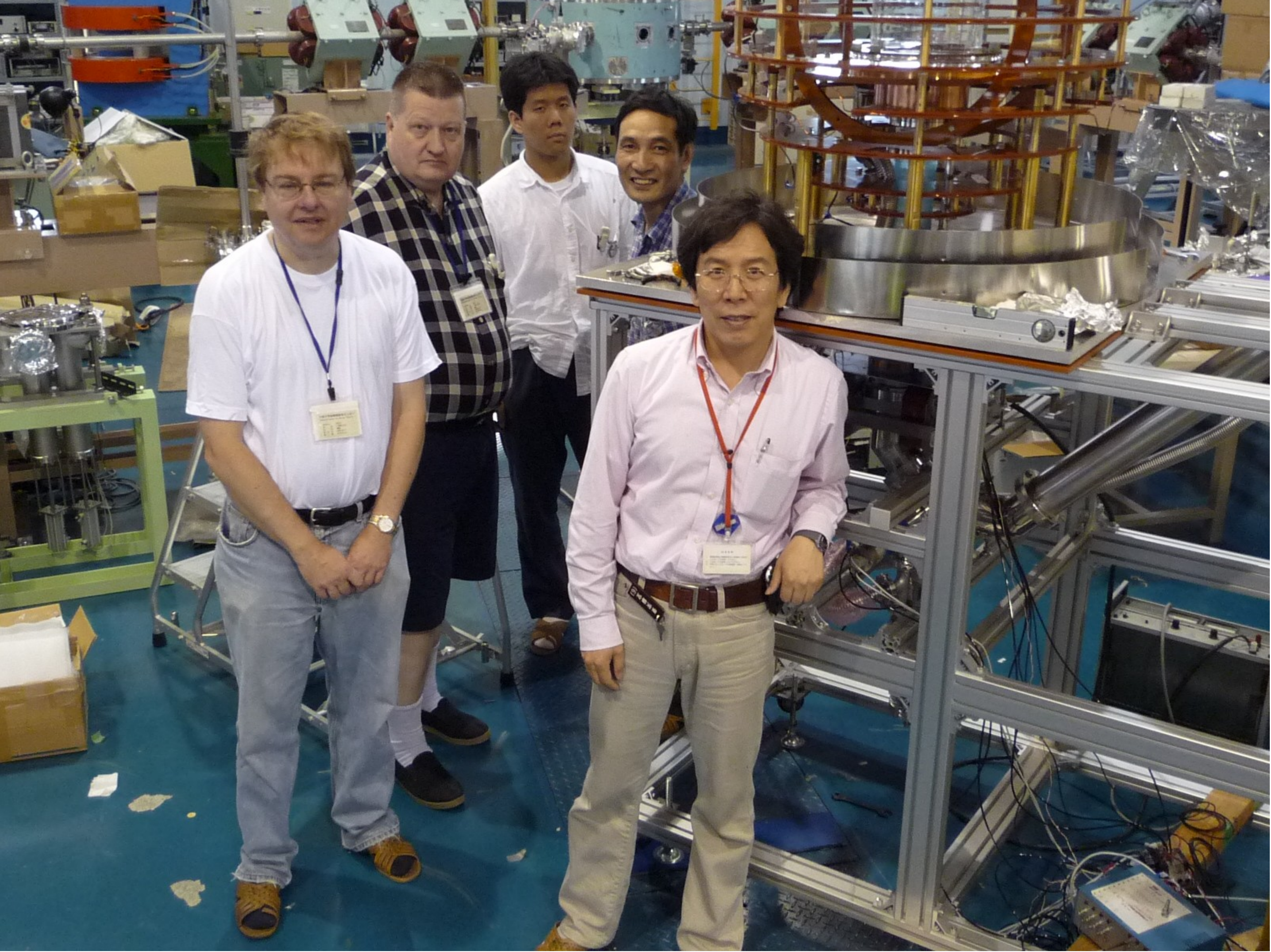
Experimental Set Up



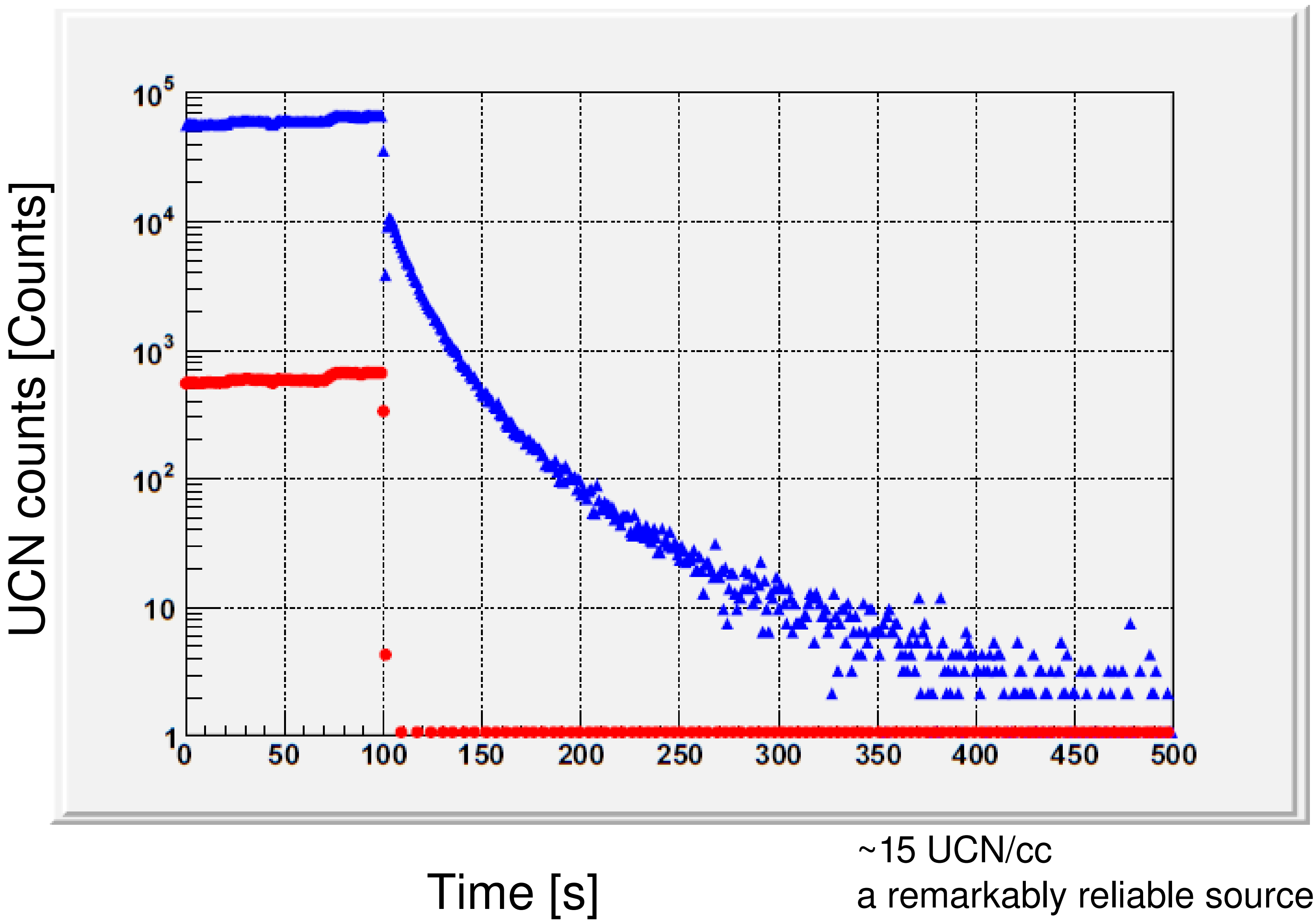
Experimental Overview



Ramsey Resonance Experimental Set up at RCNP, Osaka, Japan



Proton Beam 1μA x 100 s

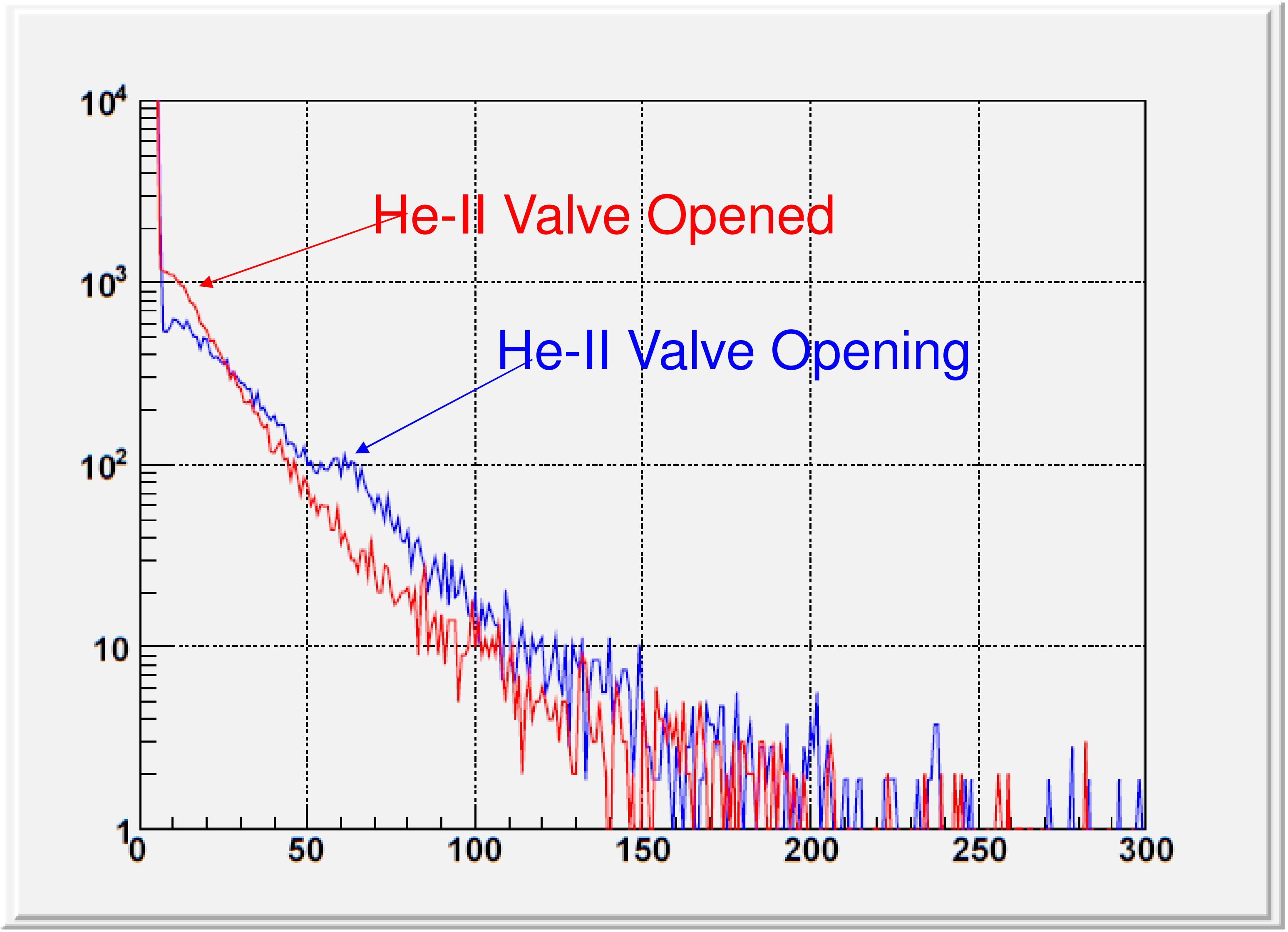


~15 UCN/cc

a remarkably reliable source of UCN

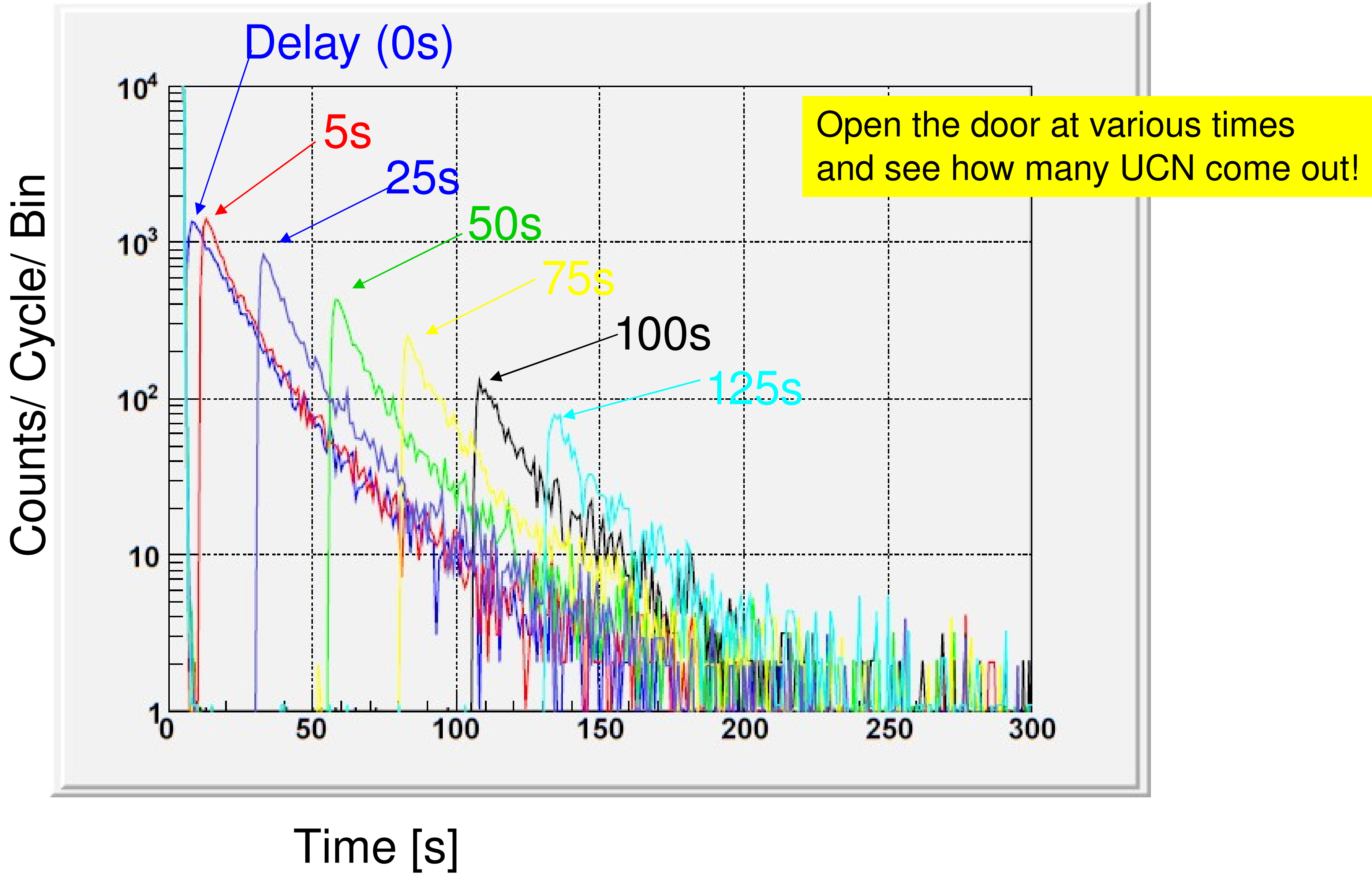
He-II Valve

Note shorter p-pulse

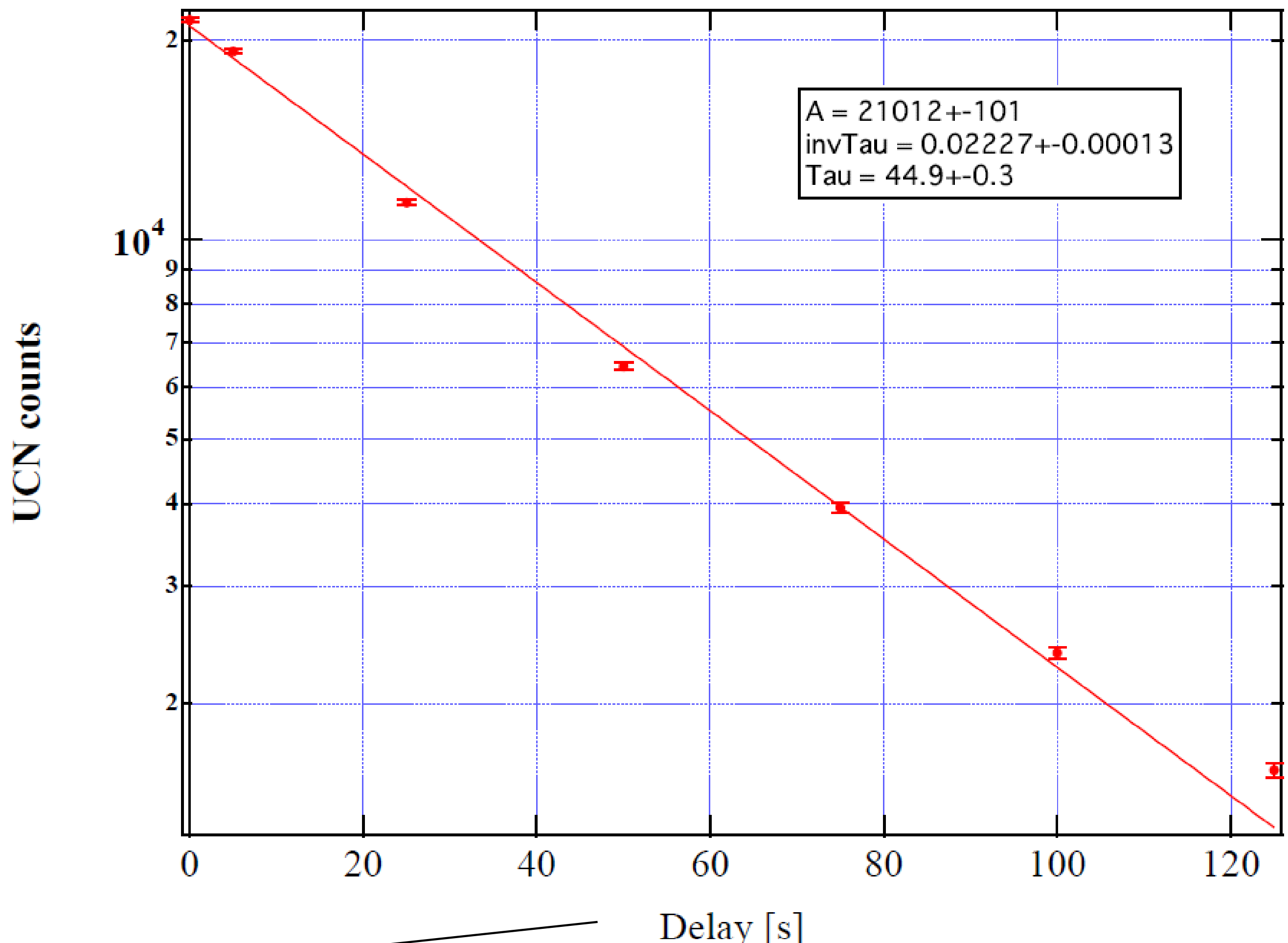


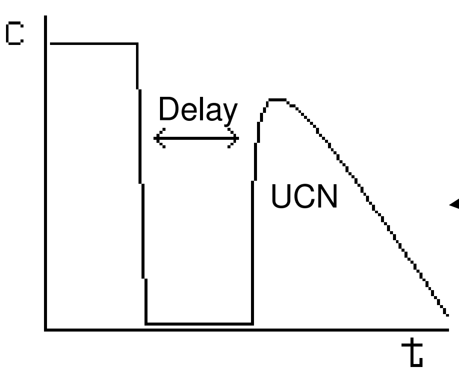
The He-II valve appeared to be stuck. Fortunately, it was mostly open.
We shelved all density optimization to a future run.
We now believe this to be an error in the use of the actuator (mfr error).

Upstream UCN Storage Time



Storage Time up to GV

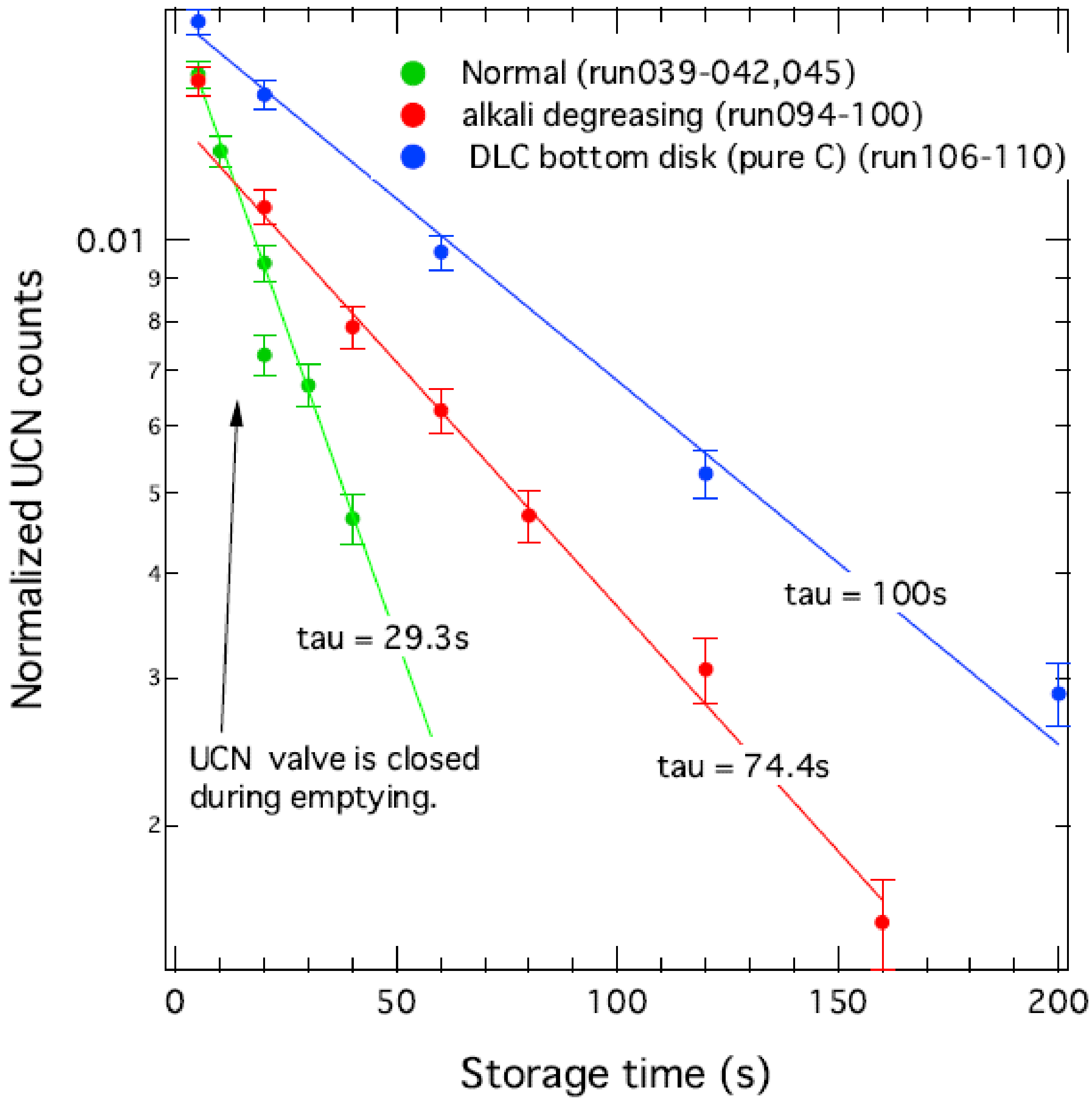




UCN Valve is closed

1μA p-beam
5s beam on time

Storage Time in EDM Cell



Polarizing UCN

- How to polarize UCN:
  - Inside a magnetized foil...

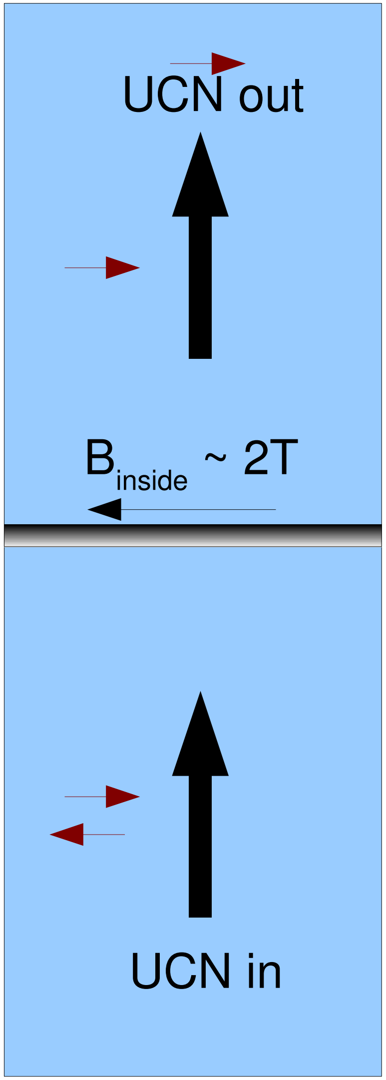
$$V = V_{Fermi} \pm \mu \cdot B$$

- For neutrons, mu = 60 neV/T
- Where our foil is located,

  100 neV < T_{UCN} < 150 neV

- For steel, V_{Fermi} ~ 250 neV

$$V = 250\, neV \pm 120\, neV$$



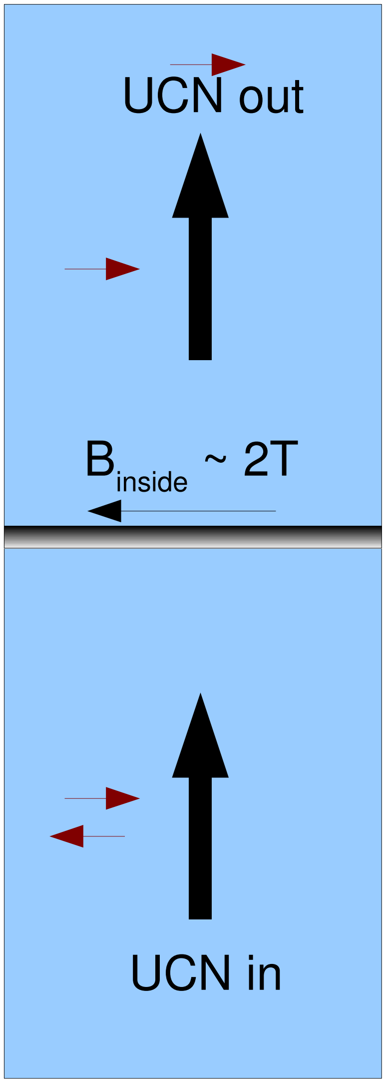
Spin Analysis

- Fine, but how do you know they're polarized?

  1. Add an analyzer magnet.

  2. Flip their spins and leak them back out through the same magnet.

- We did #2.



Spin Manipulation

- How to flip or otherwise manipulate spins:
  1. "π" pulse
  2. Adiabatic Slow Passage
  3. Adiabatic Fast Passage
- In this experiment, we use all three effects.
- The "spin flipper" uses the AFP method.

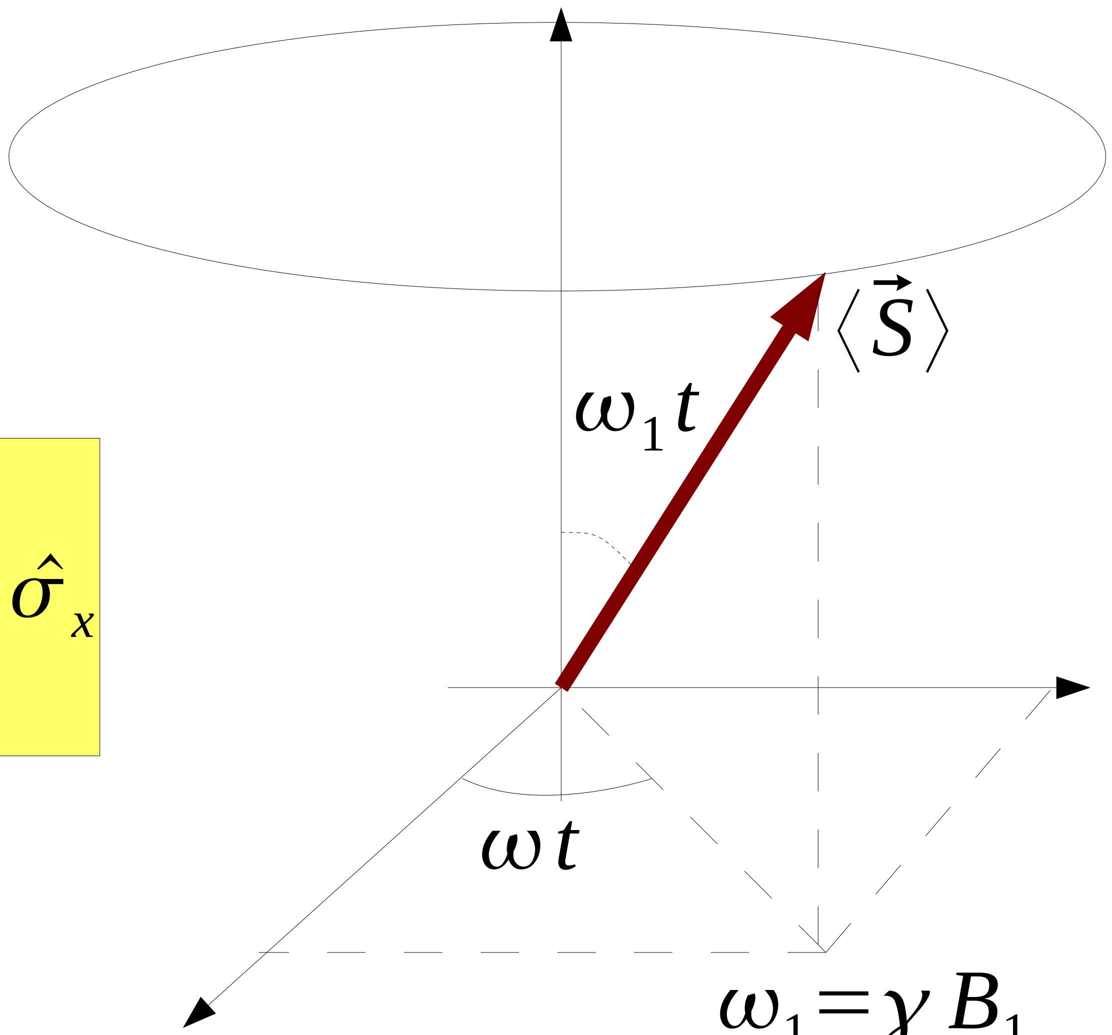
π Pulse

$$\chi(0)=\begin{pmatrix}1\\0\end{pmatrix}$$

$$H=-\mu\cdot B(t)$$
$$=-\mu B_0\hat{\sigma}_z-\mu B_1\cos\omega t\,\hat{\sigma}_x$$
$$\text{for } B_1\ll B_0,\quad \omega\approx\omega_0$$

$$\chi(t)=\begin{pmatrix}a(t)\\b(t)\end{pmatrix}$$

$$\langle S_x\rangle=\chi^\dagger\hat{S}_x\chi$$
$$\langle S_y\rangle=\chi^\dagger\hat{S}_y\chi$$
$$\langle S_z\rangle=\chi^\dagger\hat{S}_z\chi$$



$$\omega_1=\gamma B_1$$
$$\omega_0=\gamma B_0\approx\omega$$

π-pulse: $\omega_1 t = \pi$ = spin flip!

$\pi/2$-pulse: $\omega_1 t = \pi/2$

Rabi's Rotating Frame

- Spin dynamics in non-rotating frame:

$$\frac{d\vec{S}}{dt} = \gamma \vec{S} \times \vec{B}$$

- In rotating frame, time derivatives look different:

$$\frac{d\vec{S}}{dt} = \frac{\partial \vec{S}}{\partial t} + \vec{\omega} \times \vec{S}$$

- Spin dynamics in rotating frame:

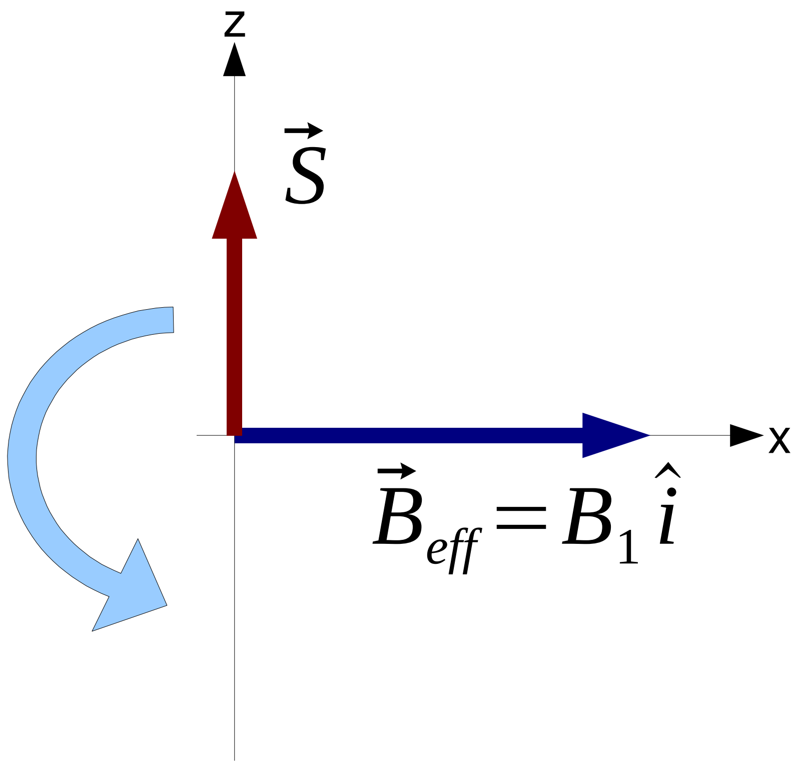
$$\frac{\partial \vec{S}}{\partial t} = \gamma \vec{S} \times \vec{B}_{eff}$$ where $$\vec{B}_{eff} = \left(B_0 - \frac{\omega}{\gamma} \right) \hat{k} + B_1 \hat{i}$$

Rabi, Ramsey, Schwinger, Rev. Mod. Phys.

Example: π-pulse in rotating frame

- On resonance:

$$\omega \approx \omega_0 = \gamma B_0$$
$$\Rightarrow \vec{B}_{eff} = B_1 \hat{i}$$

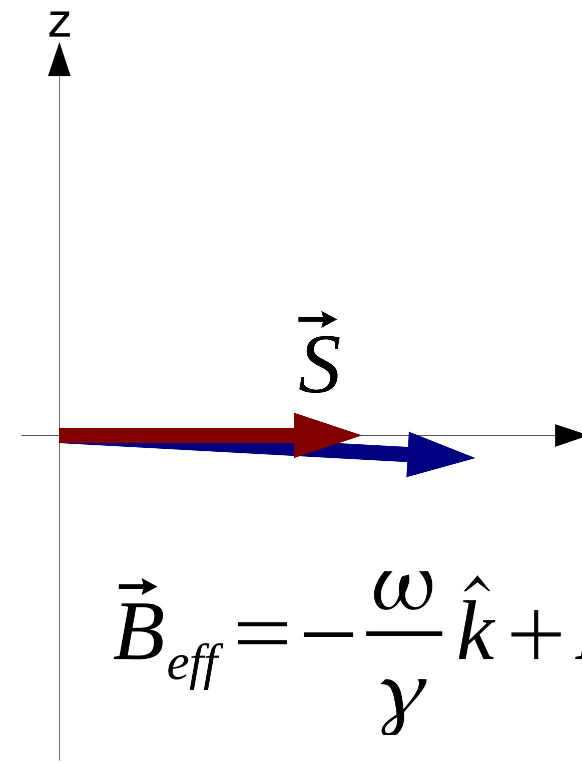


- In the rotating frame, this is free precession about the x-axis.

Adiabatic Spin Condition and Adiabatic Slow Passage

- Consider what happens if $B_0 = 0$, and the spin starts initially along the x-axis.
- The spin stays aligned with the rotating B as long as.

$$\omega \ll \gamma B = \omega_{Larmor}$$



$$\vec{B}_{eff} = -\frac{\omega}{\gamma}\hat{k} + B_1 \hat{i}$$

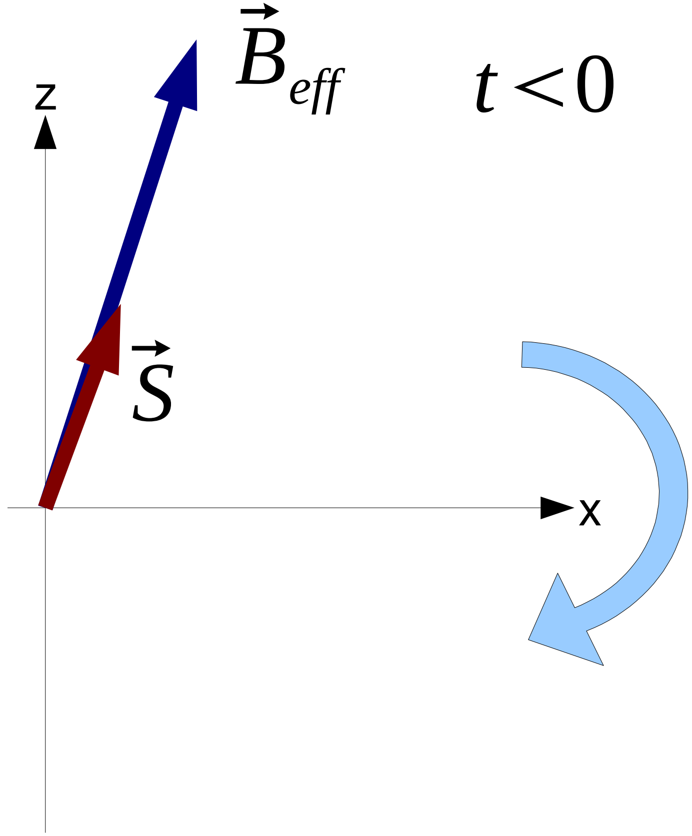
$$\frac{dB}{dt} = v_{UCN} \frac{dB}{dx} \ll \omega_{Larmor} B$$

- Adiabatic Slow Passage:
  - Spin of moving UCN tracks magnetic field direction, as long as B-field is “smooth”

Adiabatic Fast Passage

- Consider monotonically decreasing $B_0(t)$ which sweeps through resonance with RF field

$$\vec{B}_{eff} = \left(B_0(t) - \frac{\omega}{\gamma} \right) \hat{k} + B_1 \hat{i}$$

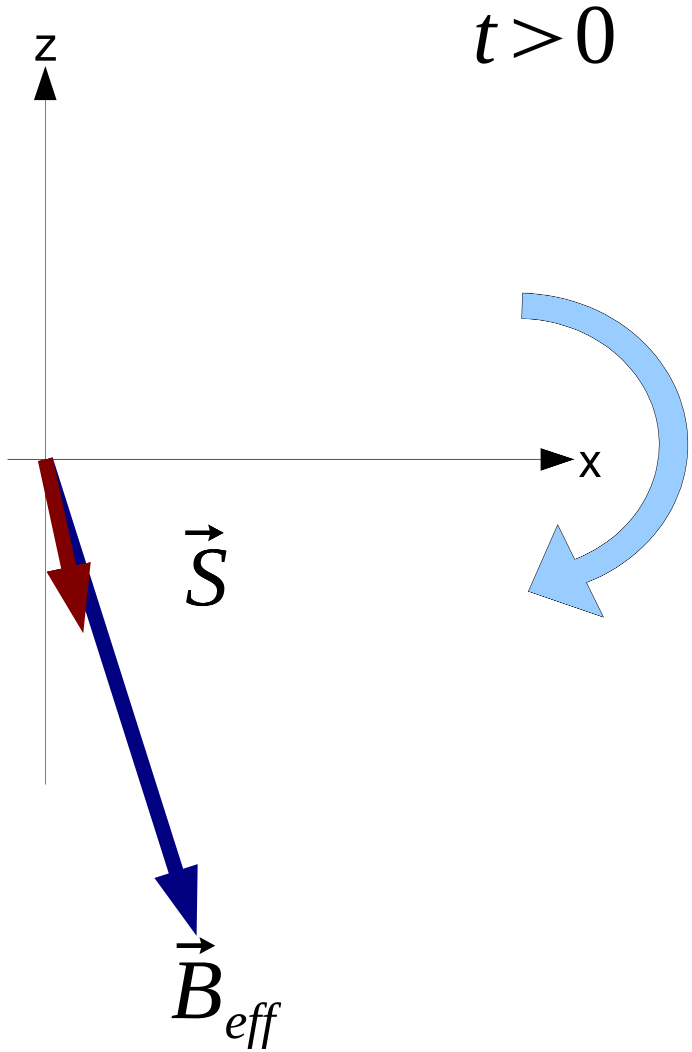


Adiabatic Fast Passage

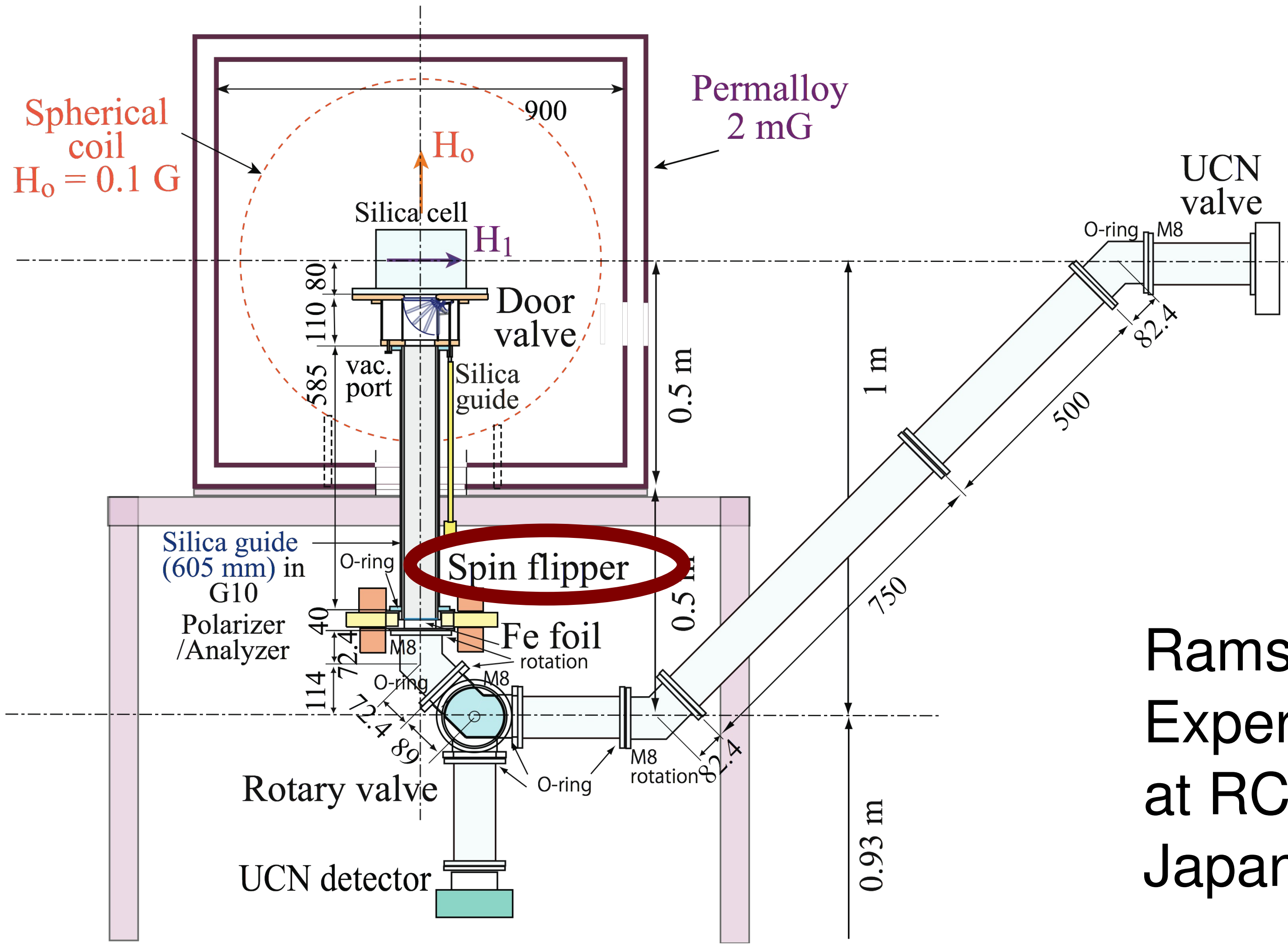
- Consider monotonically decreasing $B_0(t)$ which sweeps through resonance with RF field.

$$\vec{B}_{eff}=\left(B_0(t)-\frac{\omega}{\gamma}\right)\hat{k}+B_1\hat{i}$$

- AFP is ASP in the rotating frame.
- UCN passed through RF field in a DC gradient will spin flip.

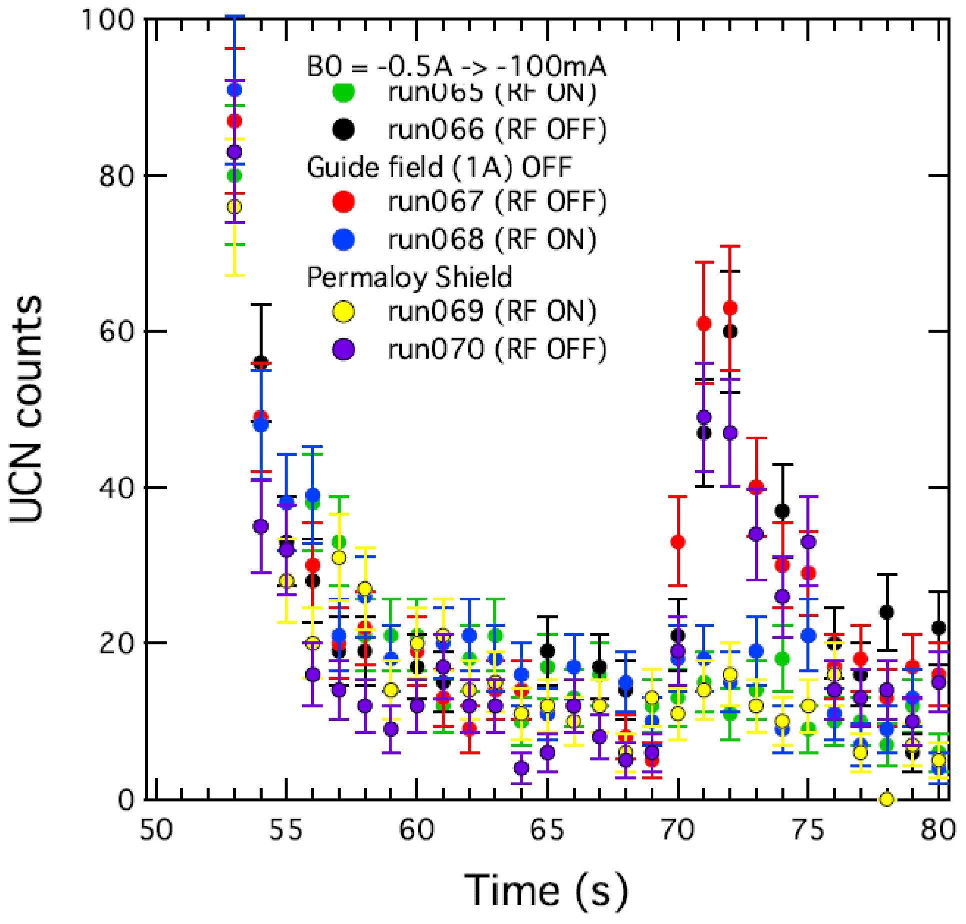


Experimental Overview

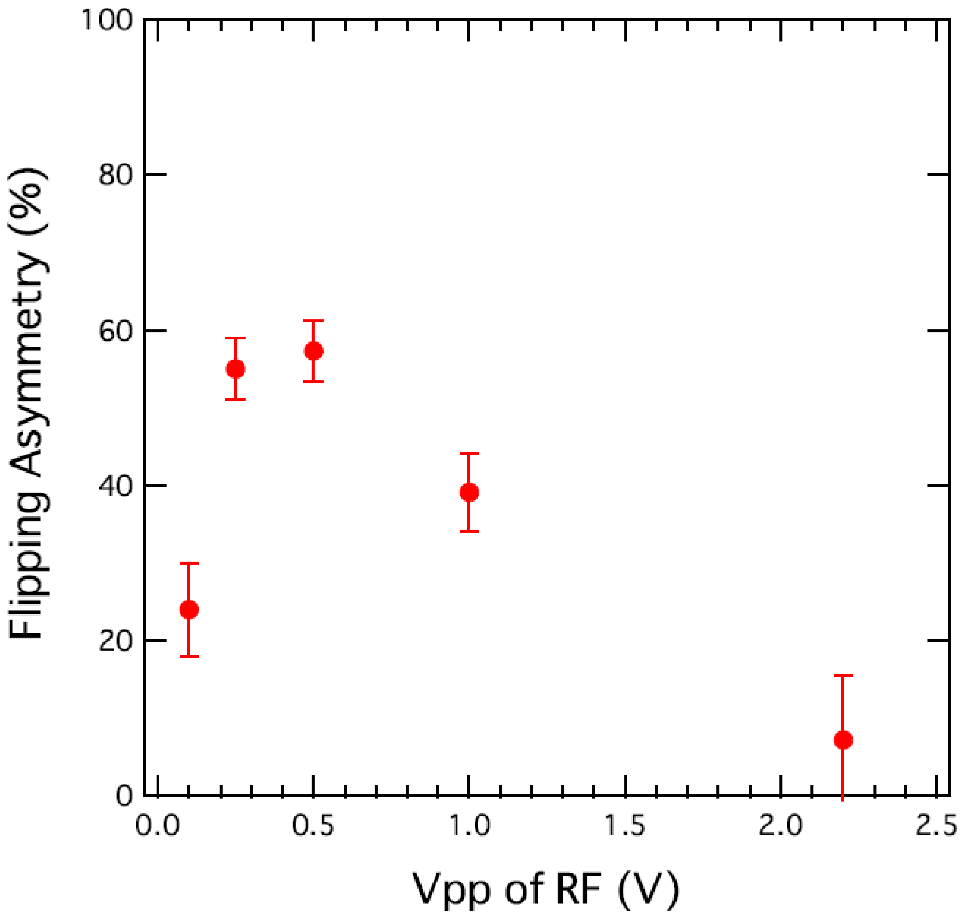


Ramsey Resonance Experimental Set up at RCNP, Osaka, Japan

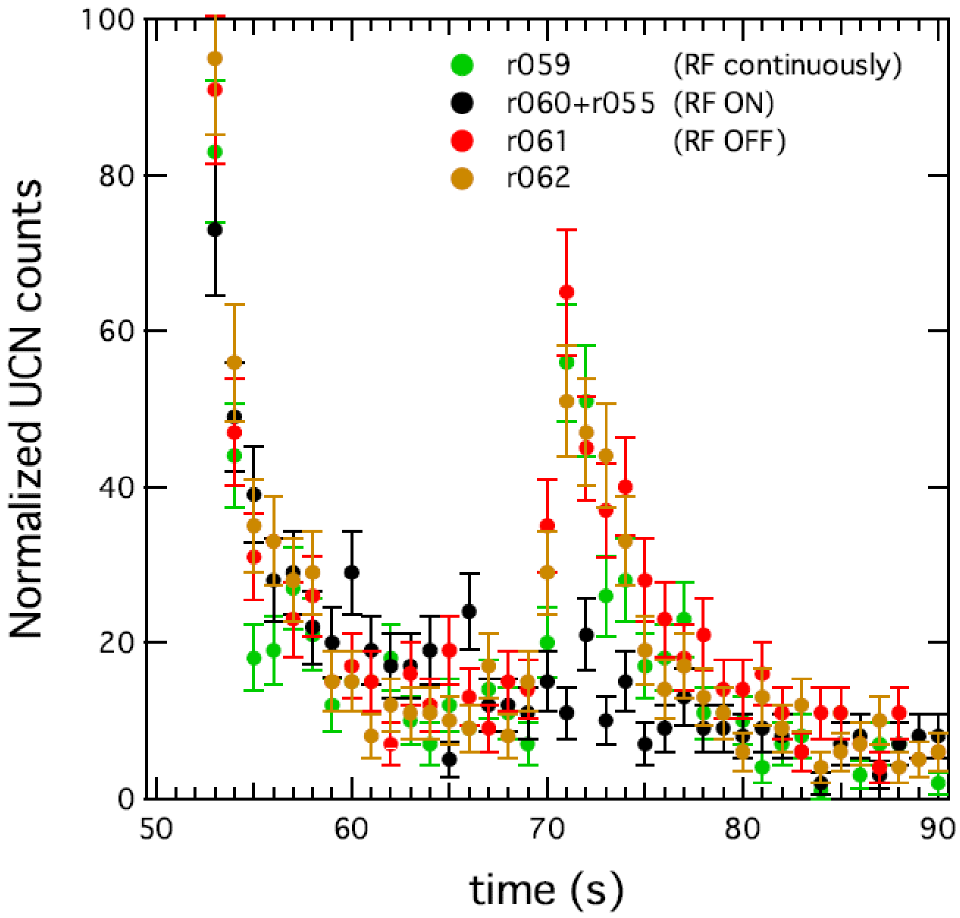
Optimization of UCN Polarization



RF Dependence for AFP Spin Flipper

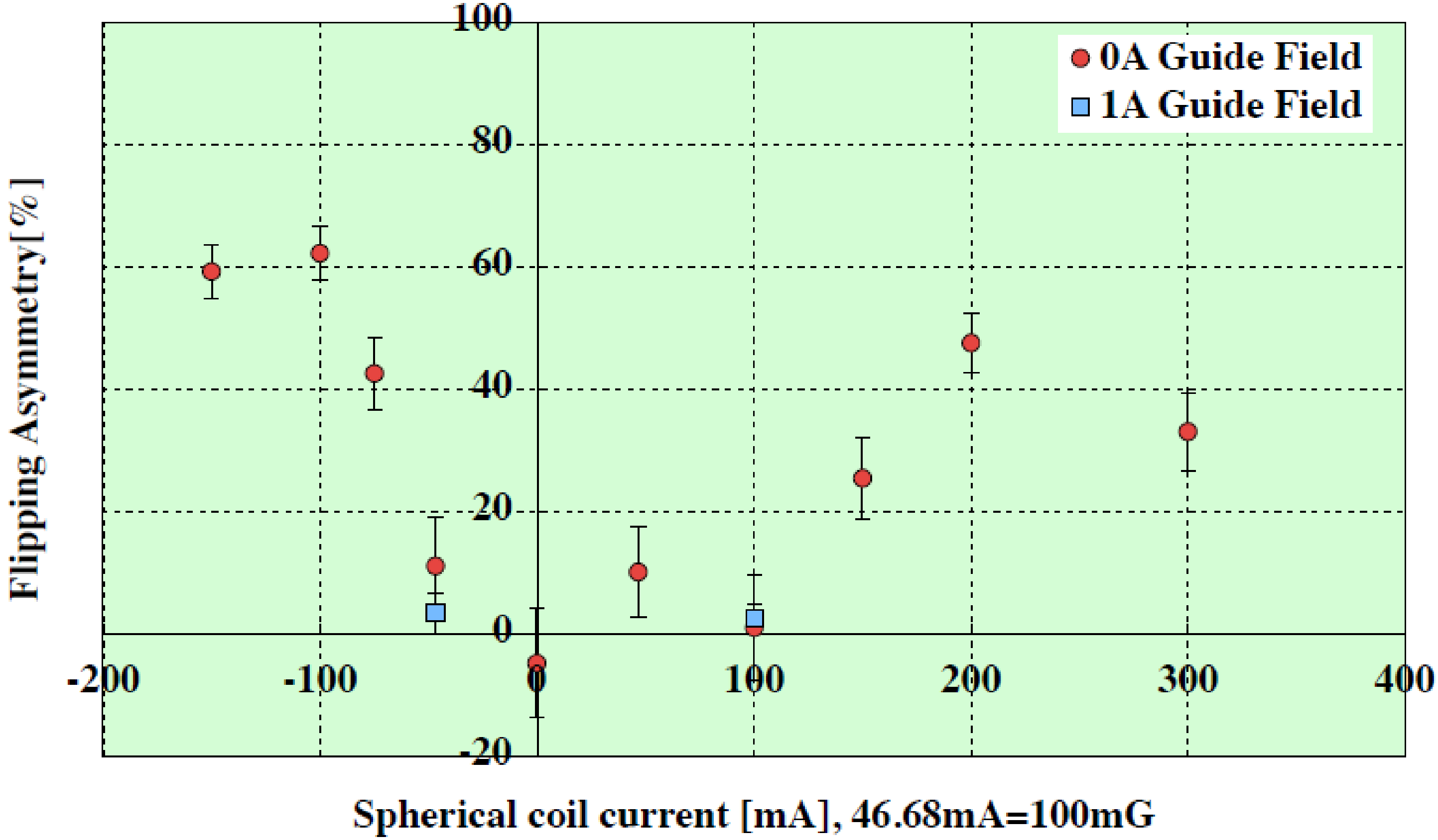


Spin Flipper Efficiency



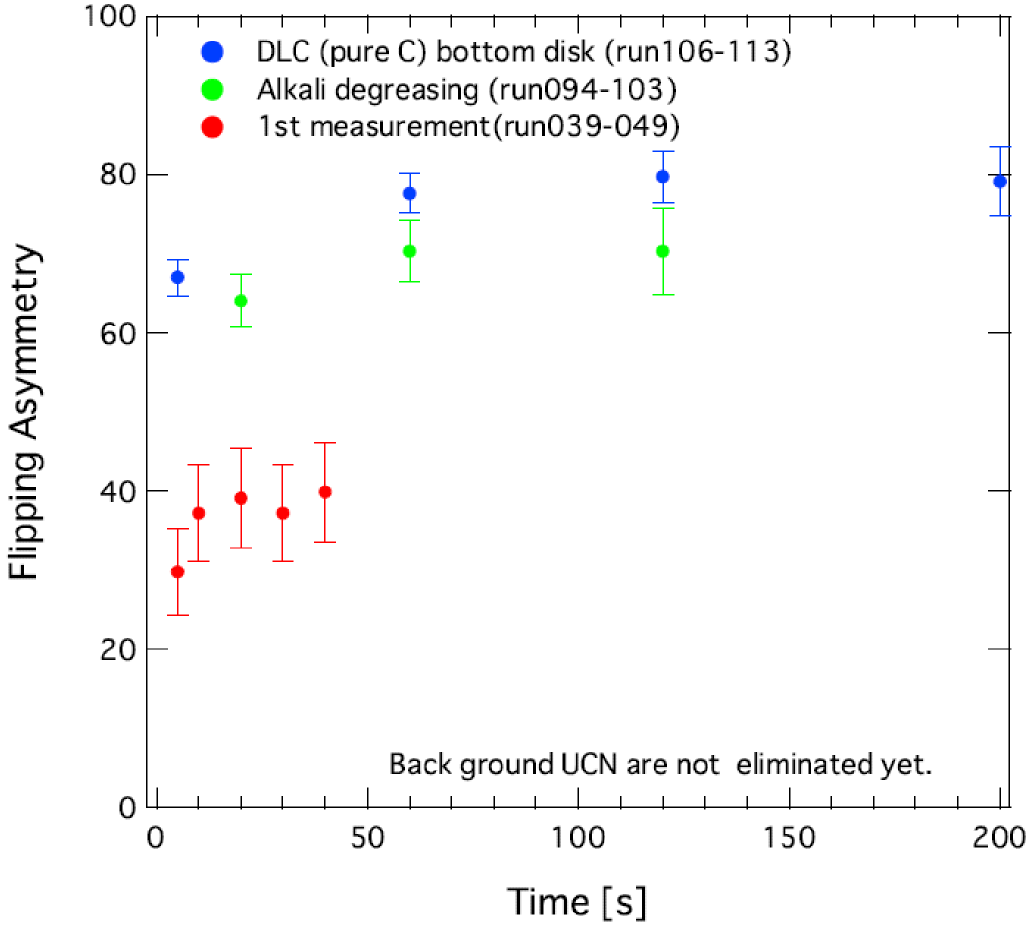
Efficiency > 90%

Spherical Coil Current Selection



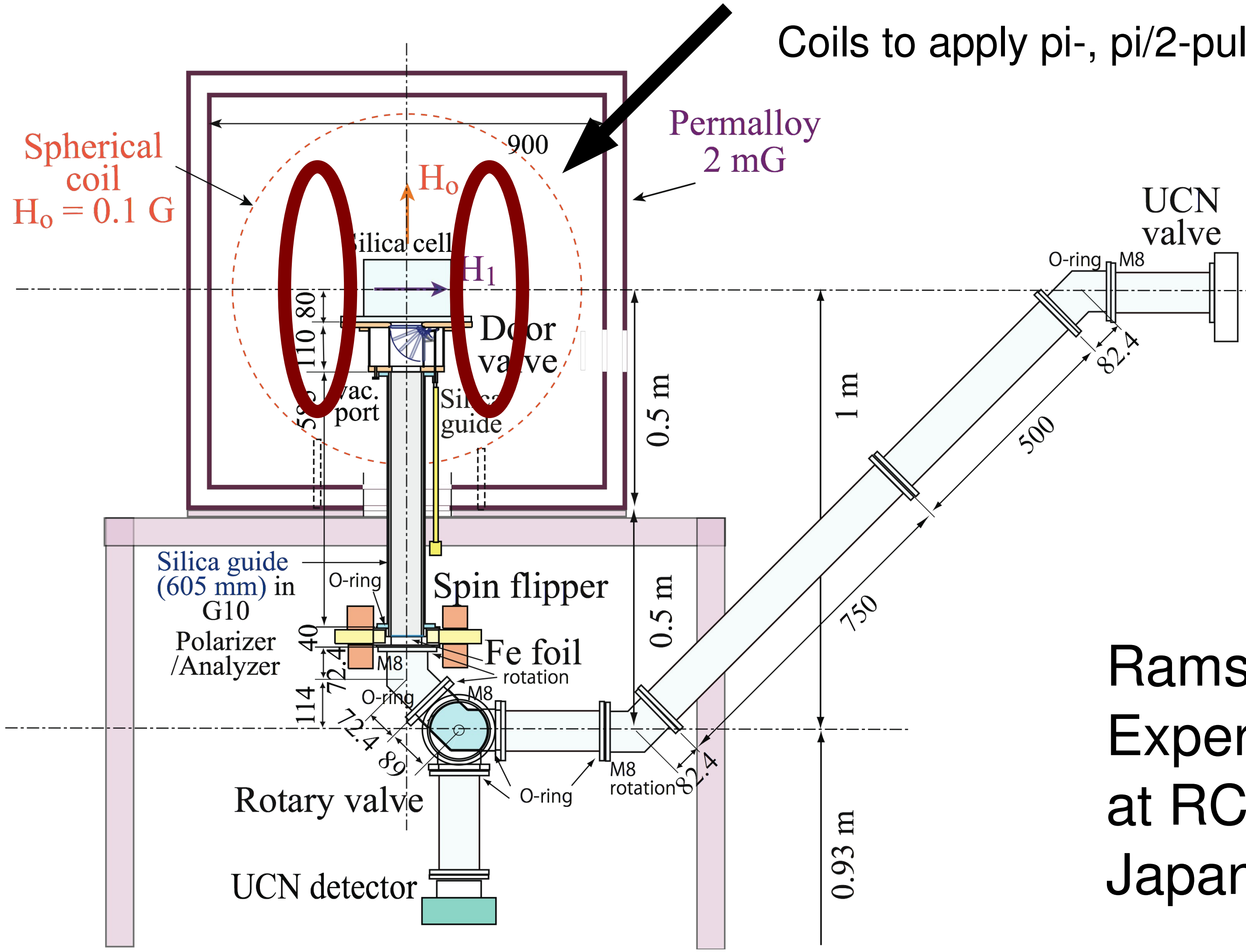
Needed ~200 mG field (big) to keep polarization

Asymmetry Lifetime



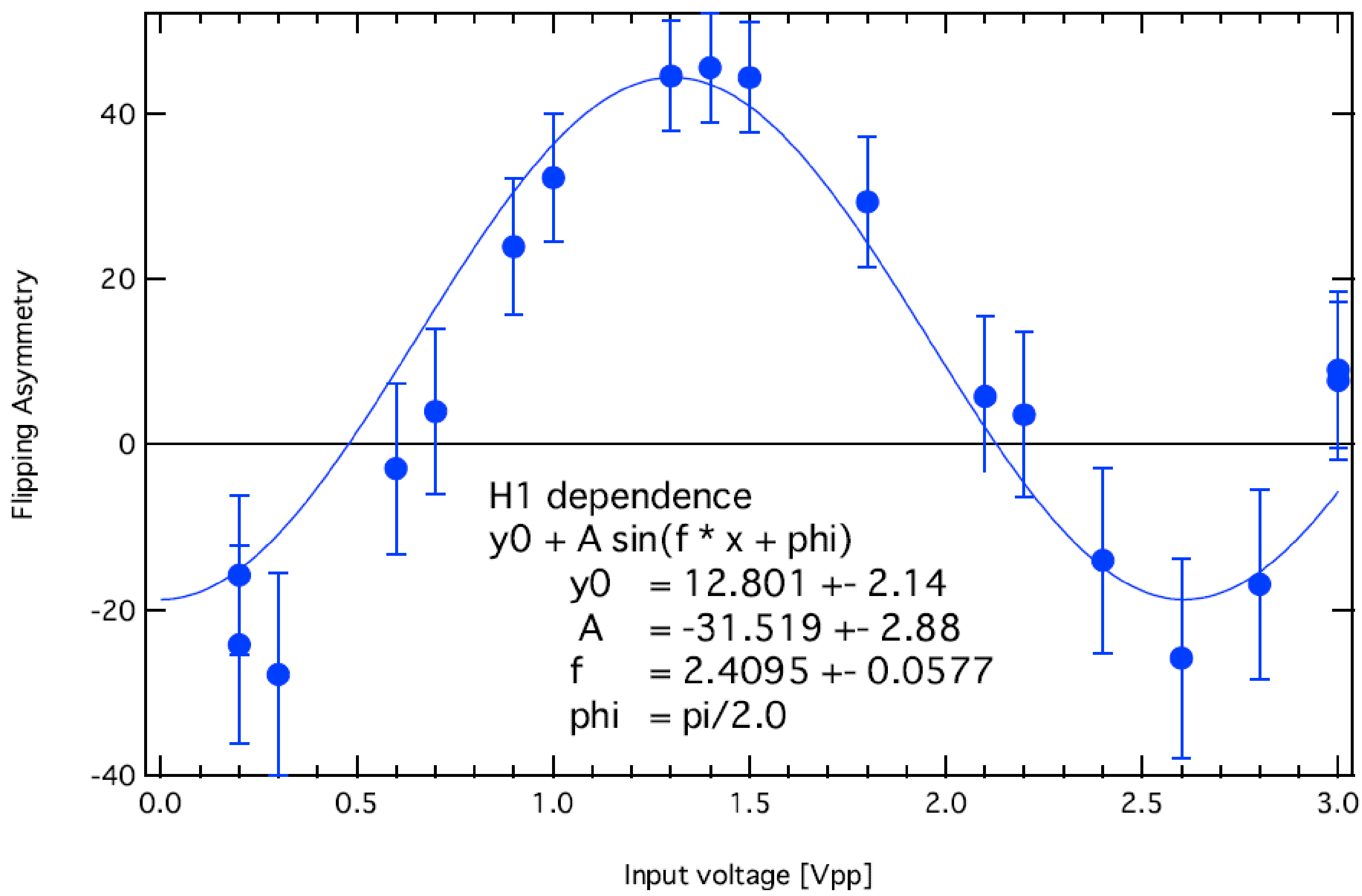
Experimental Overview

Coils to apply pi-, pi/2-pulses

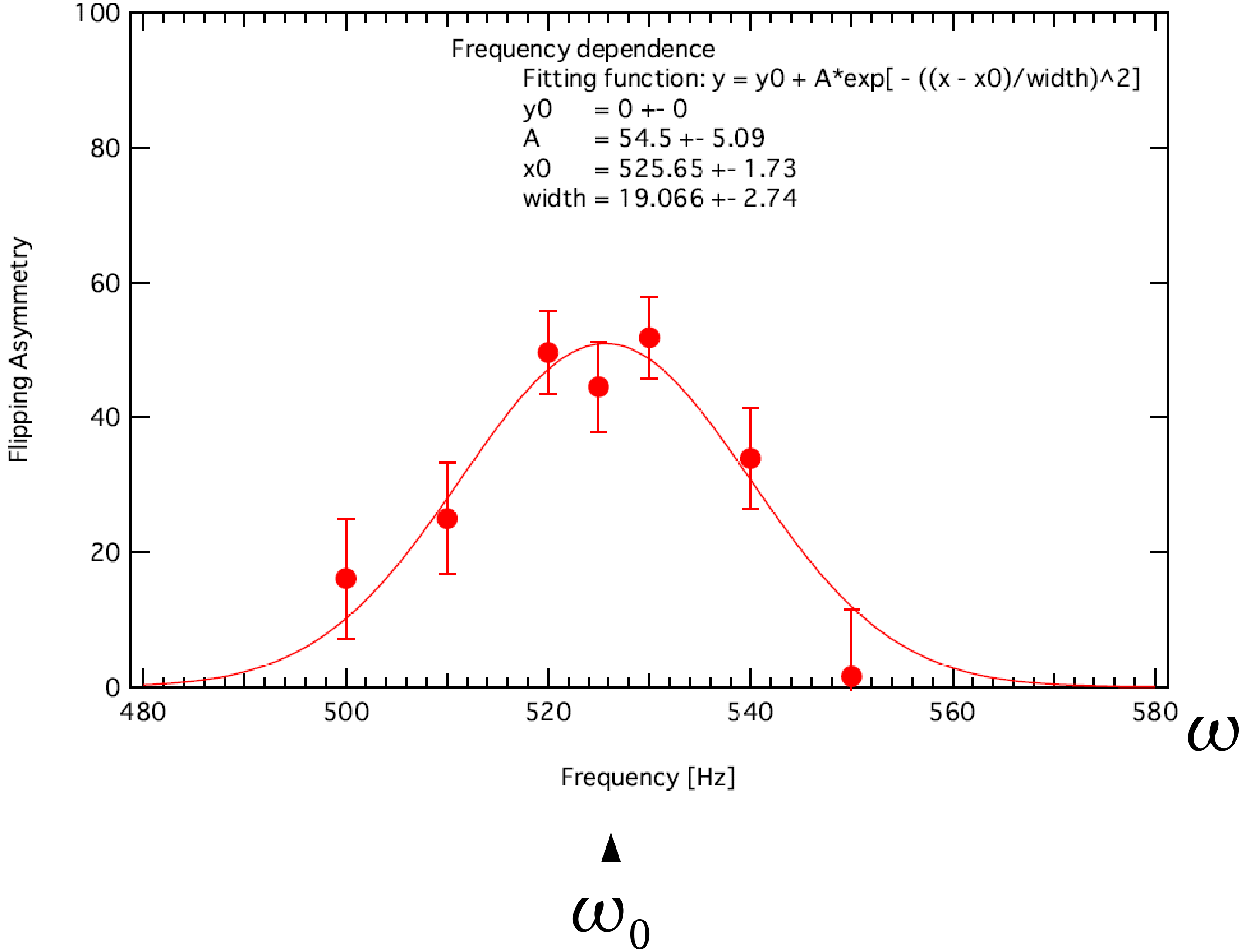


Ramsey Resonance Experimental Set up at RCNP, Osaka, Japan

Asymmetry vs. Applied B_1

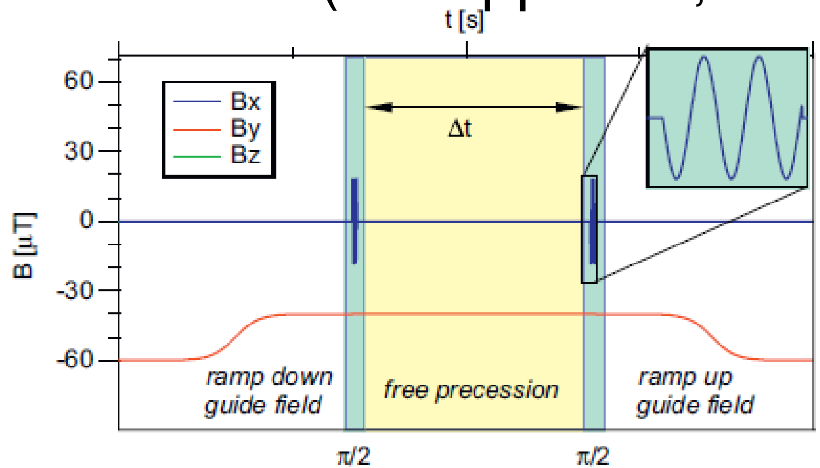


Asymmetry vs. Frequency



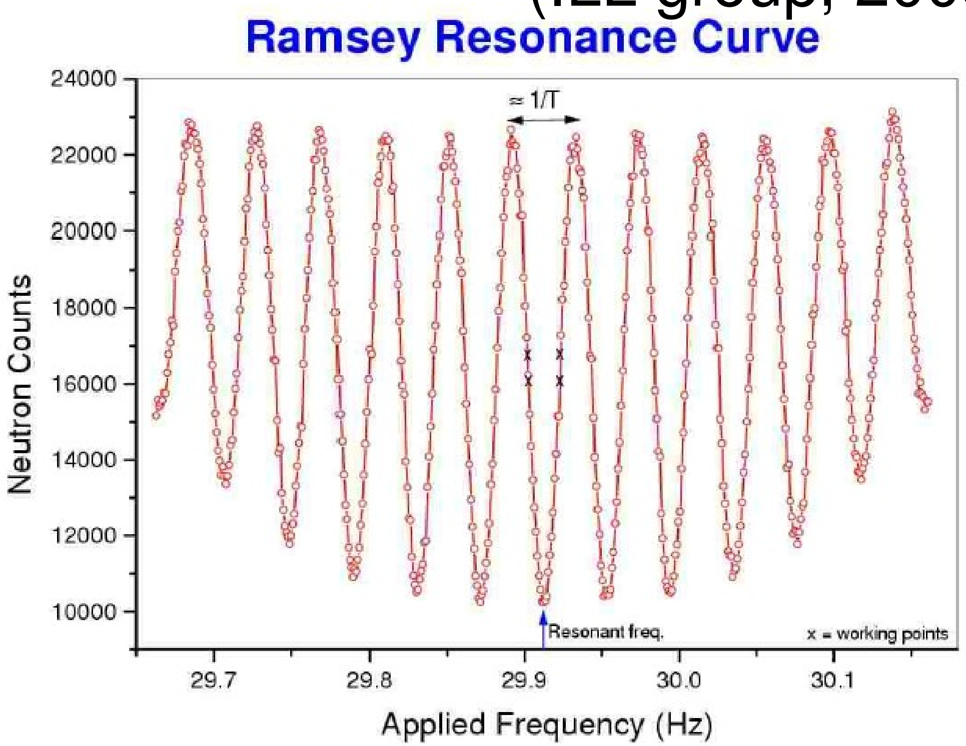
Ramsey Resonance

(S.Filipp et al, 2009)

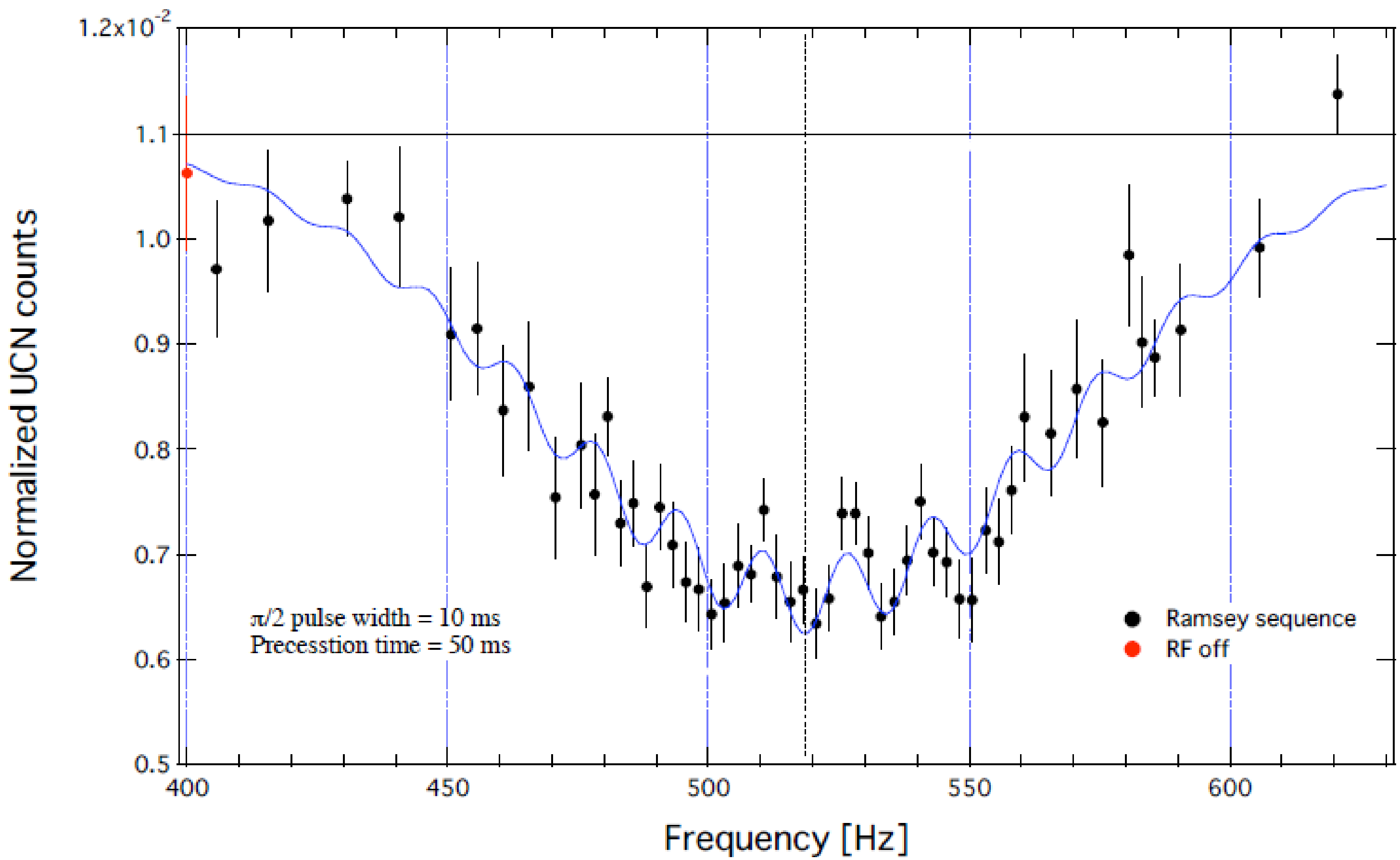


- π/2 pulse
- free precession time τ
- π/2 pulse
- For $\omega = \omega_0$, no UCN.
- Vary ω and narrow "Ramsey fringes" are observed.
- Width of fringe ~ $1/\tau$

(ILL group, 2003)



Ramsey Resonance Results
Masuda et al 2009



T = 50 ms, we also did T = 25 ms

Problems: Dephasing (τ_2)

- Statics spins: $$\tau_2 \sim \frac{1}{\delta\omega} = \frac{1}{\omega_0(\delta B_0 / B_0)}$$
- Moving spins: ("motional narrowing") $$\tau_2 \sim \frac{1}{(\delta\omega)^2 \tau_c} = \frac{1}{\omega_0^2 (\delta B_0 / B_0)^2 \tau_c}$$

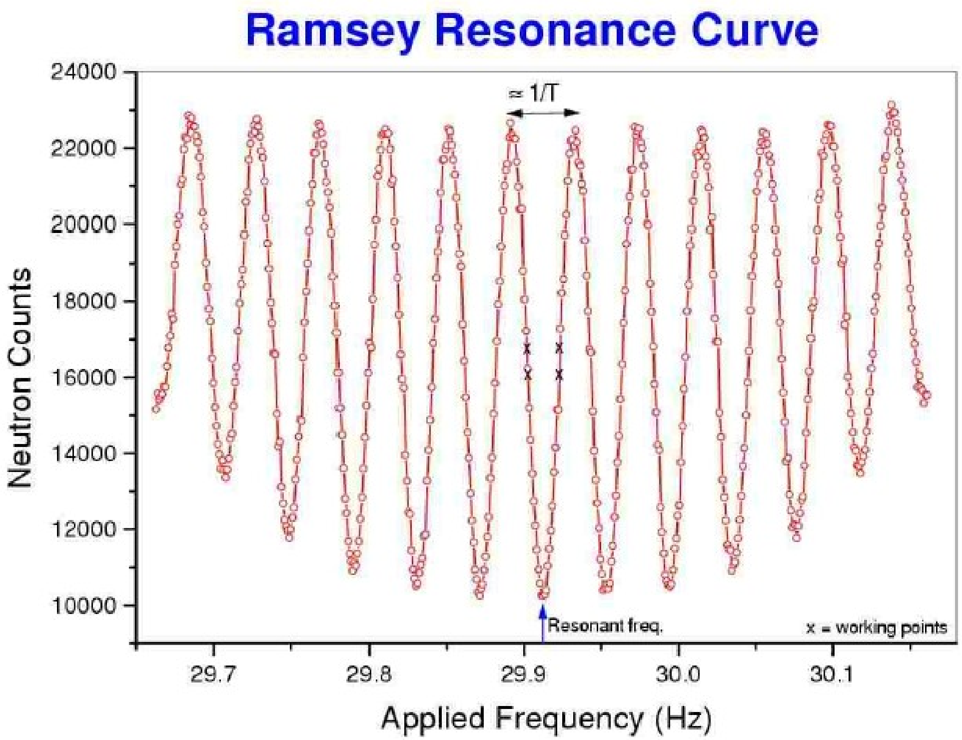
τ_c = correlation time
~ MFP / v_{UCN}
~ 0.1 s

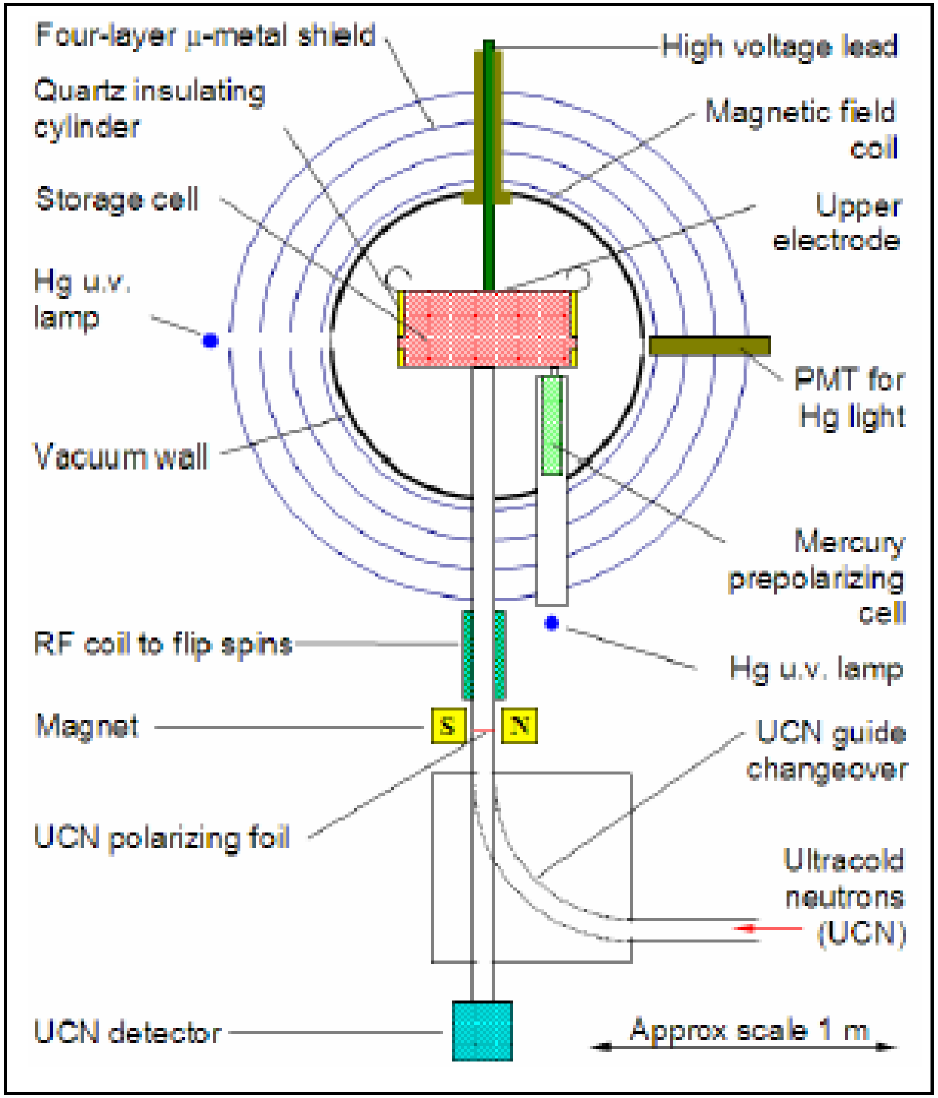
- Typical parameters for us:

$$\omega_{.} = ۲\pi ۵۰۰\, Hz$$
$$\delta B_{.} / B_{.} = ۱۰^{-۲}$$
$$\Rightarrow \tau_{۲} = ۱۰\, ms$$ (bad)

- Simply reducing ω_0 and inhomogeneity by factor 10 each would give T_2 = 100 s. (ILL 130 s)

EDM Method





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

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

EDM Statistics

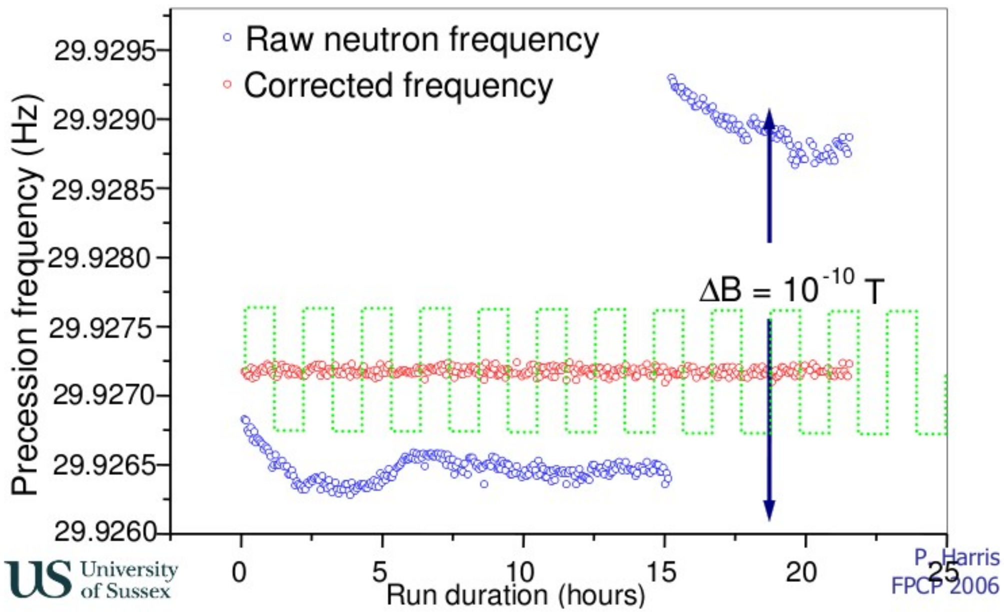
$$\sigma\left(d_n\right) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

- ILL:
  - α=0.64, τ=130 s, E=10 kV, N=14000 UCN/cycle
  - 1 UCN/cc: $\sigma(d_n)=1.7 \times 10^{-25}$ e-cm/day
  - Final stat. error: $\sigma(d_n)=1.5 \times 10^{-26}$ e-cm
- TRIUMF projected:
  - 10^4 UCN/cc: $\sigma(d_n)=1.7 \times 10^{-27}$ e-cm/day
- e.g. SNS projected:
  - $\sigma(d_n) \sim 3 \times 10^{-27}$ e-cm/day (B. Filippone, FNAL seminar 06)

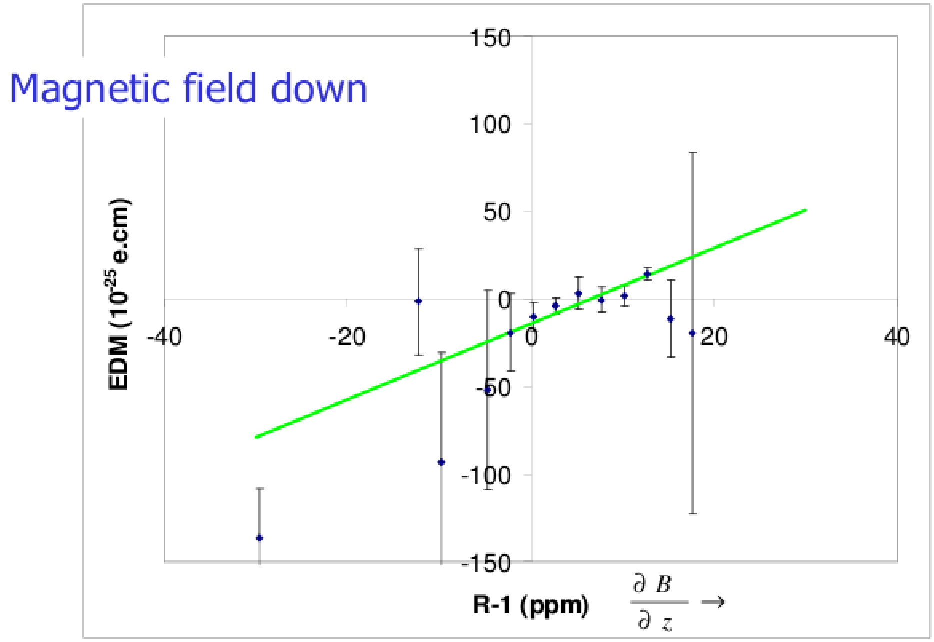
n-EDM Systematics

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

(co)magnetometry



comagnetometry



false EDM (GP) effect

Plans for TRIUMF

- Complete experiments in Japan, 2009-2011.
- Develop proposal for TRIUMF ~ 2011.
  - higher UCN density allows smaller cell size
    - smaller GP effect, also Xe comagnetometer buffer gas.
- We are building our experience in this field and we have already come a long way.
- NEW: involvement of K. Asahi (Tokyo Inst of Tech) for Xe comagnetometry. Also, experience of C. Bidinosti (UWpg), M. Hayden (SFU).

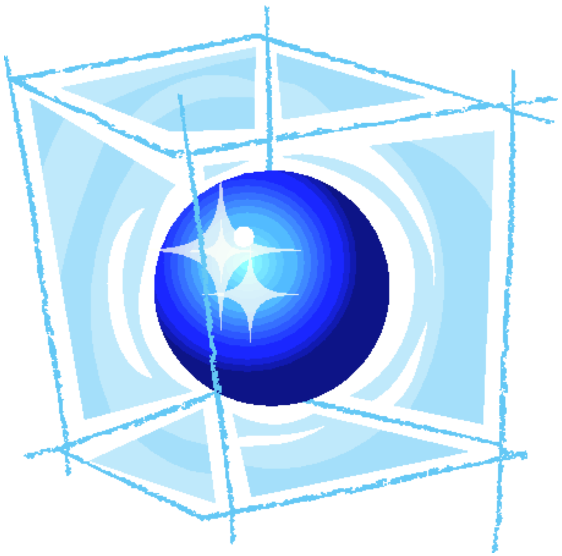
Involvement from more Canadian collaborators in this exciting experiment is very welcome!

Timeline

- 2007-8: UCN source supported by TRIUMF committees, included in plan for TRIUMF
- 2008: CFI NIF proposal submitted
- June 2009: JSPS and CFI support received
- 2009-13:
  - develop UCN source in Japan, EDM experiments
  - preparations and design in Canada
  - develop collaborations and proposals for experiments
- 2013-14: Install, commission at TRIUMF
- 2013-15: First experiments

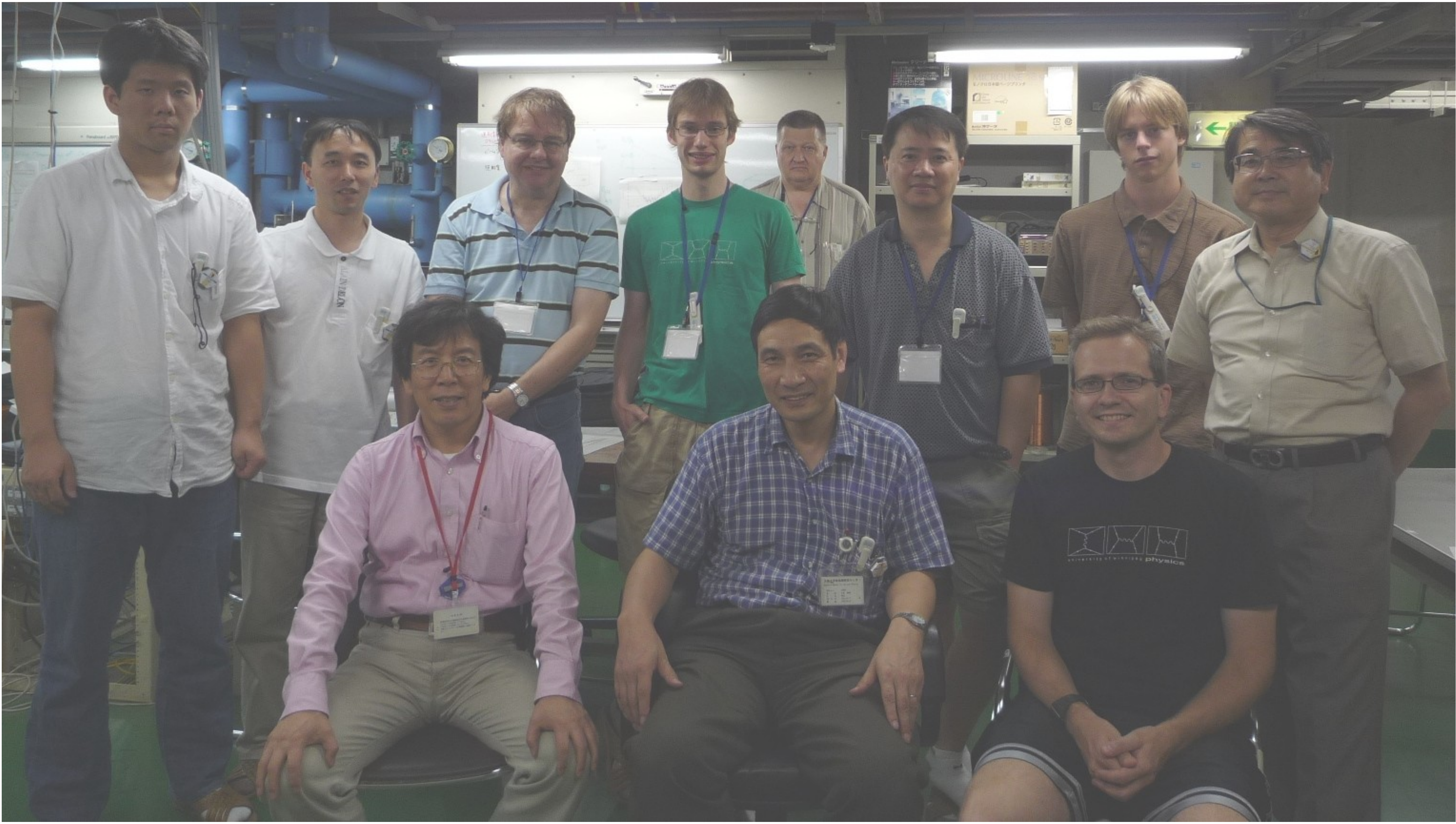
Summary

- Ultracold neutrons are very interesting objects.
- We can use them for a variety of fundamental physics experiments with a long-term future.



- Low field NMR can be applied to neutrons to search for their electric dipole moment and hence new sources of CP violation.

Thank you!



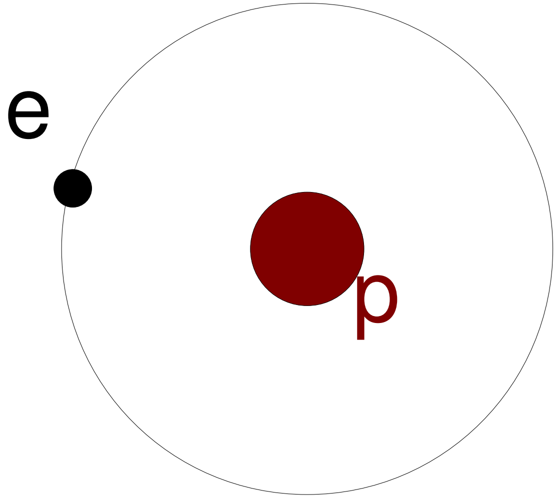
Summary of CFI request

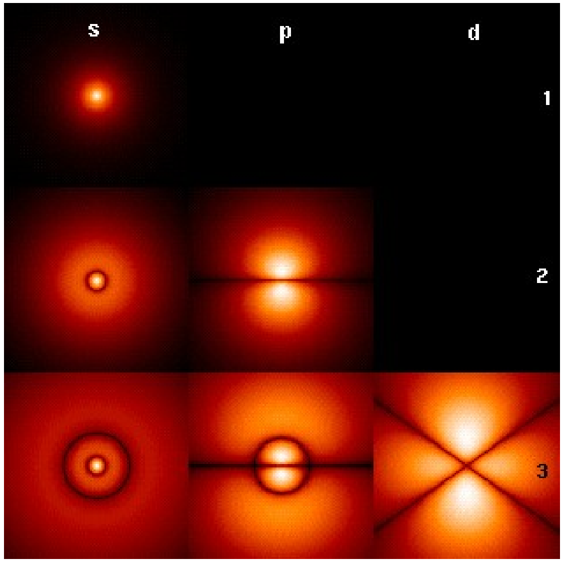
Item	Cost	Funding Source
UCN cryostat system	$4M	Japanese collaborators
Beamline	$2M	TRIUMF
Kickers, shielding, spallation target	$4.225M	CFI NIF
Moderator design	$0.675M	Manitoba + Acsion Industries
Total	$10.9M	

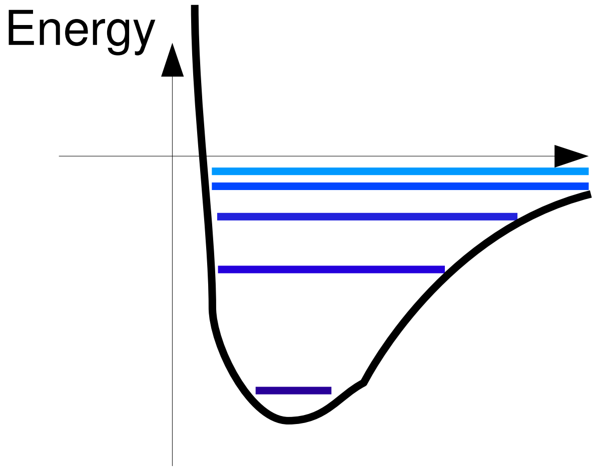
- UCN cryostat system includes:
  - Existing UCN source ($2M)
  - Modifications to source for TRIUMF ($2M)
    - Horizontal extraction, improved guide technology, etc.
- Canadian money for physics experiments:
  - separate budget from NSERC.

Quantum Physics

- We think that everything in the universe is governed by the laws of quantum physics.
- However, quantum physics effects are only seen, generally, in really small things. (e.g. atoms ~ 0.1 nm = one-billionth of ten centimeters)
- One successful prediction of quantum mechanics is the “quantization” of energy levels for particles bound in potential wells. (e.g. H-atoms)

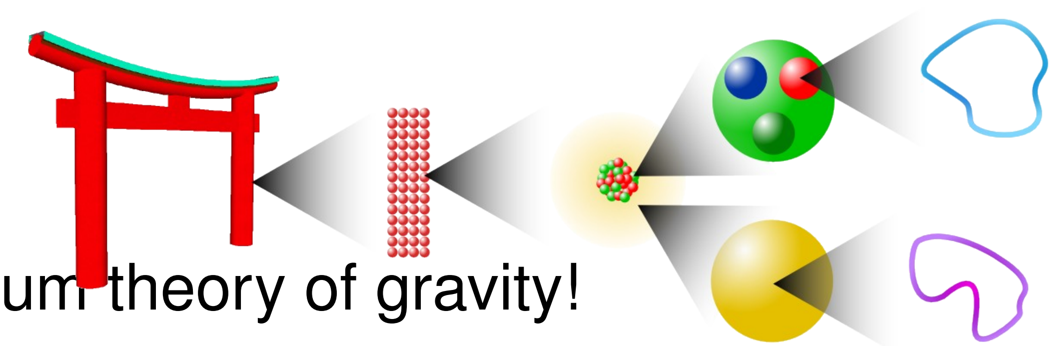






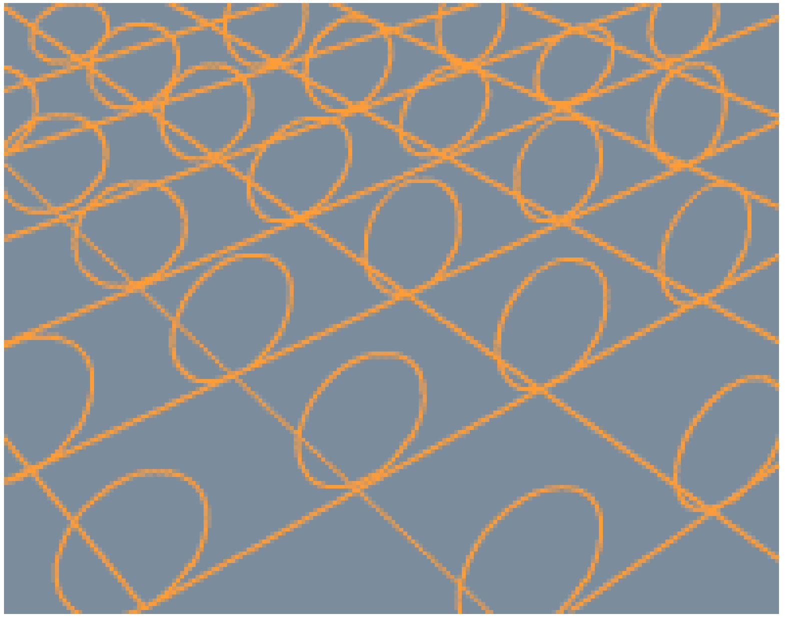
Quantum Physics and Gravity: They Don't Work Well Together

- So far, no one has figured out how to make gravity work with quantum physics.
- But people are trying:
  - string theory
    - might be the real quantum theory of gravity!
  - models of quantum behavior in black holes
    - J. Ziprick, G. Kunstatter, and R. Kobes, U. Winnipeg



Extra Dimensions?

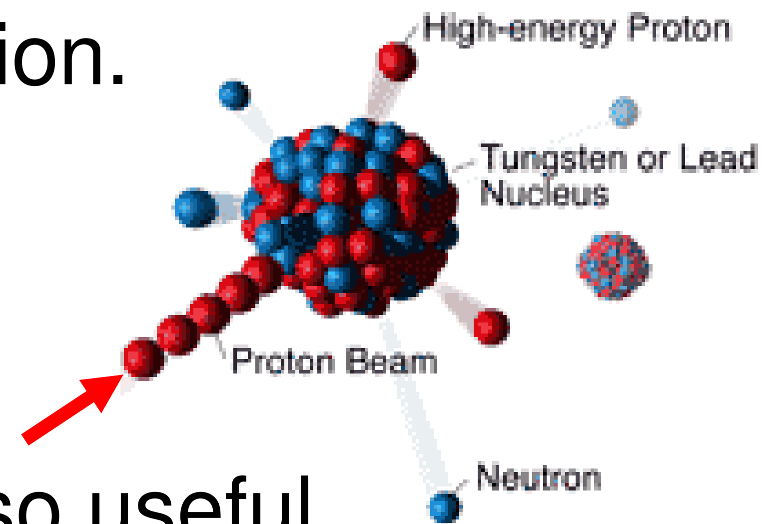
- One "prediction" of string theory is extra dimensions.
- If they exist, where are they?



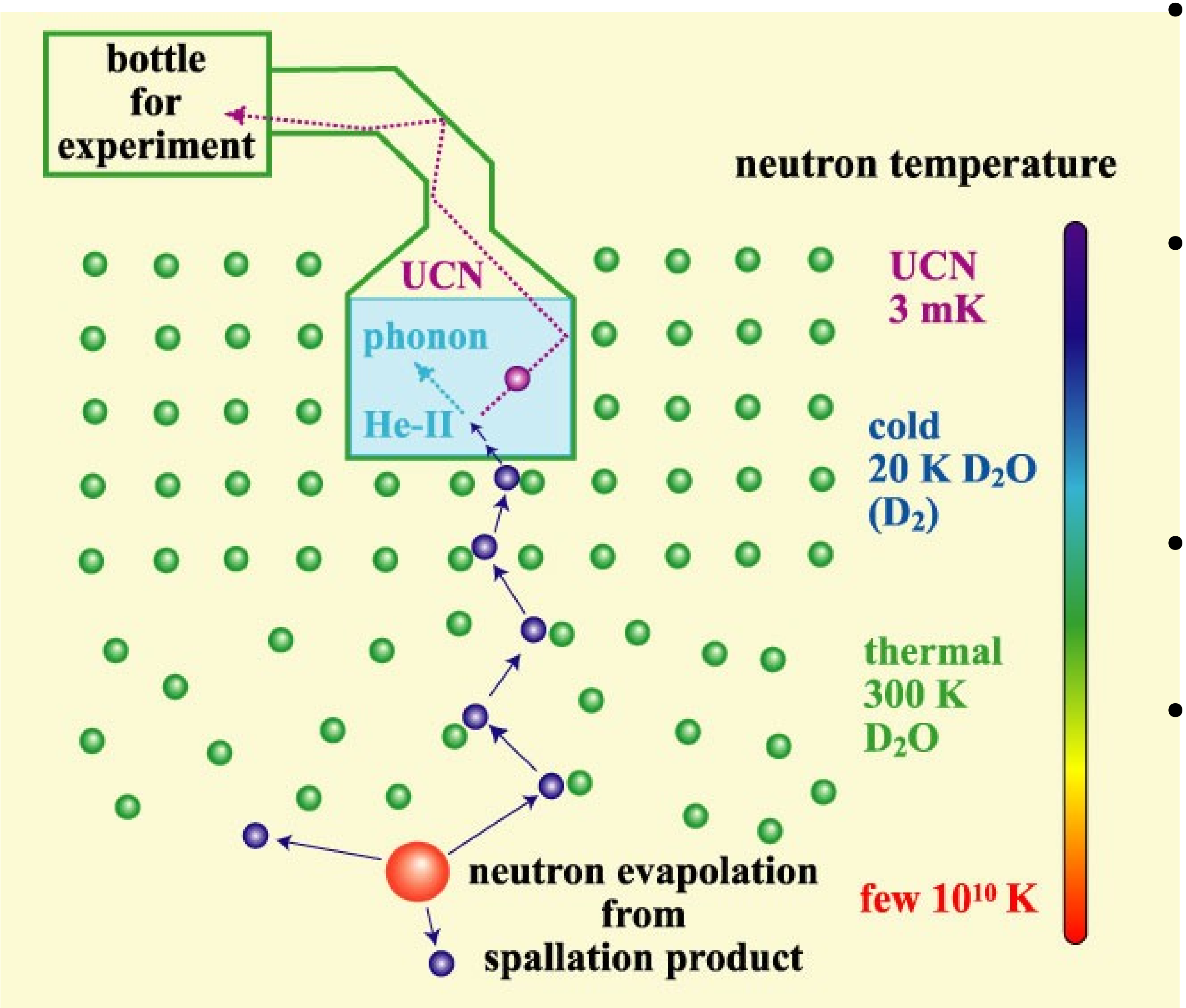
- Clever theorists have suggested that maybe they are "curled up" or "compactified".
- These curled up dimensions would modify gravity at scales below the size of the curling.
- If gravity is modified at these scales, neutron gravity experiments should see it.

How we will make neutrons.

- Using proton-induced spallation.
- This makes very fast-moving neutrons (T = 1 billion K)
- Such “hot” neutrons are not so useful.
- We need to cool them down to make them useful (I'll show you why in a moment).



How we cool neutrons
Step One: Cold Neutrons



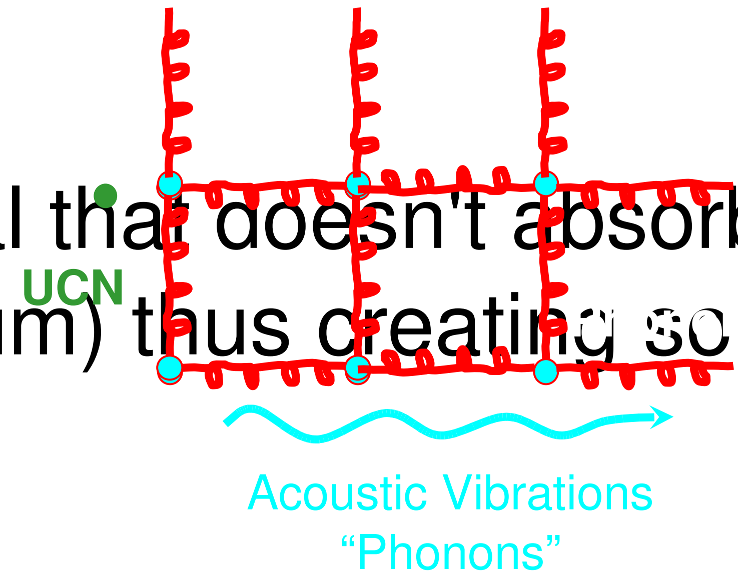
- Bring them into contact with a material at some temperature T.
- The neutrons bounce around for a while and eventually come into equilibrium with the material
- T = 20 K. (20 degrees above absolute zero.)
- But we desire ultracold neutrons

How we cool neutrons
Step Two: Ultracold Neutrons

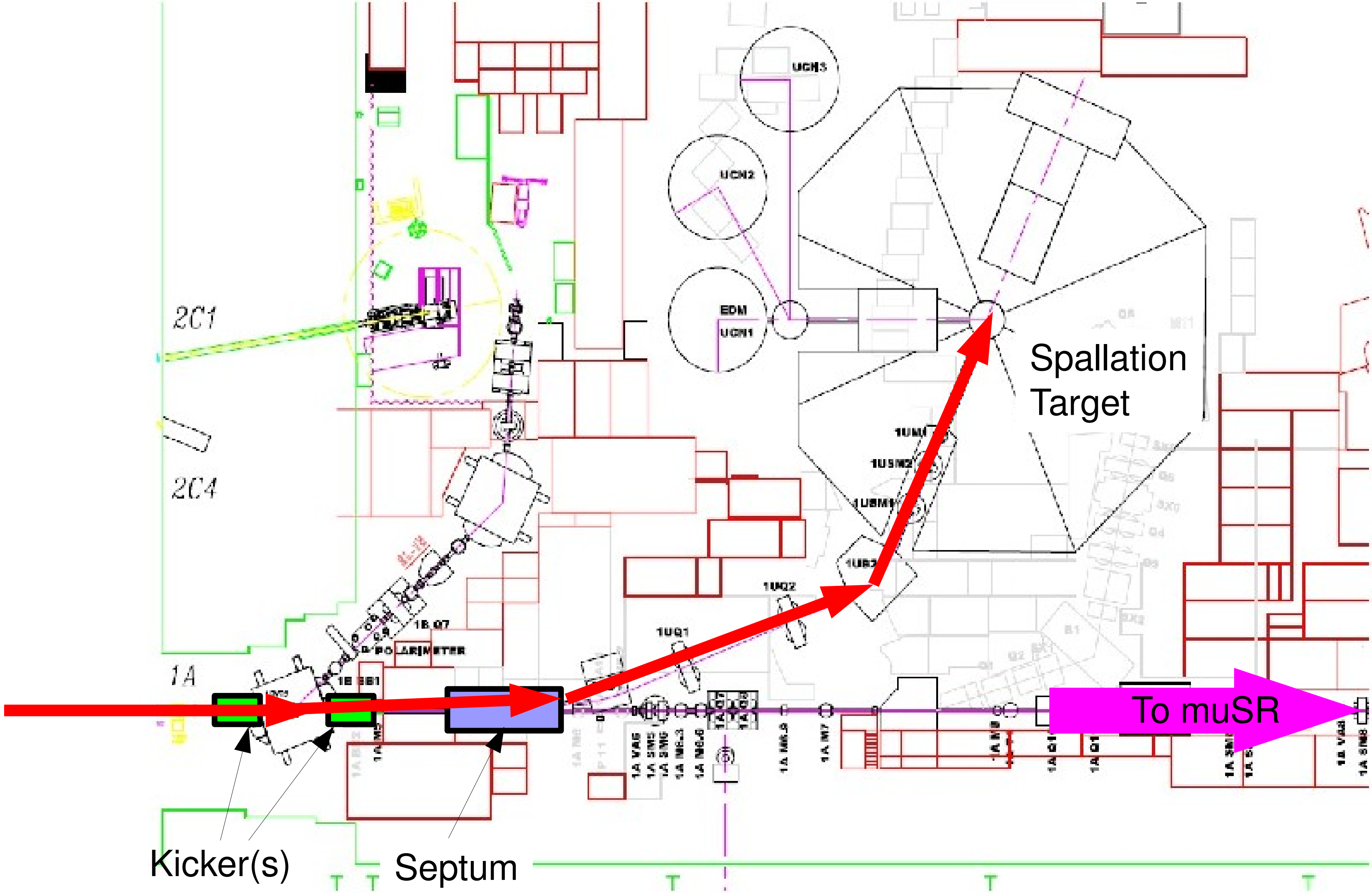
- Scatter them off a material that doesn't absorb them (e.g. superfluid helium)

How we cool neutrons
Step Two: Ultracold Neutrons

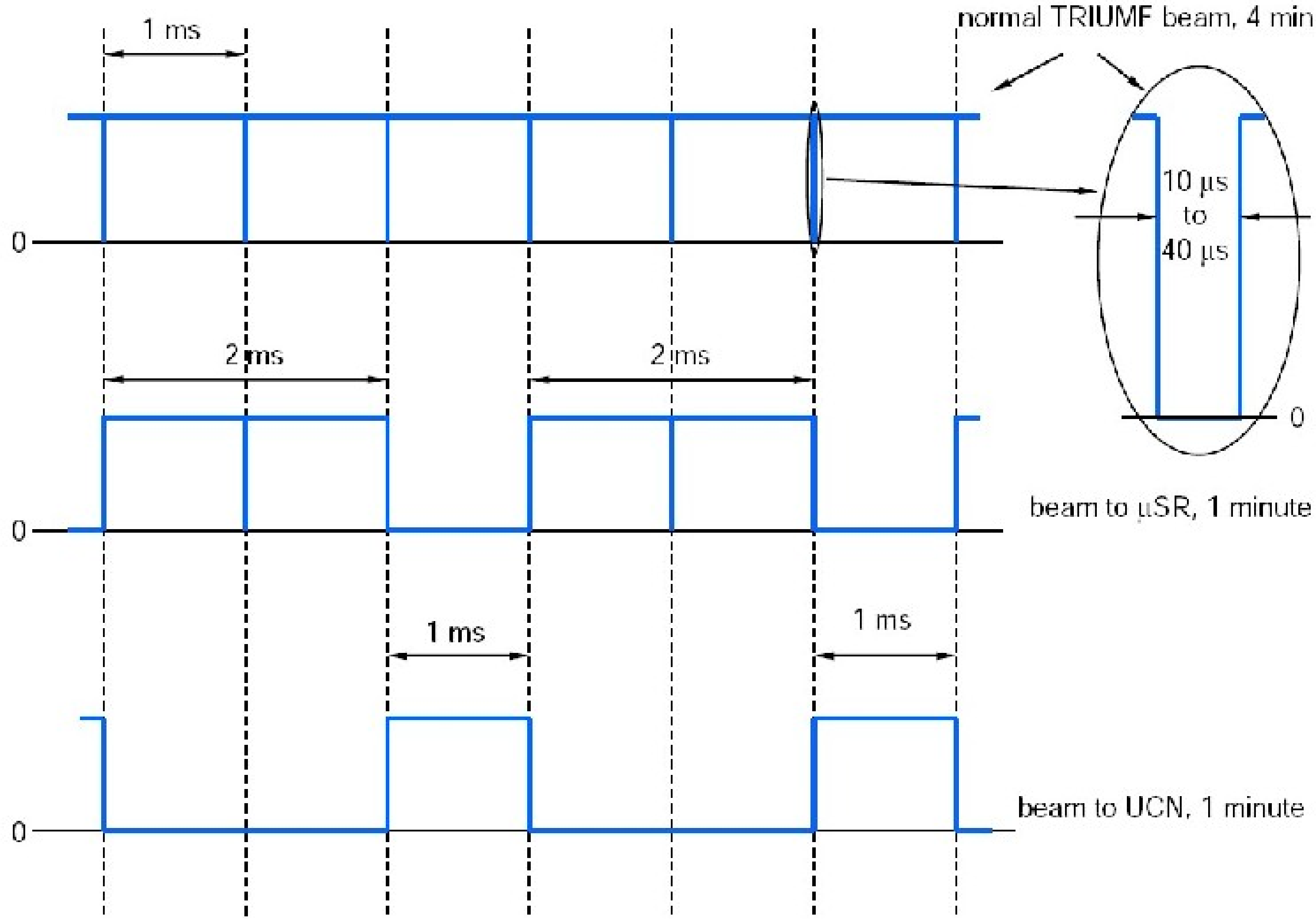
- Scatter them off a material that doesn't absorb them (e.g. superfluid helium) thus creating sound waves ("phonons").



Kicker Concept



Kicker Concept



- Downstream users affected only at 7% level.
- UCN data when cyclotron is on (8 months/yr.)