Ultracold Neutrons at TRIUMF

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NSERC
CRSNG

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

Outline:

- UCN Production and source
- Physics experiments at the UCN source: neutron EDM

TRIUMF

International Spallation Ultracold Neutron Source

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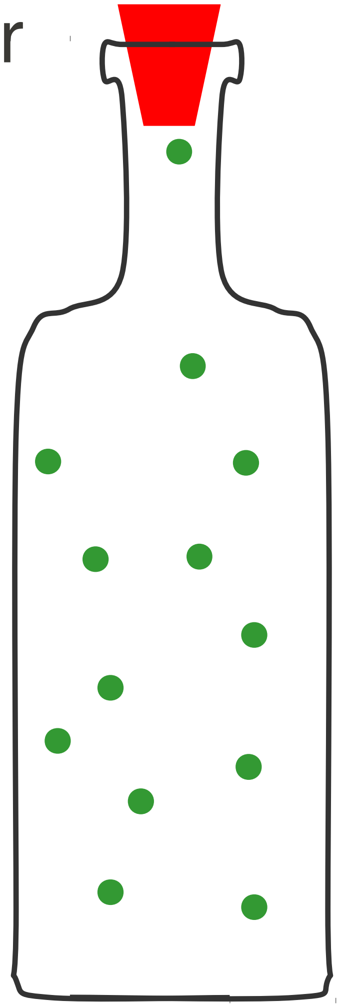
(KEK, Titech, Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, Tokyo, UNBC, Osaka, Kentucky)

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.

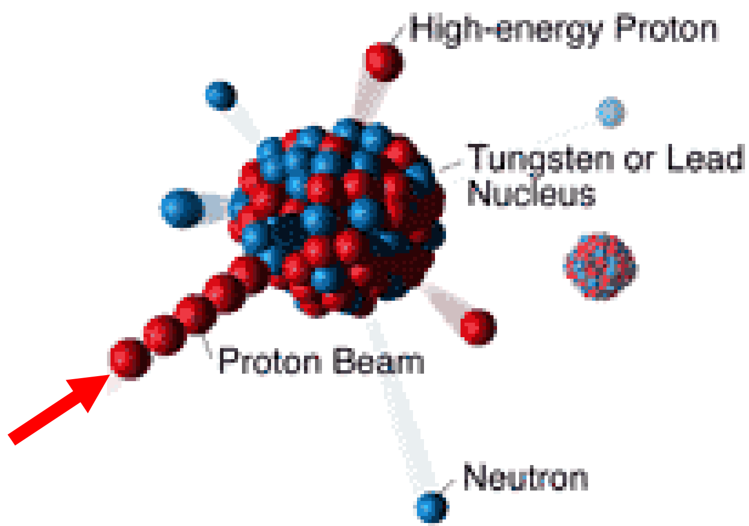
Ultracold Neutrons (UCN)

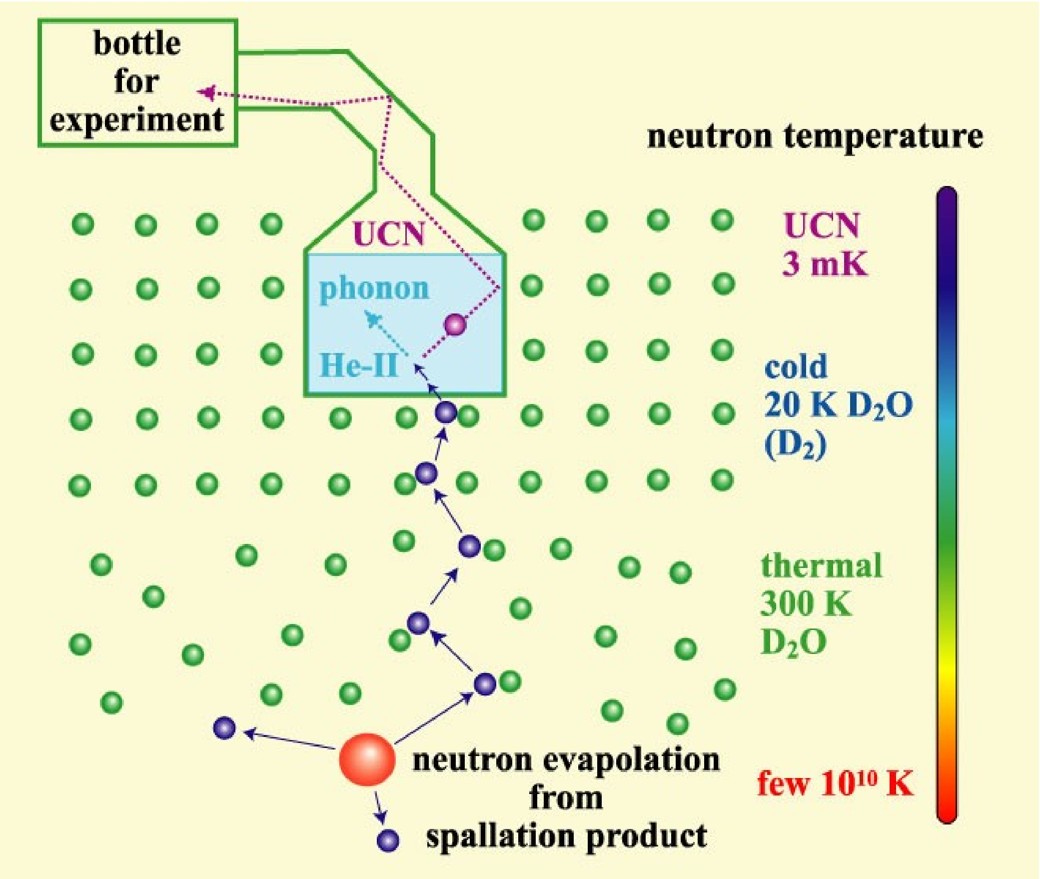
- UCN are neutrons that are moving so slowly that they are totally reflected from a variety of materials.
- So, they can be confined in material bottles for long periods of time.
- Typical parameters:
  - velocity < 8 m/s = 30 km/h = 20 mph
  - temperature < 4 mK
  - kinetic energy < 300 neV
- Interactions:
  - 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



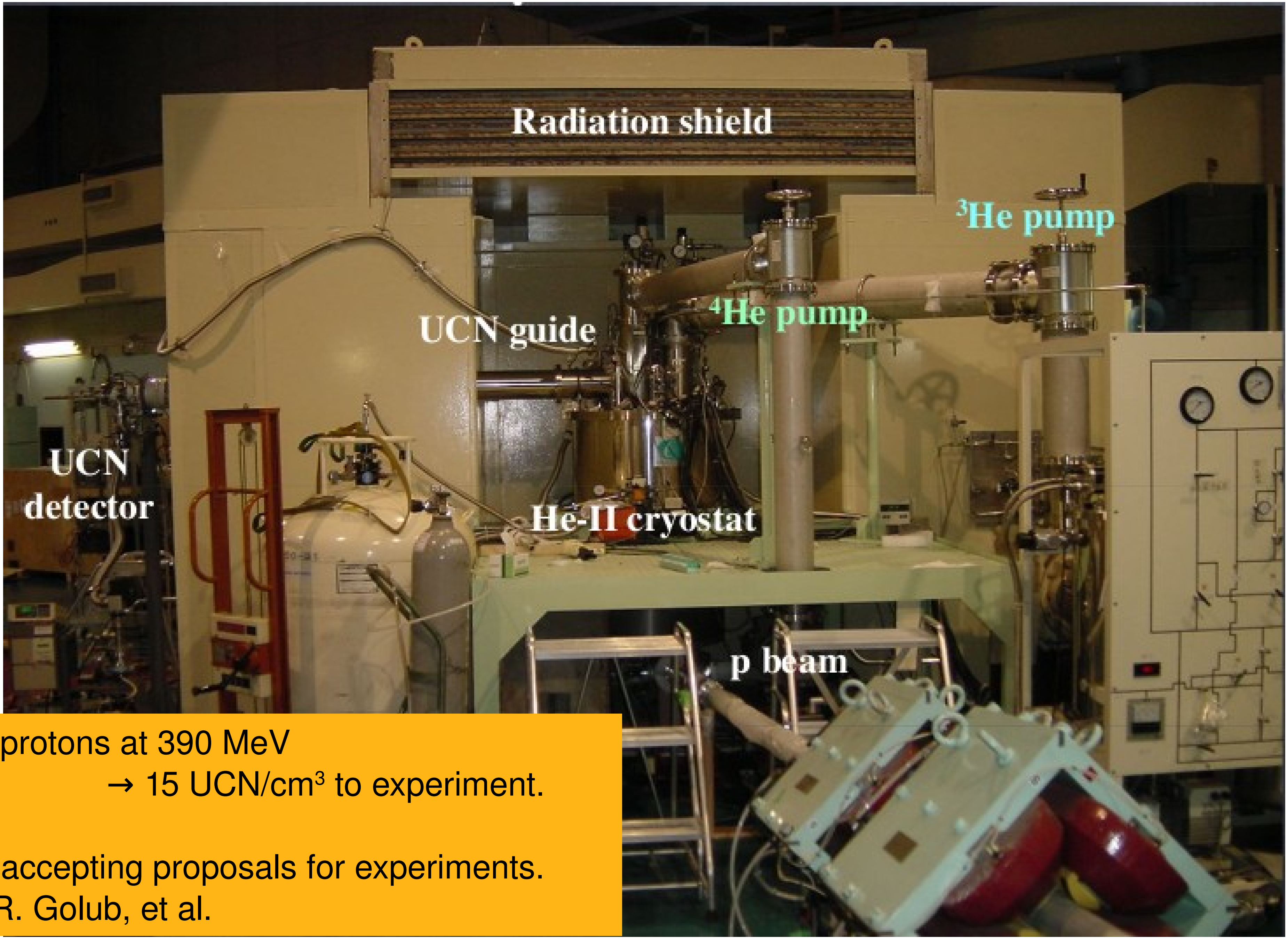
How to make UCN

- 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.

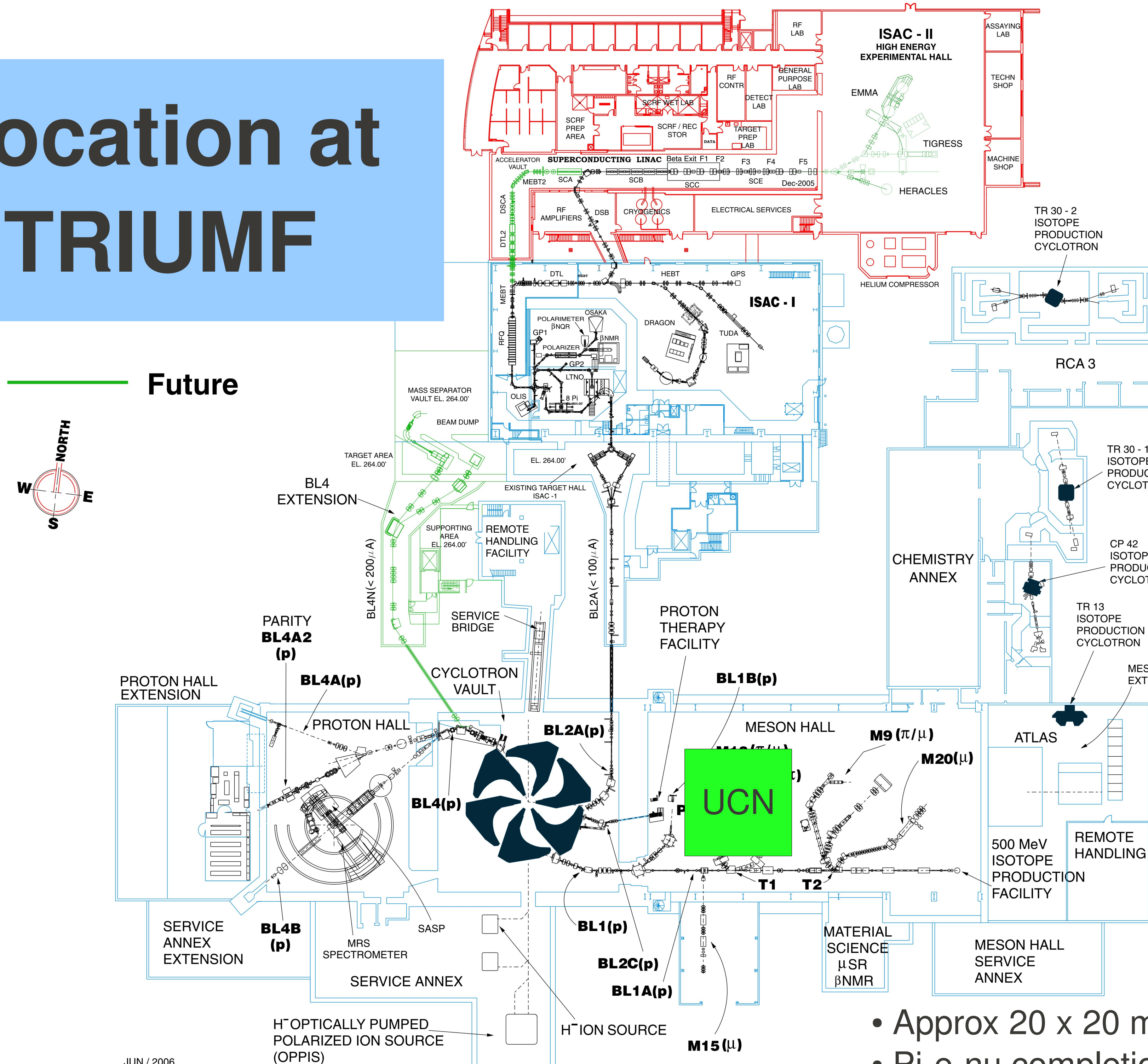
Now accepting proposals for experiments.
e.g. R. Golub, et al.

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

World's UCN projects

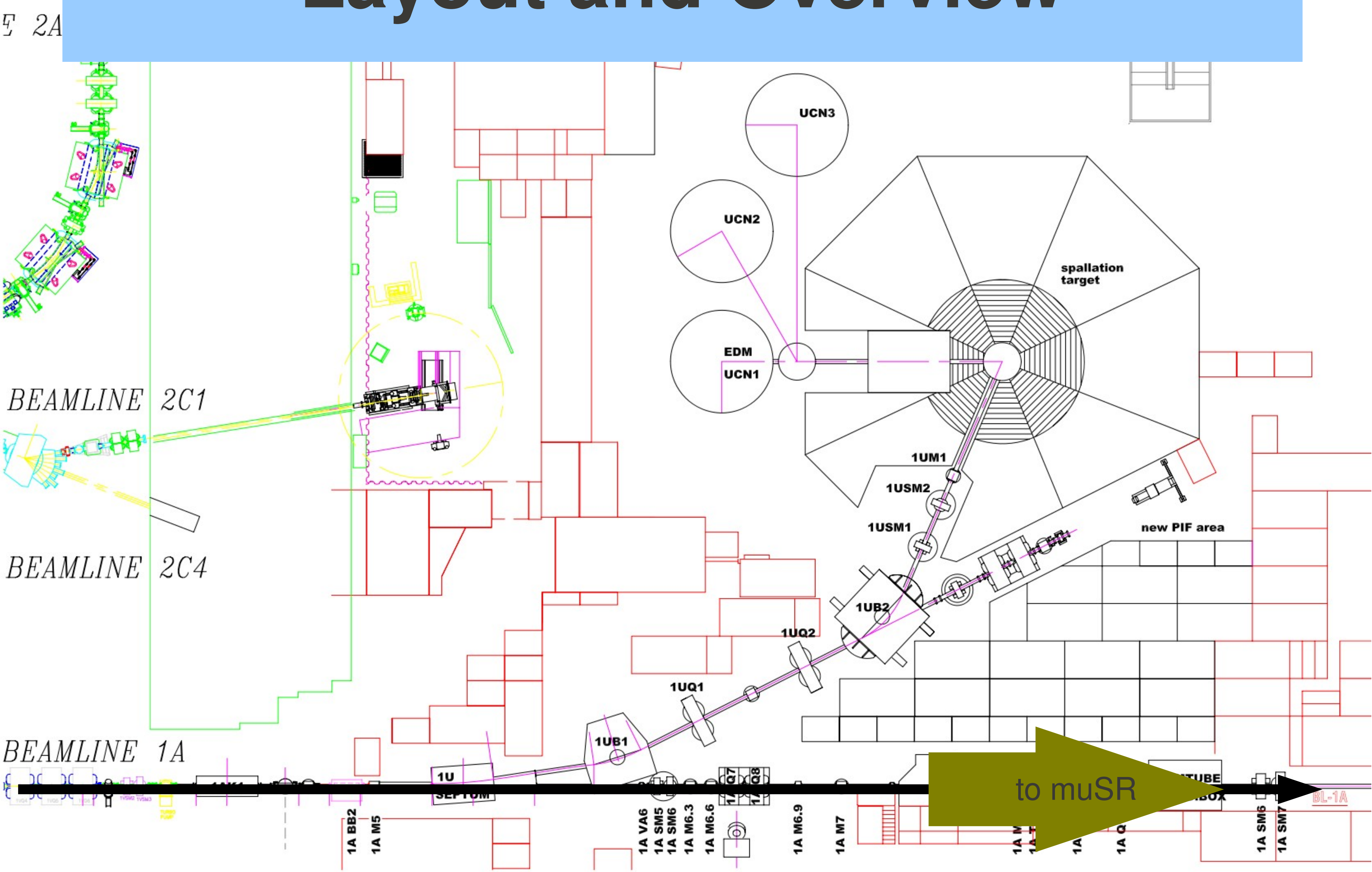
	source type	E_c neV	P_{UCN} /cm^3/s	T_s s	ε_{ext}	ρ_{UCN} /cm^3 source/exp.
TRIUMF	spallation He-II	210	0.4×10^4 (10L)	150	~1	3×10^5 (20L) 1-5 x 10^4
ILL	n beam He-II	250	10	150	~1	**/1000
SNS	n beam He-II	134	0.3 (7L)	500	1	**/150
LANL *	spallation SD2	250	4.4×10^4 (240cm^3)	1.6	1.3×10^3/ 4.4×10^4	**/120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

Location at TRIUMF

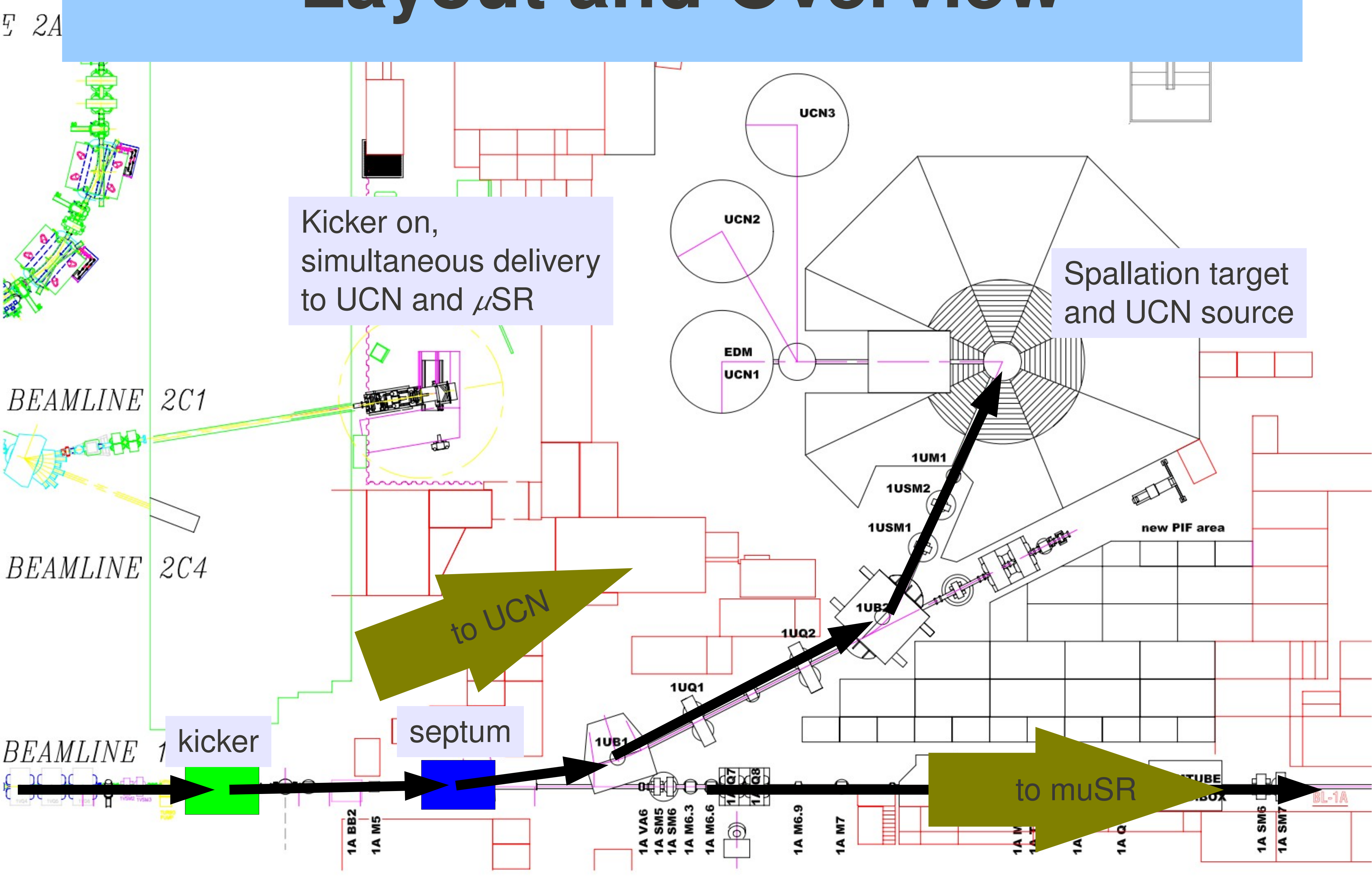


- Approx 20 x 20 m^2 box
- Pi-e-nu completion 2011

Layout and Overview

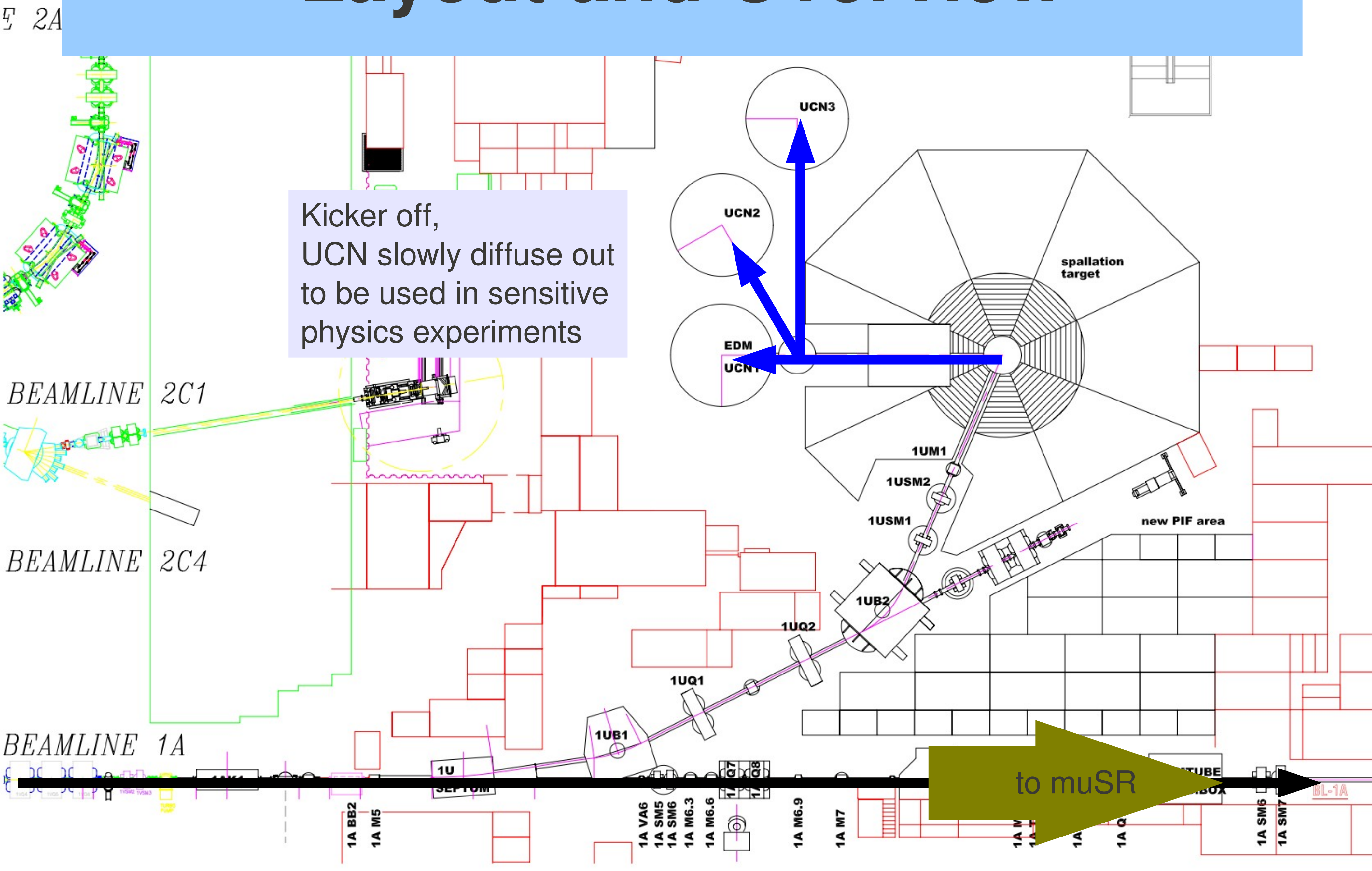


Layout and Overview



Layout and Overview

Kicker off,
UCN slowly diffuse out
to be used in sensitive
physics experiments



Kicker

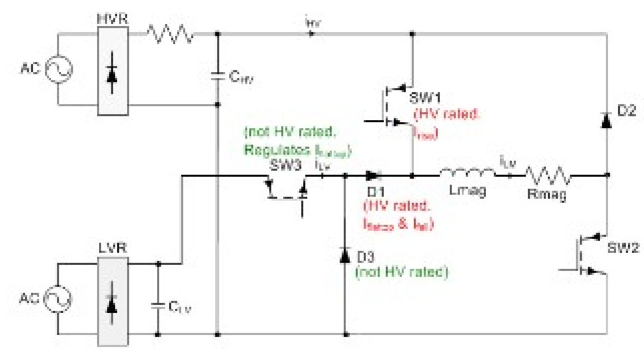
- Redirect 1A beam into UCN line on kHz timescale using existing TRIUMF beam structure.
- Integrated 7% to UCN, 93% to CMMS users.
- TRIUMF/CERN design
  - HV SS switches
  - Fast dipole magnet
- Engineering design.

Kicker Specs:

- 500 MeV protons (p = 1090 MeV/c)
- 15 mr maximum deflection (B*dl* = 0.0545 Tm); normal deflection 12 mr
- effective length 1.5 m (physical available 2 m)
- aperture 100 mm x 100 mm
- field uniform to ±5% over central 80 mm diameter region
- flat top 1 ms, flat to ±5% over the 1 ms
- fires every 3 ms (330 Hz rep. rate, able to run continuously)

Examples:

rise/fall time (μs)	turns	inductance (μH)	flattop current	peak voltage
5	4	30	725 A	4500 V
15	8	120	360 A	2900 V
26	12	270	240 A	2500 V



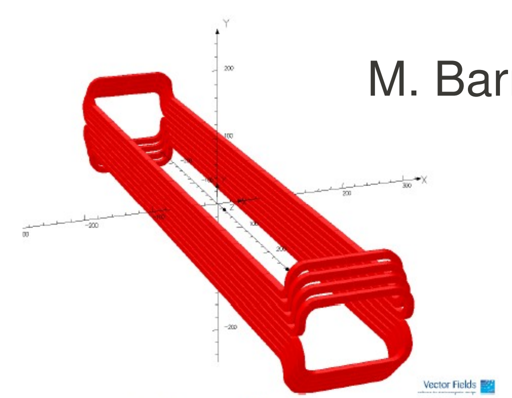
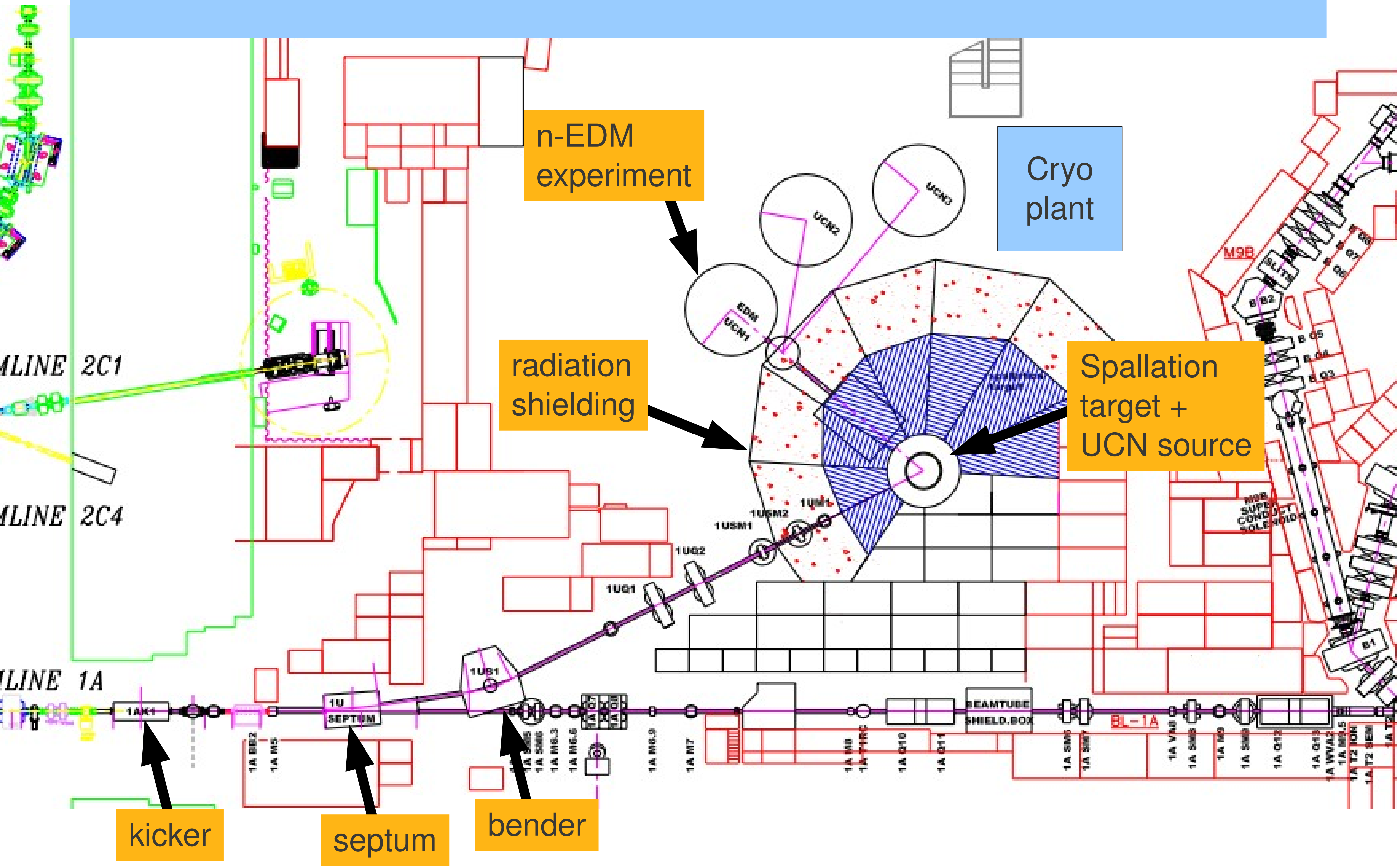


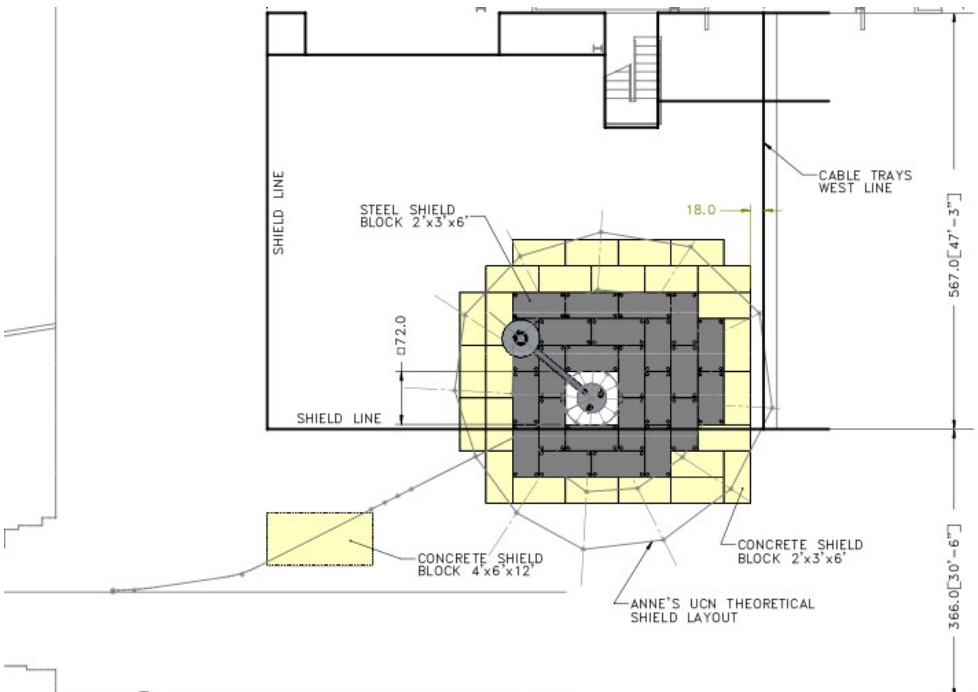
Fig. 1: Proposed coils for UCN kicker

M. Barnes

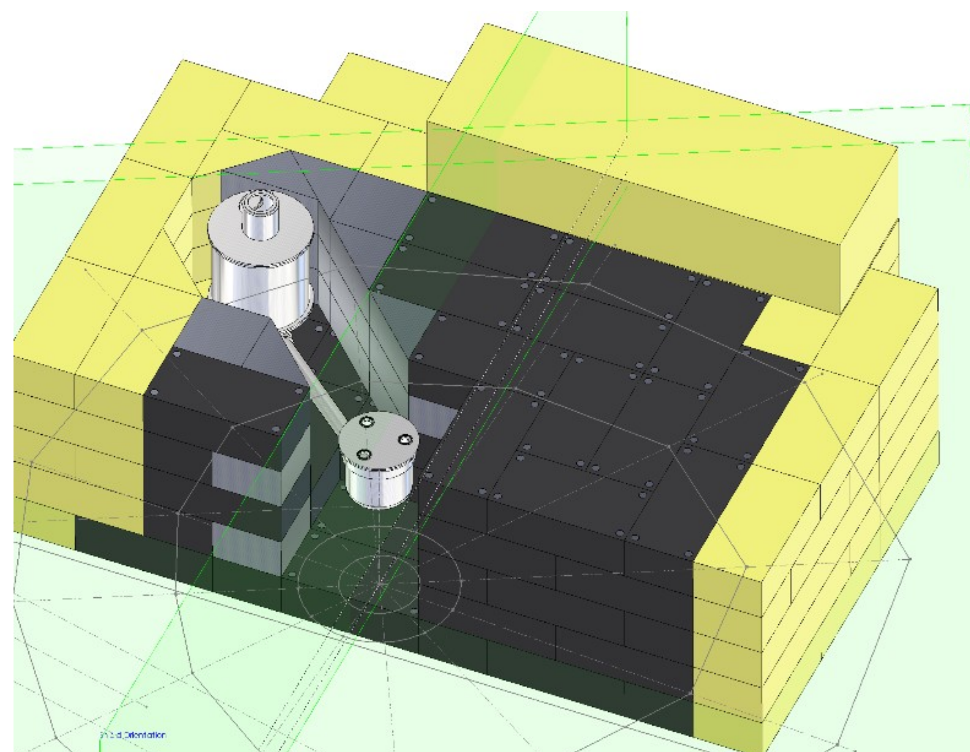
Revised Layout, April 2010



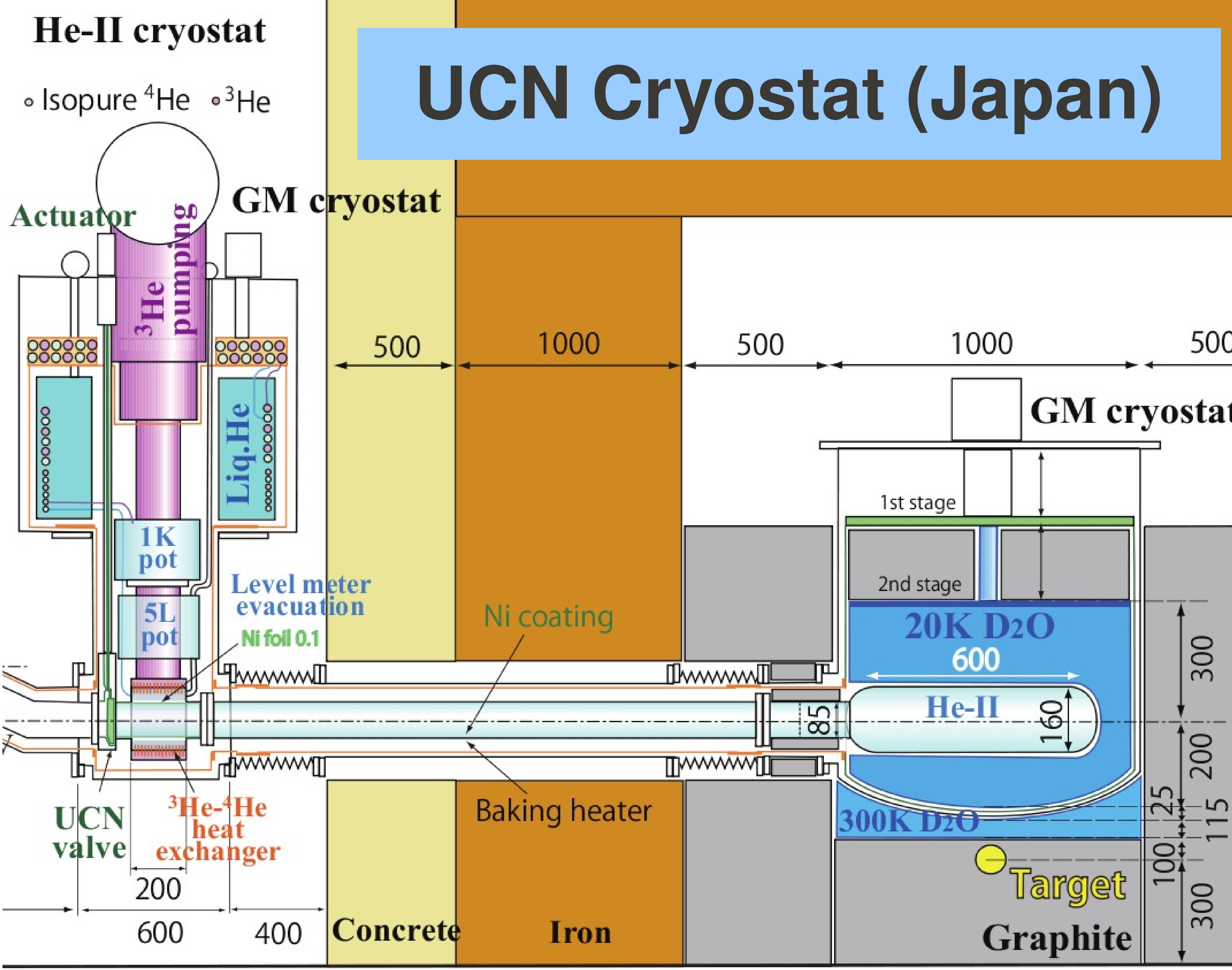
Revised Layout, April 2010



- Building out shield package.
- Recycling shielding where possible.
- Gives confidence in cost.
- Needs consistency with remote handling, installation.



UCN Cryostat (Japan)



Physics Experiments for the TRIUMF UCN Source

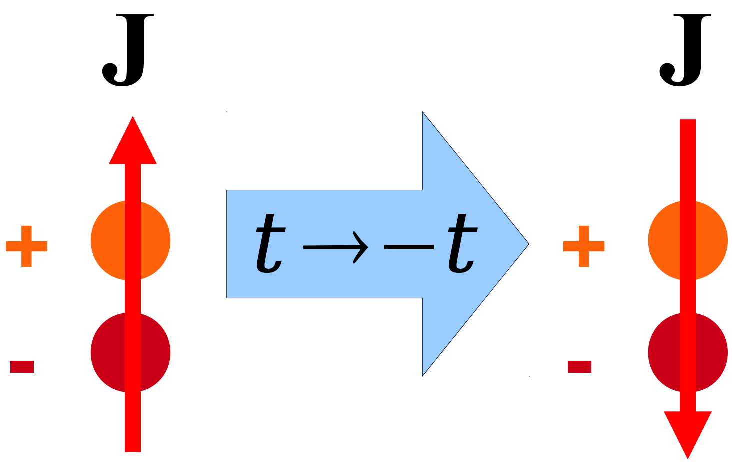
- neutron lifetime
- gravity levels
- n-EDM
- $n\bar{n}$-oscillations
- Free n target

near term (neutron lifetime, gravity levels, n-EDM)

dreams ($n\bar{n}$-oscillations, Free n target)

All ideas / letters / proposals welcome

Neutron Electric Dipole Moment (n-EDM, d_n)



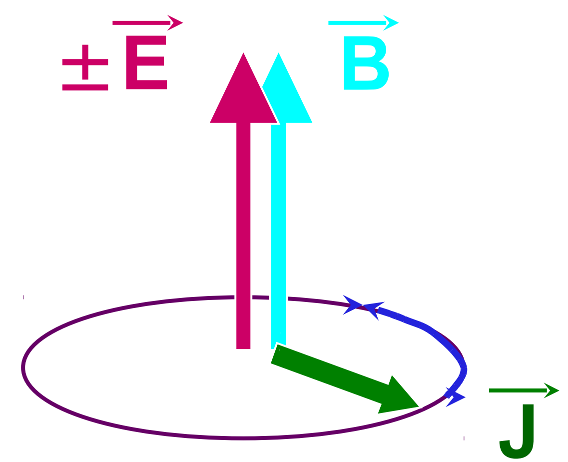
$$d_n \Rightarrow \not{T} \Rightarrow \not{CP}$$

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

- Complementary to Rn-EDM TRIUMF ISAC.

Experimental technique:

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

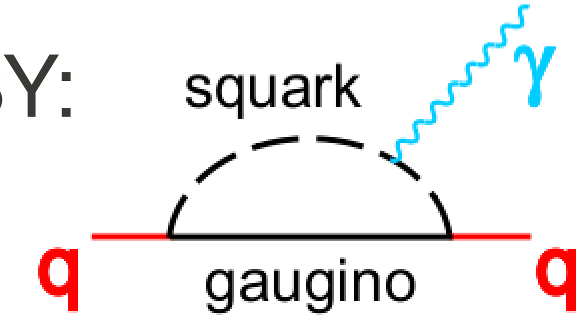


$$h\nu = 2\mu_n B \pm 2 d_e E$$

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:

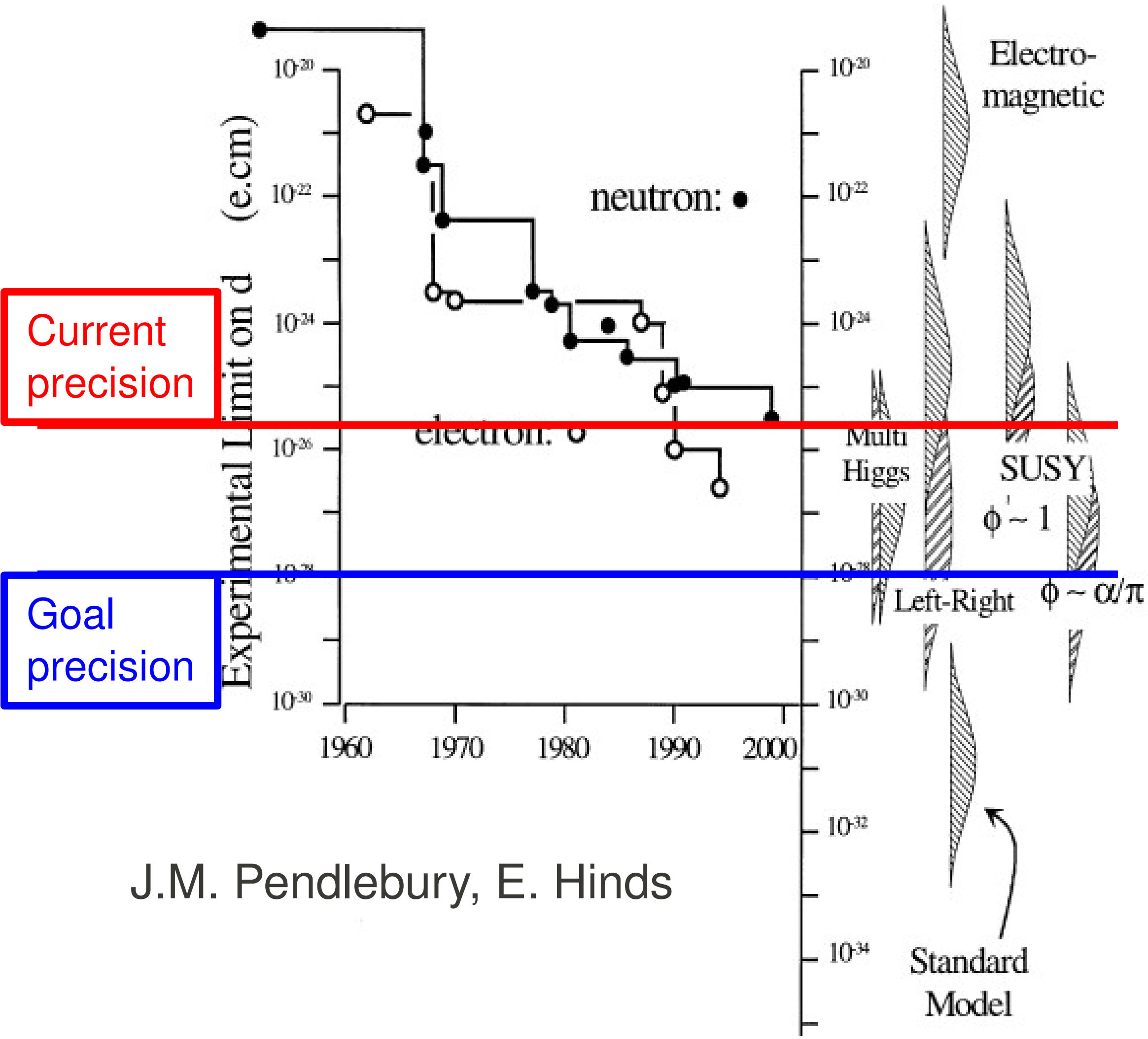
$$d_q \sim 3 \times 10^{-24}\, e \cdot cm$$

- 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:
  - $\Lambda_{\mathrm{SUSY}} > 2$ TeV and/or $\theta_{\mathrm{CP}} < 0.01$
  - "SUSY CP problem"

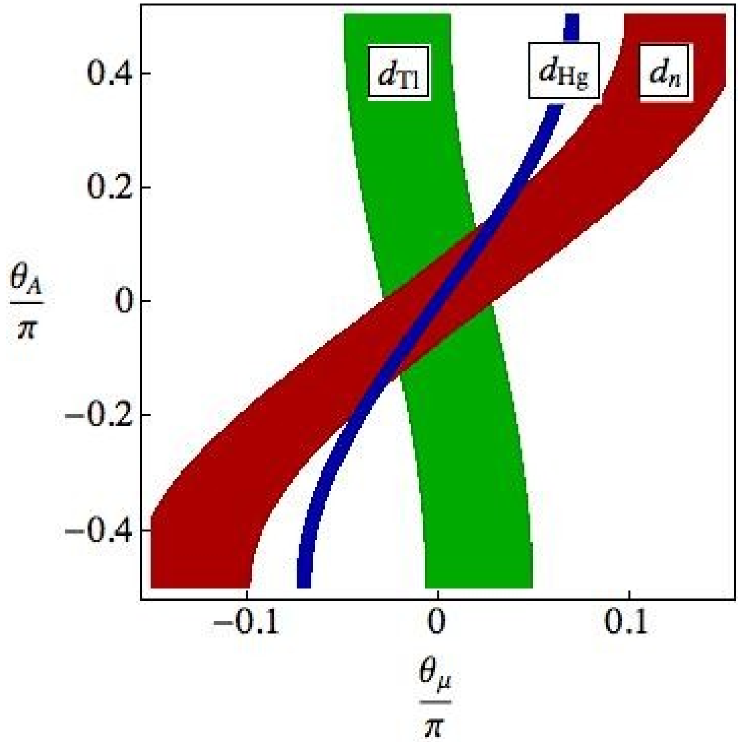
EDMs, the SM, and beyond



J.M. Pendlebury, E. Hinds

A. Ritz, M. Pospelov, et al

SUSY M = 1 TeV, tanβ = 3

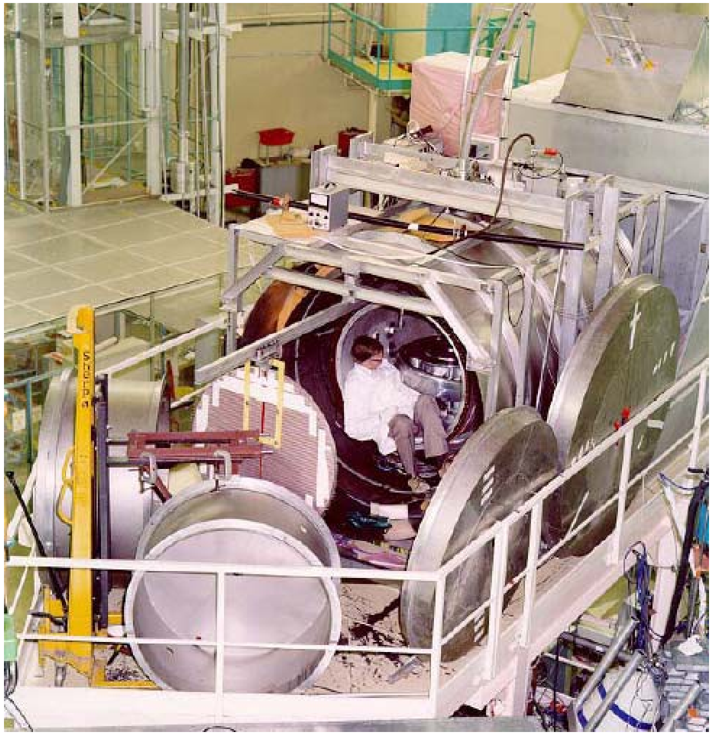


Note: universality assumptions are now even being tested

- Ultimate goal: reach the SM limit

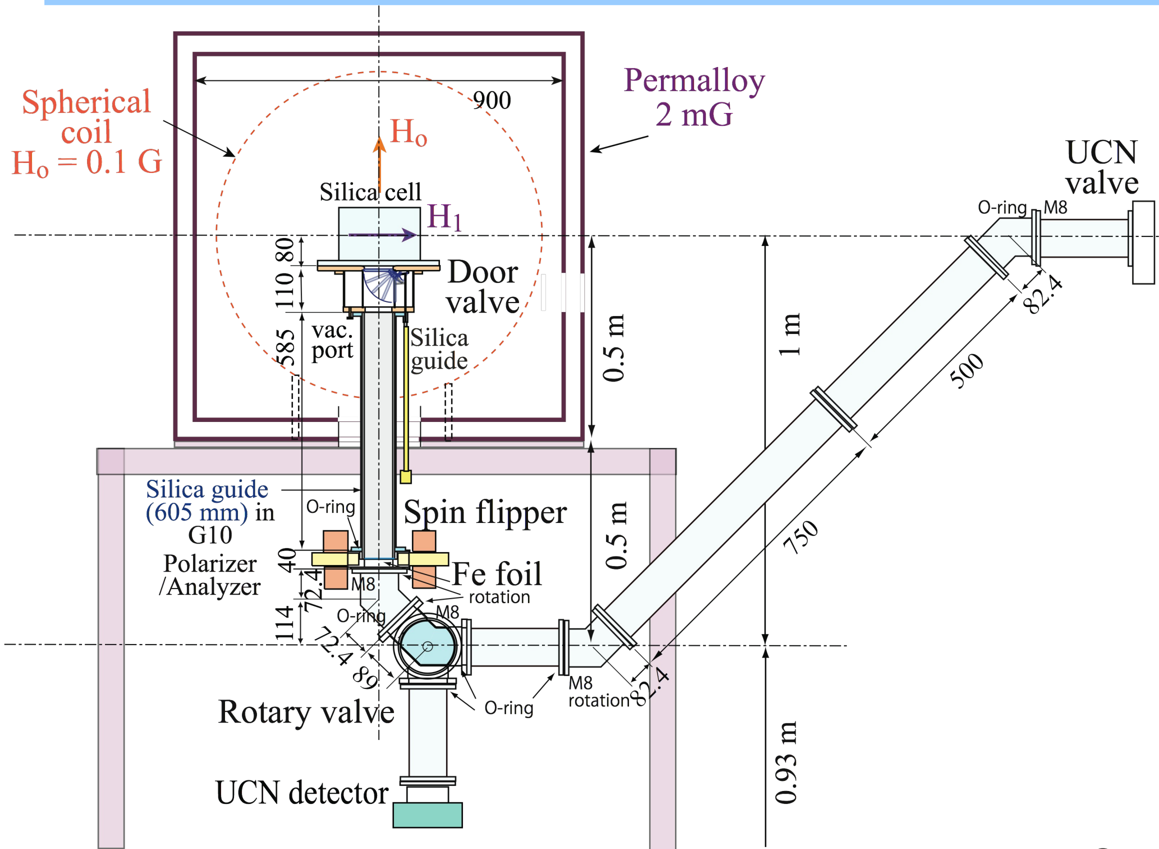
Past and Future n-EDM efforts

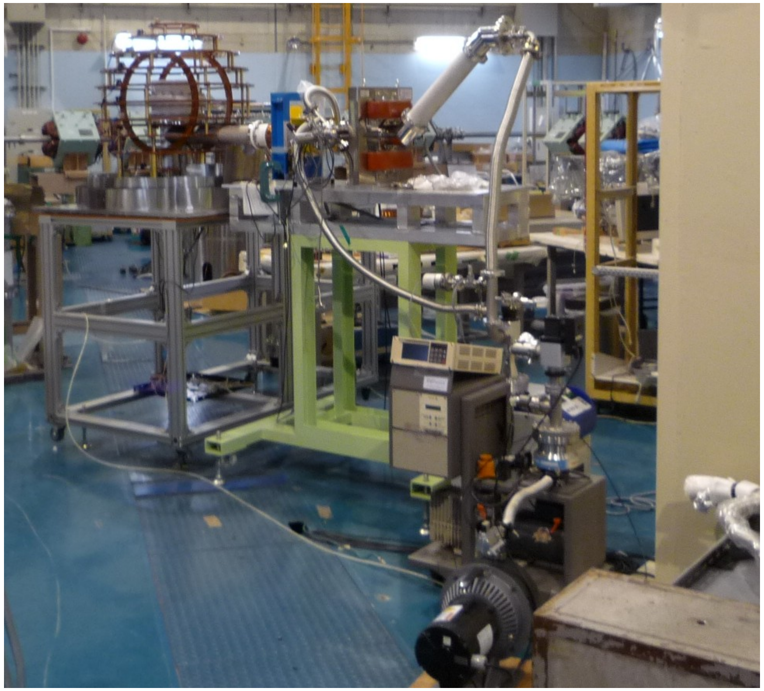
- Sussex-RAL-ILL expt. ($d_n < 3\times10^{-26}$ e-cm)
  - 0.7 UCN/cc, room temp, in vacuo
- CryoEDM (Sussex-RAL-ILL)
  - 1000 UCN/cc, in superfluid ^{4}He
- SNS
  - 430 UCN/cc, in superfluid ^{4}He
- PSI
  - 1000 UCN/cc, in vacuo
- TRIUMF: 10,000 UCN/cc



Sussex-RAL-ILL experiment

n-EDM development in Japan





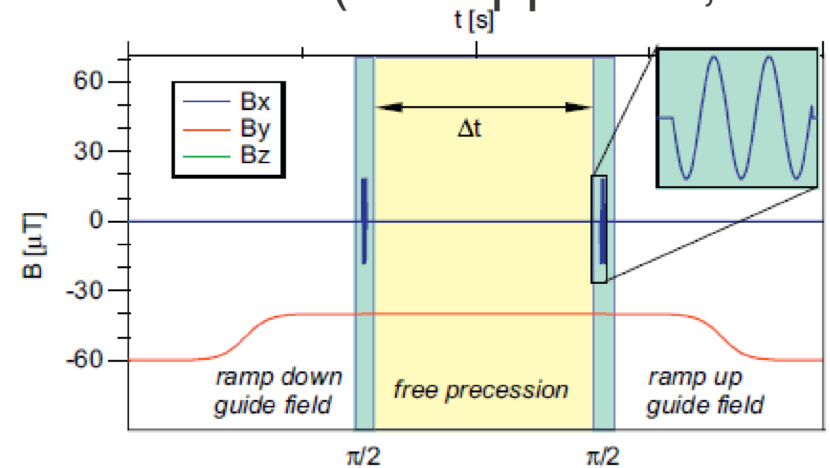
- Masuda, et al. Beam tests July, December 2009, April 2010 8-13.

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

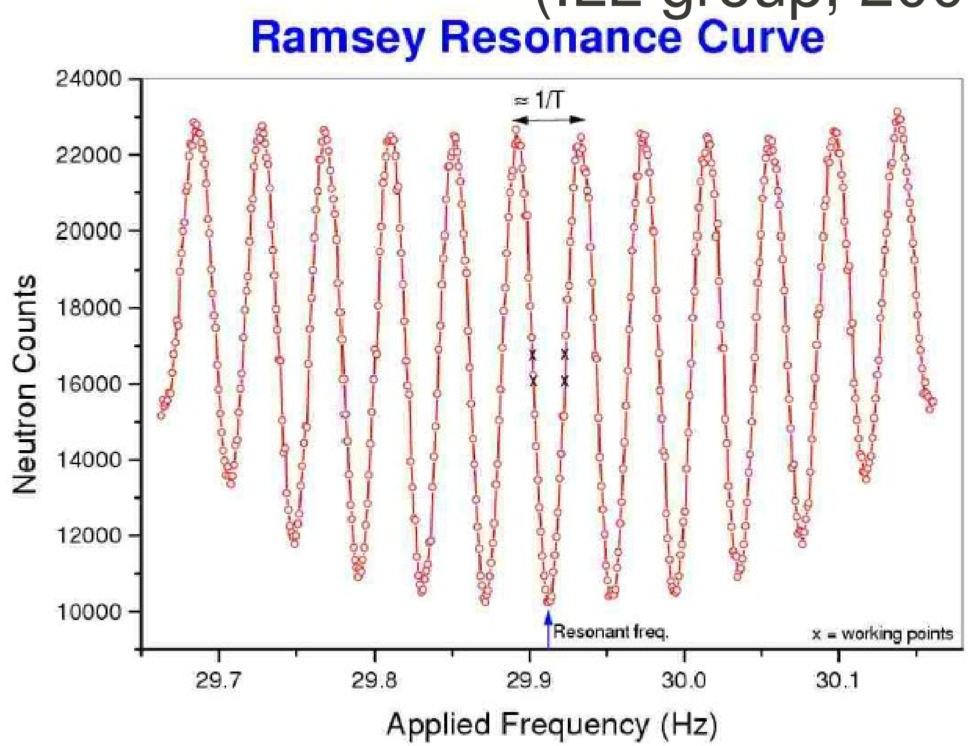
Ramsey Resonance

- 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 ~ $1/\tau$

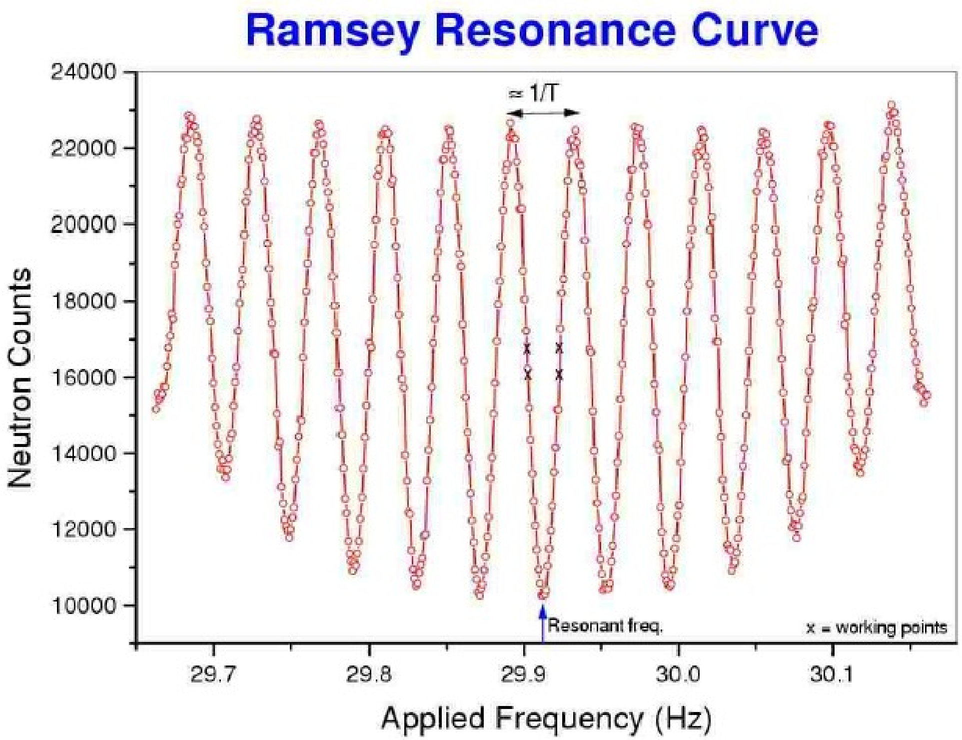
(S.Filipp et al, 2009)

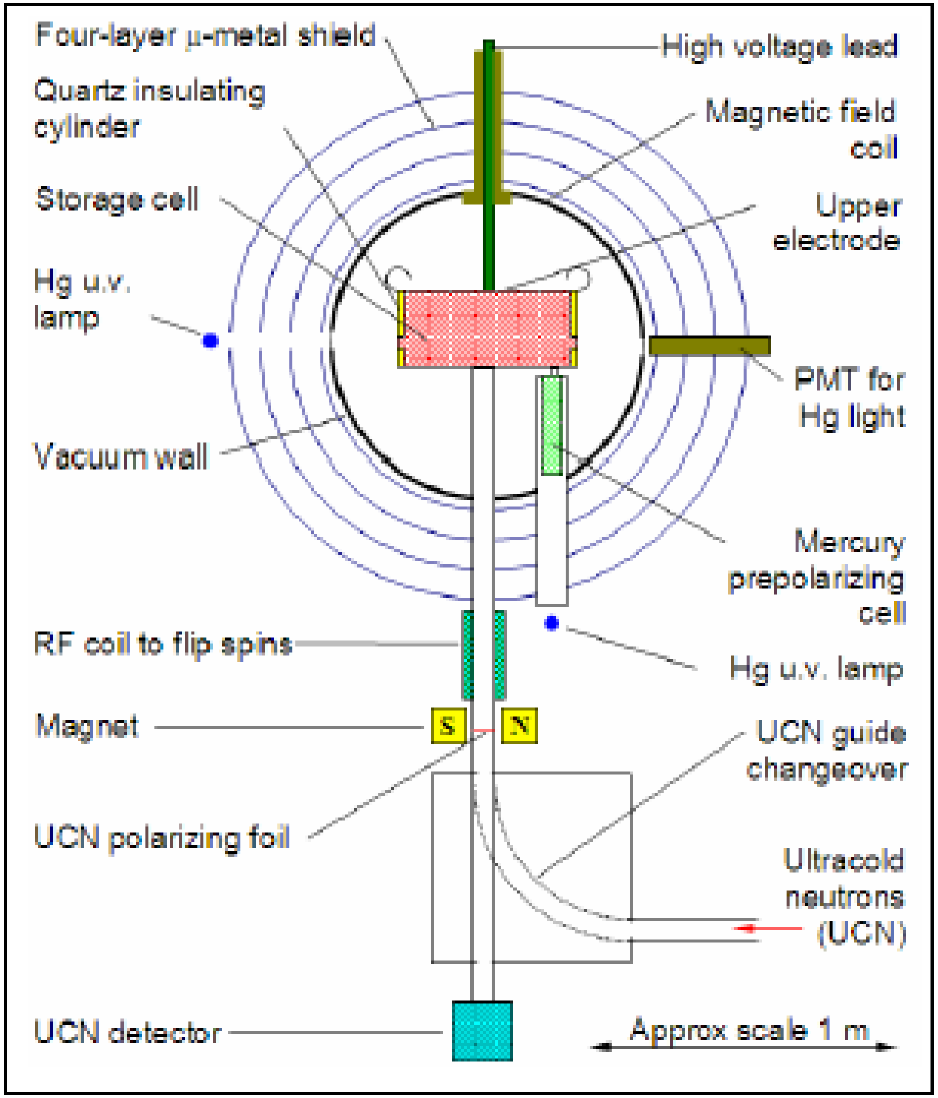


(ILL group, 2003)



n-EDM measurement sequence



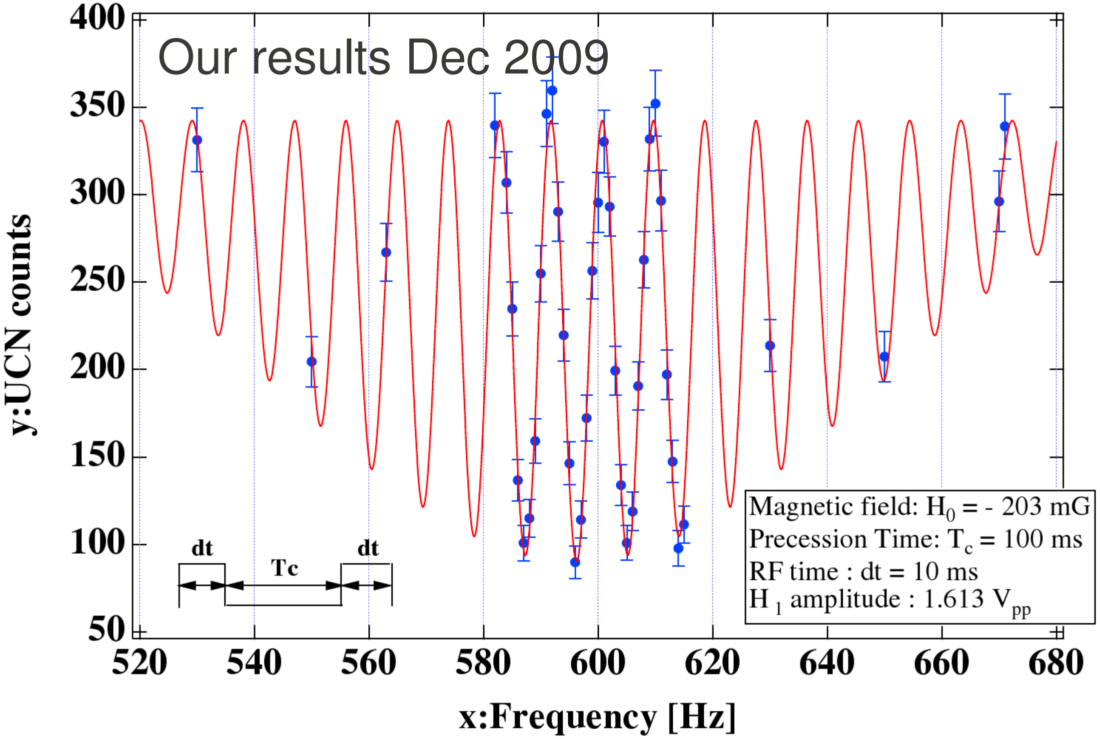


ILL apparatus

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

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

Ramsey Resonance Results
Y. Masuda, et al, in preparation



Dec. 2009, achieved:

T_2 ~ 300 ms

April 2010, achieved:

T_2 > 30 s !!!

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

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

- Successful demonstration of the basic technique behind precision EDM measurements.
- Improvements in field homogeneity, profile, magnitude, shielding for longer T_2.

EDM Statistics

- ILL:

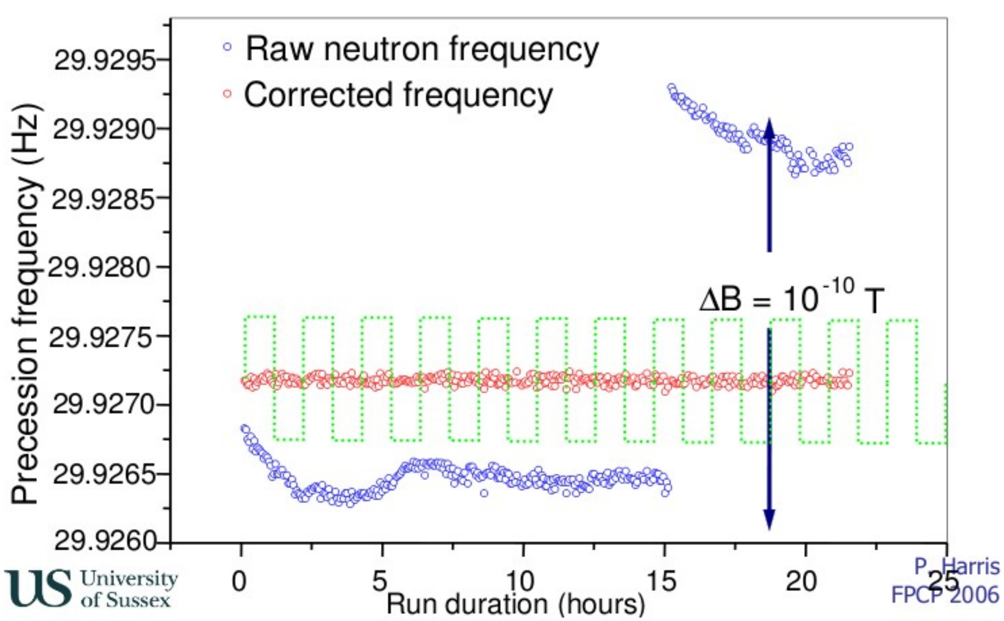
$$\sigma\left(d_n\right) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

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

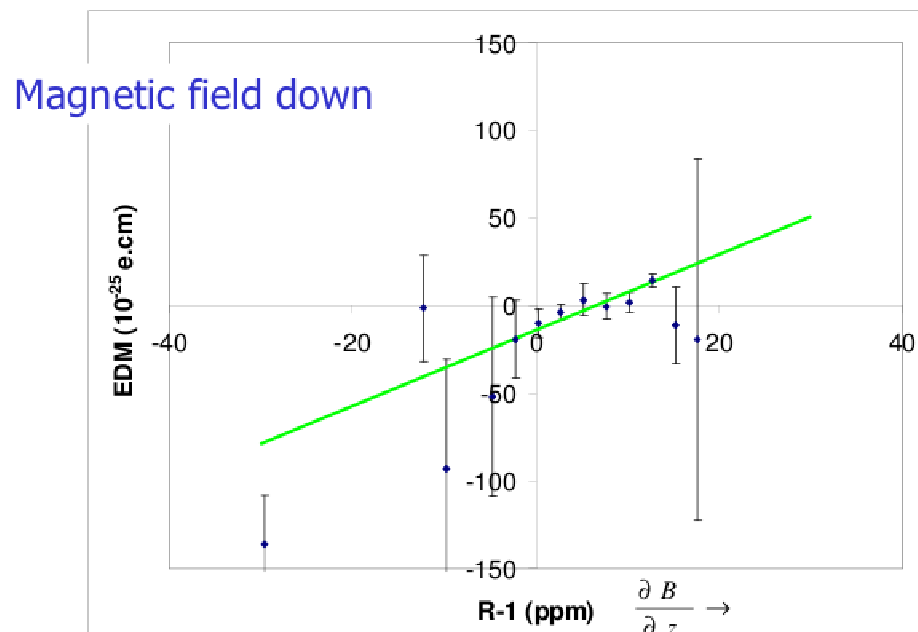
n-EDM Systematics

- 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

n-EDM at TRIUMF

- Complete experiments in Japan, 2009-2012.
- Develop LOI/proposal for TRIUMF ~ 2010-11.
- Unique aspects of the EDM work in Japan:
  - New UCN production mechanism aiming for highest density
  - Higher UCN density allows smaller cell size
  - New DC coil geometry
  - Xe comagnetometer

We gratefully welcome new collaborators to this exciting experiment!!!

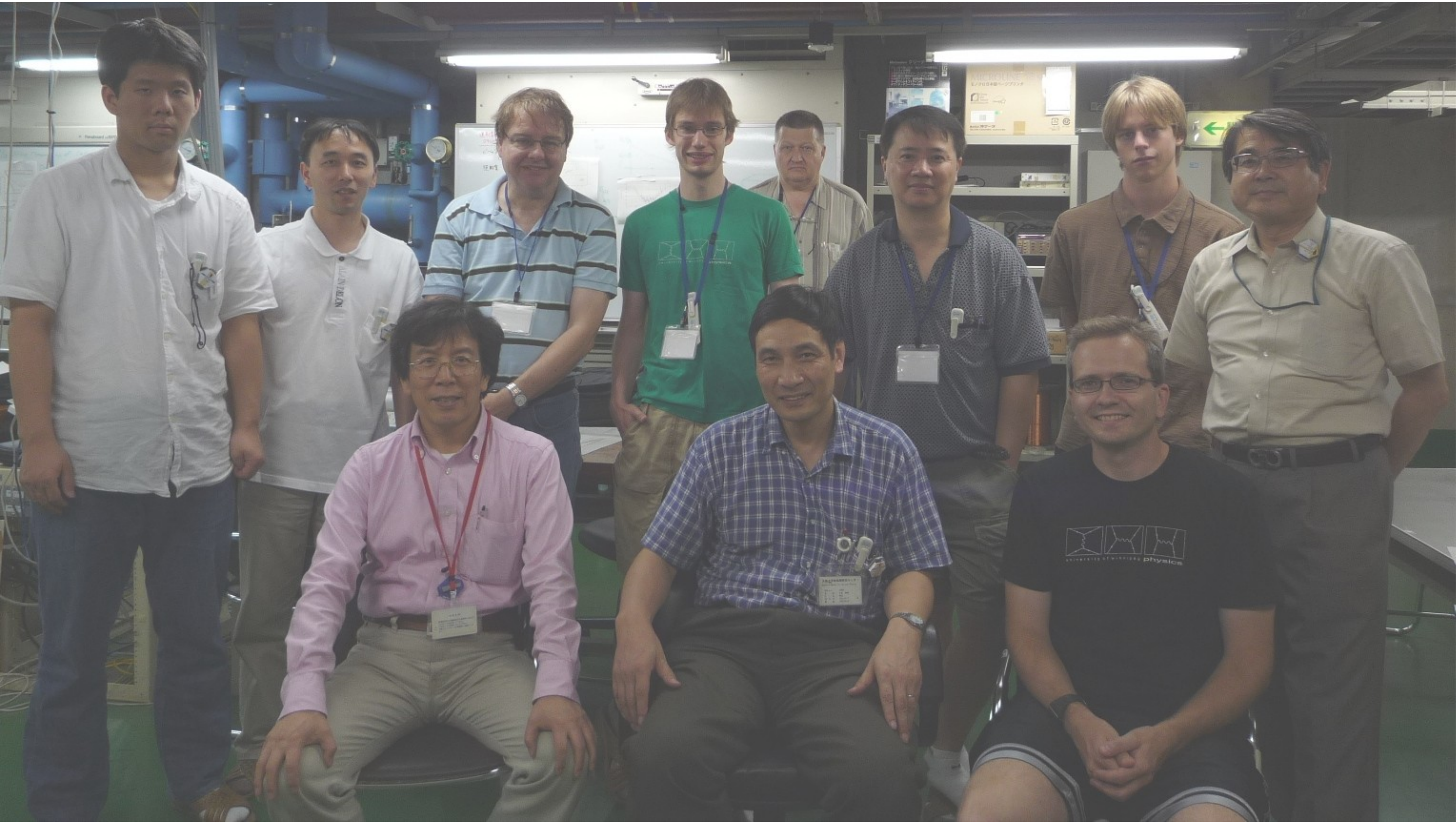
UCN and you!
research opportunities

- Development state-of-the-art technology in low-field NMR, related to medical MRI's. Precision (co)magnetometry, shielding.
- Quantum mechanics and quantum computing studies using UCN spins.
- Development of UCN detectors.
- Electronics, DAQ (MIDAS), data collection, analysis, and simulation.
- Development of future UCN experiments - lifetime, gravity, quantum computing, surface physics, others.

Timeline

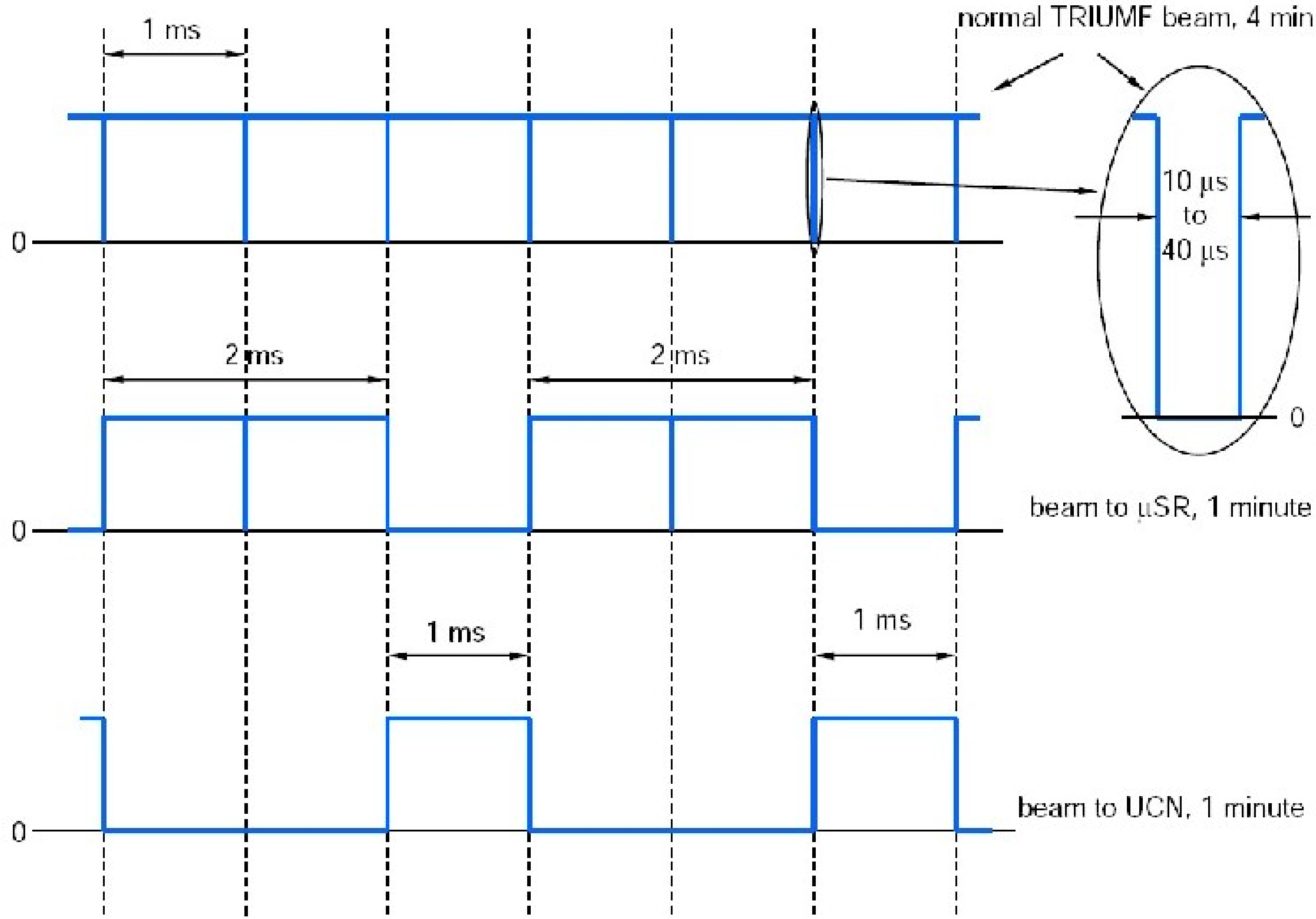
- June 2009: Source funded in Canada and Japan
  - JSPS, CFI, TRIUMF, Acsion Ind., Govt of MB, UWpg.
- 2009-12:
  - develop UCN source in Japan, EDM experiment
  - preparations and design at TRIUMF
  - develop collaborations and proposals for experiments
- 2012-14: Install, commission at TRIUMF
- 2014-15: First experiments

Thank you!



Osaka, July 2009.

Kicker Concept



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

Summary of CFI request

Item	Cost	Funding Source
UCN cryostat system	$4M	Japanese collaborators
Beamline	$2M	TRIUMF 5YP request
Kickers, shielding, spallation target	$4.225M	CFI NIF
Moderator design	$0.675M	Manitoba + Acsion Industries
Total	$10.9M	+$0.25 M UWpg

- 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.

TRIUMF support for University Initiatives