

Ultracold Neutrons at TRIUMF

Jeff Martin

The University of Winnipeg

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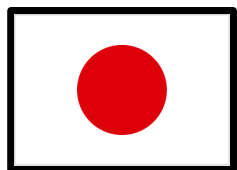
Canada Foundation for Innovation

Manitoba Research & Innovation Fund

Japan Society for the Promotion of Science



International Spallation Ultracold Neutron Source



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

Collaborators: J. Birchall, J.D. Bowman, L. Buchmann, L. Clarke, C. Davis, B.W. Filippone, M. Gericke, R. Golub, K. Hatanaka, M. Hayden, T.M. Ito, S. Jeong, I. Kato, S. Komamiya, E. Korobkina, E. Korkmaz, L. Lee, K. Matsuta, A. Micherdzinska, W.D. Ramsay, S.A. Page, B. Plaster, I. Tanihata, W.T.H. van Oers, Y. Watanabe, S. Yamashita, T. Yoshioka

(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.

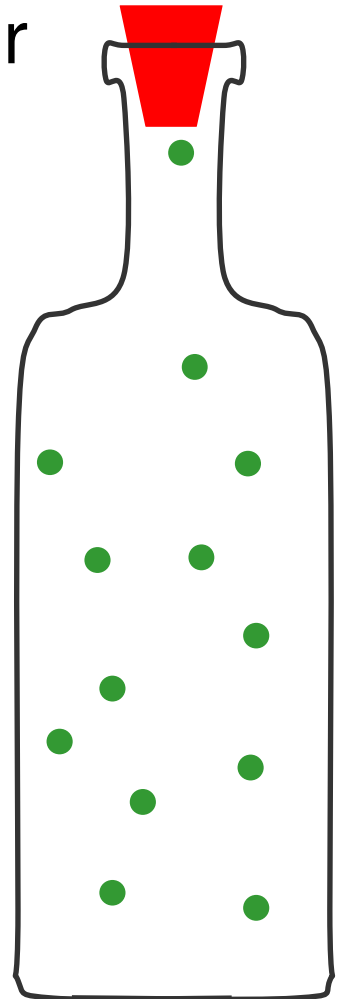
News: \$10.9M proposal now funded in Canada and Japan.

Outline

- UCN production and source
 - Technical progress at TRIUMF
- Physics experiments at the UCN source
 - Prototyping experiments we're conducting in Japan toward a measurement of the neutron electric dipole moment.

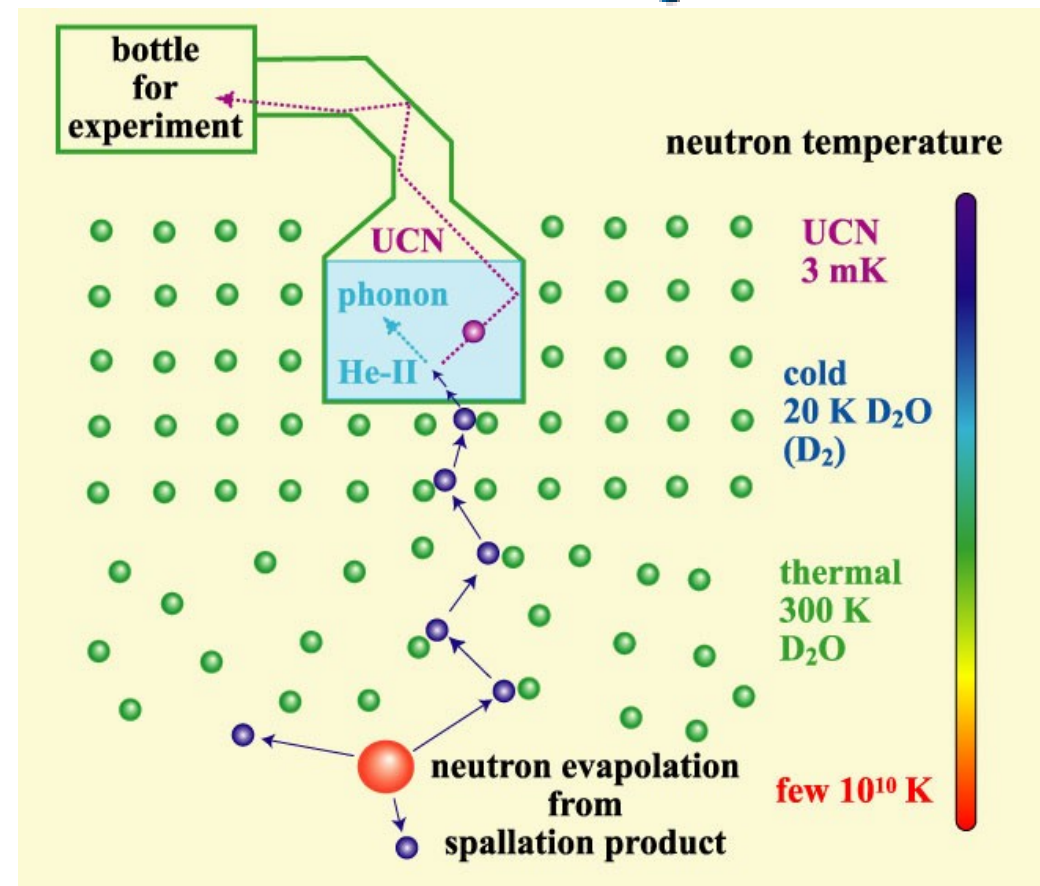
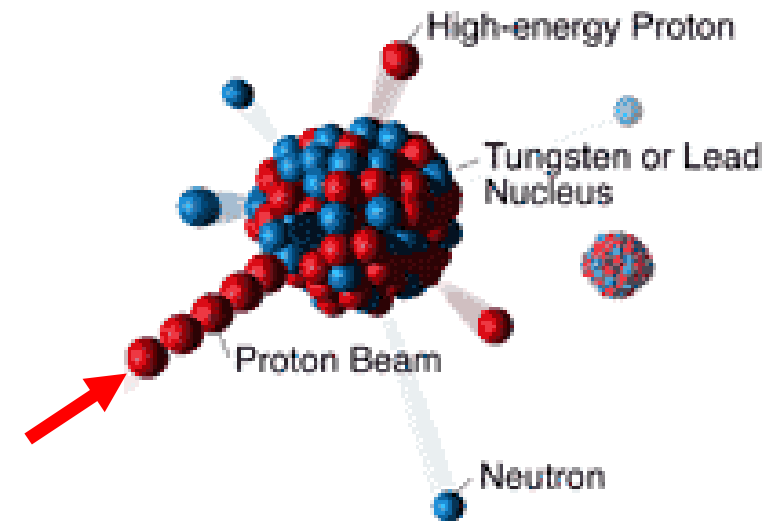
Ultracold Neutrons (UCN)

- 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 $< 8 \text{ m/s} = 30 \text{ km/h} = 20 \text{ mph}$
 - temperature $< 4 \text{ mK}$
 - kinetic energy $< 300 \text{ neV}$
- Interactions:
 - Gravity: $V = mgh$ $mg = 100 \text{ neV/m}$
 - Magnetic: $V = -\mu \cdot B$ $\mu = 60 \text{ neV/T}$
 - Strong: $V = V_{\text{eff}}$ $V_{\text{eff}} < 335 \text{ neV}$
 - Weak: $\tau = 885.7 \text{ s} = 15 \text{ mins}$

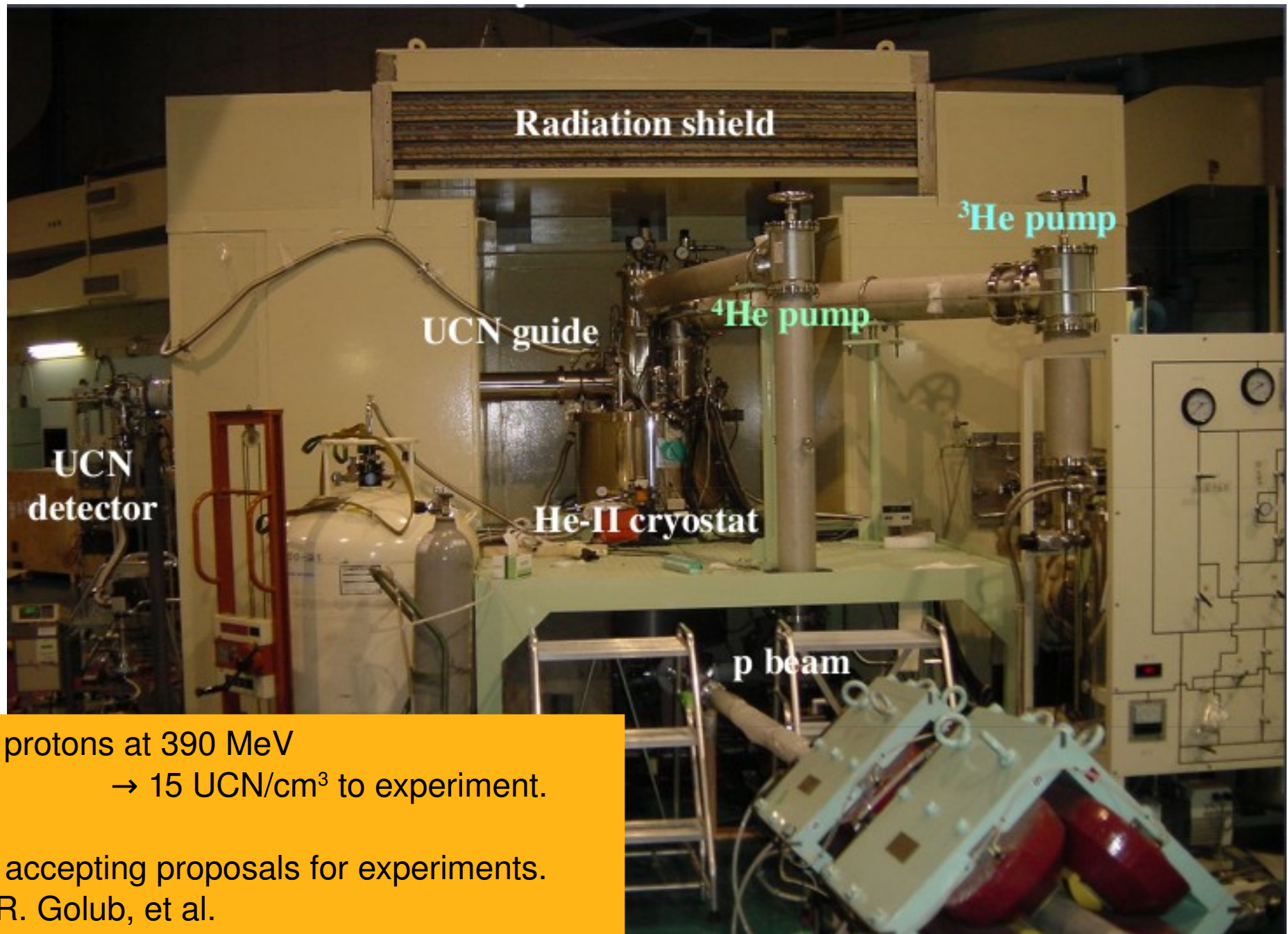


How to make UCN

- 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 μ a protons at 390 MeV
→ 15 UCN/cm³ to experiment.

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



TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

- Proposed beam parameters for TRIUMF UCN source:
 - 500 MeV protons at $40 \mu\text{A}$
- At RCNP, Osaka:
 - 390 MeV protons at $1 \mu\text{A}$
- A fifty-fold increase in beam power.
- Cyclotron operates ~ 8 months/yr.



LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

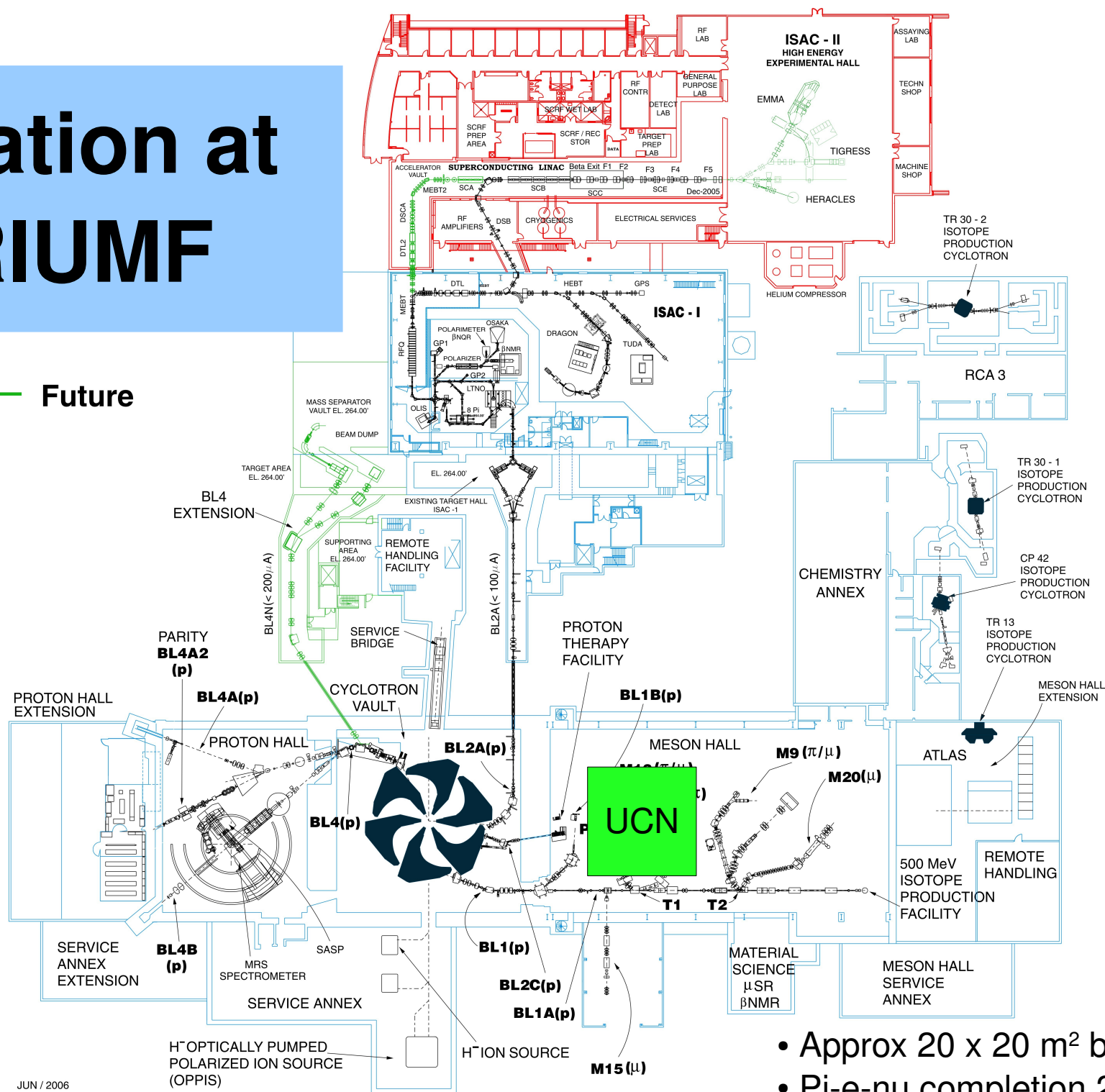
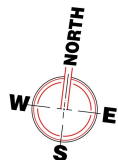
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

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) $1-5 \times 10^4$
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	$1.3 \times 10^3 / 4.4 \times 10^4$	**/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

Future



- Approx 20 x 20 m² box
- Pi-e-nu completion 2011

Technical Progress @ TRIUMF

- Layout
- Kicker
- Beamline
- Target / remote extraction / shielding
- (Cryostat), cryogenics
- Installation
- Cost / schedule / personnel requirements
- MOU's

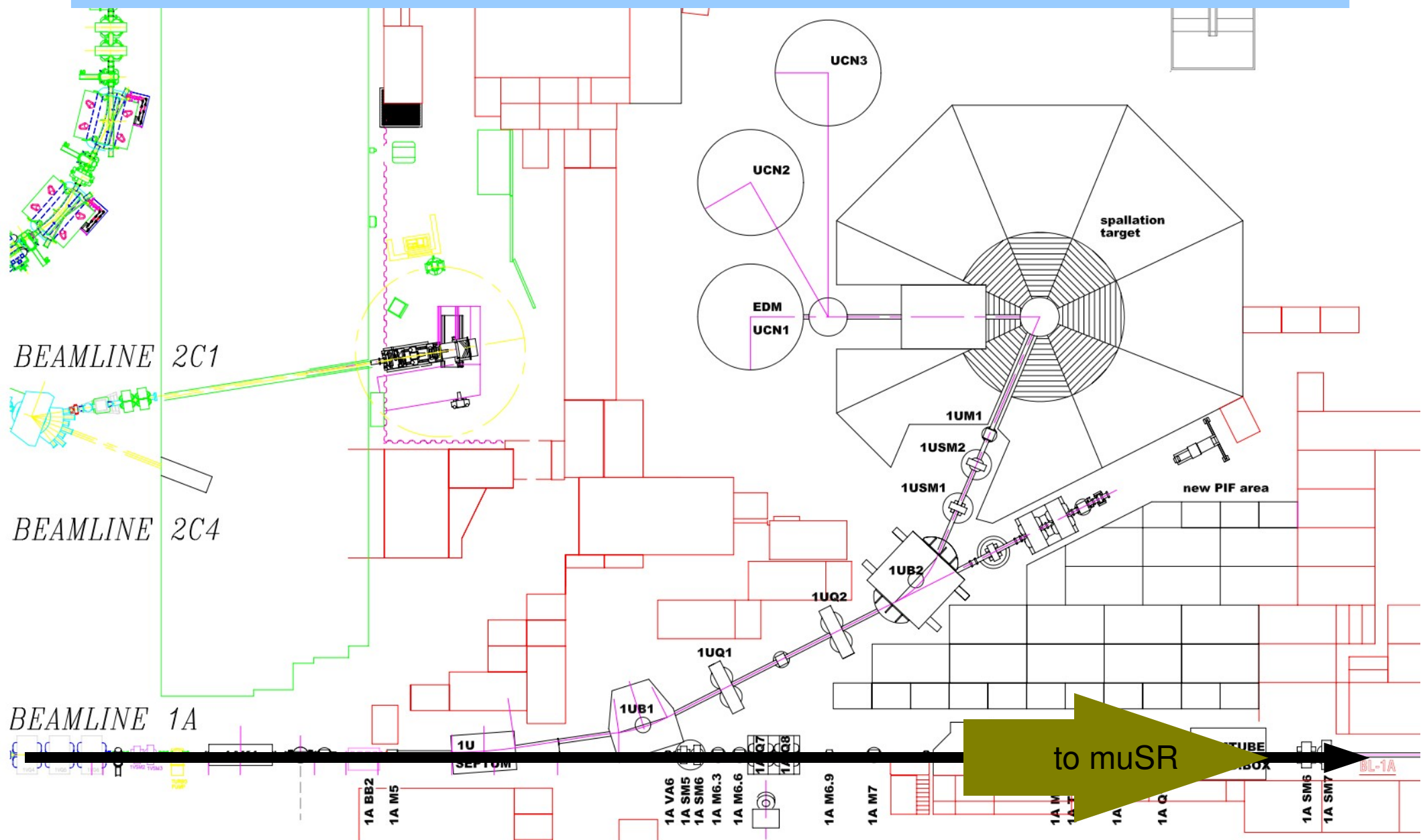
See: <https://documents.triumf.ca/>

- > Non-QMS collections
- > Experimental Facilities
- > UCN

for minutes, docs, etc.

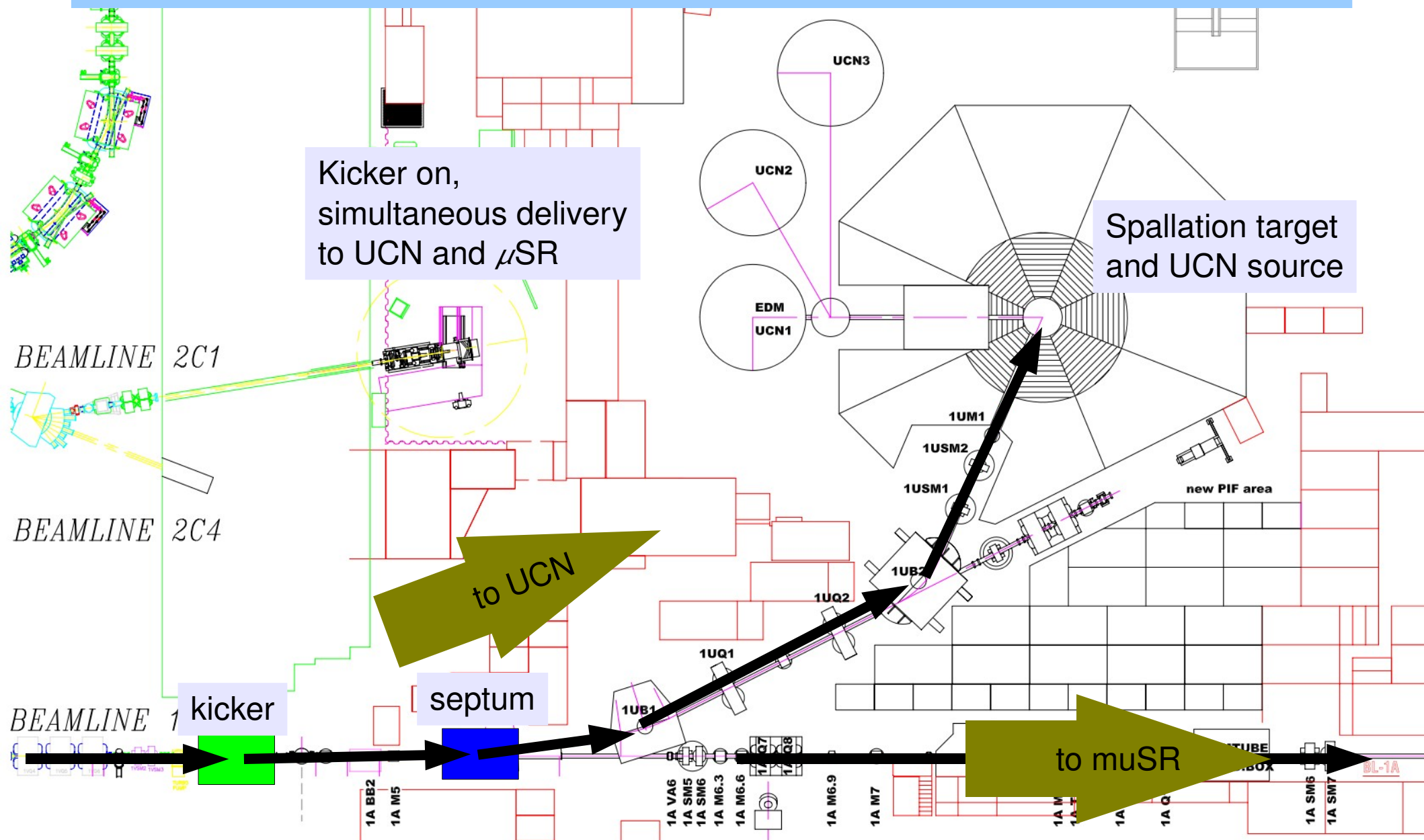
Layout and Overview

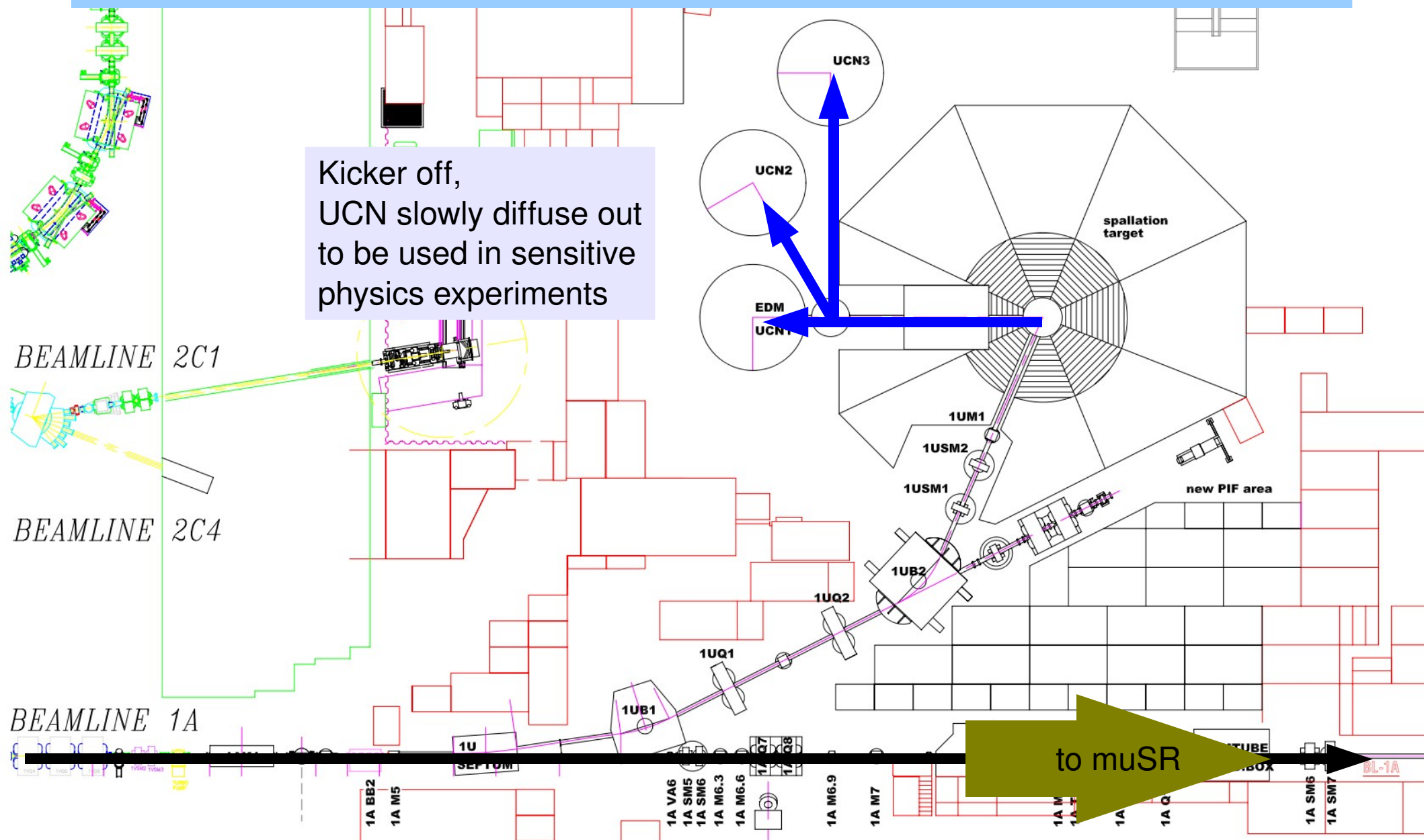
7 2A



Layout and Overview

E 2A



$\mathbb{F}_{2A}$ 

Kicker

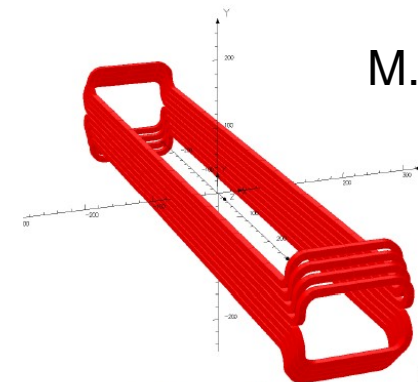
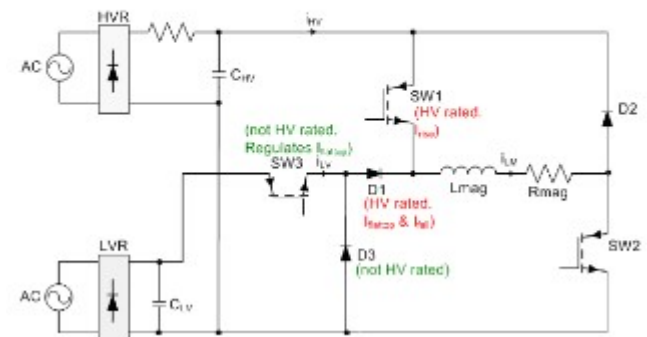
- Redirect 1A beam into UCN line on kHz timescale using existing TRIUMF beam structure.
- Integrated 7% to UCN, 93% to CMMS users.
- TRIUMF/CERN design
 - HV SS switches
 - Fast dipole magnet
- Engineering design.

Kicker Specs:

- 500 MeV protons ($p = 1090 \text{ MeV/c}$)
- 15 mr maximum deflection ($Bd = 0.0545 \text{ Tm}$); normal deflection 12 mr
- effective length 1.5 m (physical available 2 m)
- aperture 100 mm x 100 mm
- field uniform to $\pm 5\%$ over central 80 mm diameter region
- flat top 1 ms, flat to $\pm 5\%$ 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

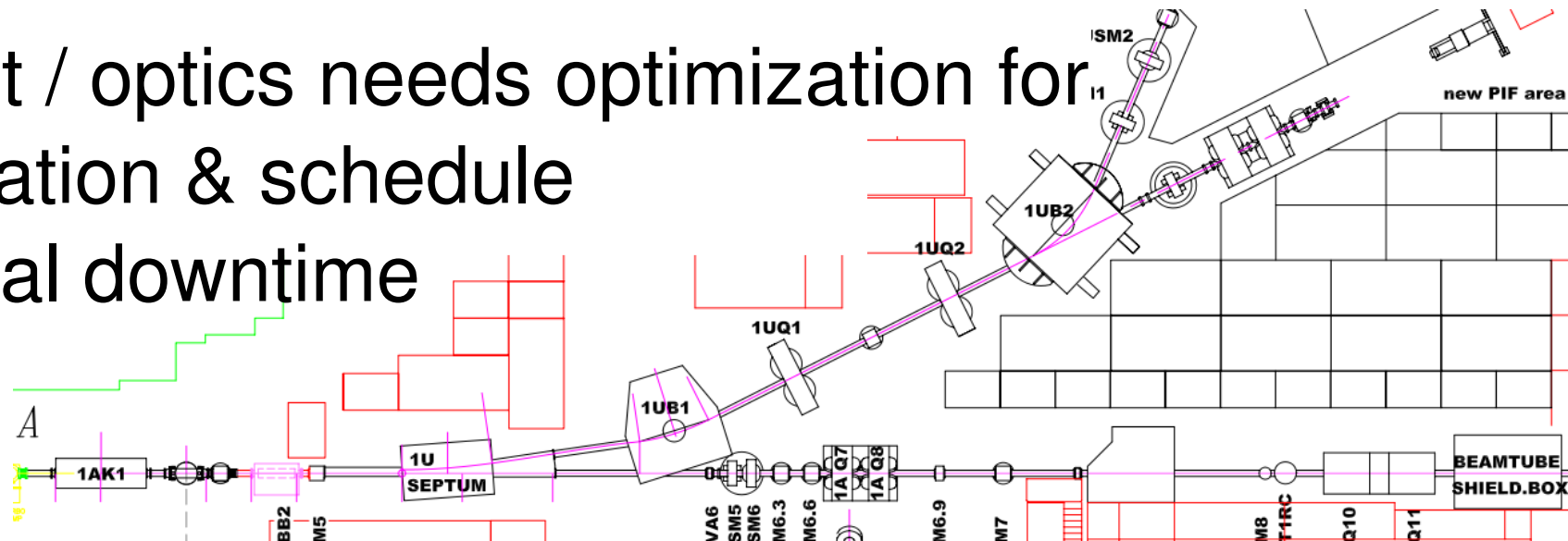


M. Barnes

Fig. 1: Proposed coils for UCN kicker

Beamline

- Optics studies for new layout (J. Doornbos)
 - small spot size achievable at spallation target.
- Beamline can use refurbished parts.
- Septum and first bender are new. Specs to develop with kicker group.
- Layout / optics needs optimization for installation & schedule minimal downtime



Target / Remote Handling / Shielding

- 3 cm dia x 12 cm long W.
- Shielding calcs
 - 3 m steel, 2 m concrete
- Growth of target activity manageable.
- Remote extraction via custom plug.
- Design to be consistent with remote handling, existing MH infrastructure.

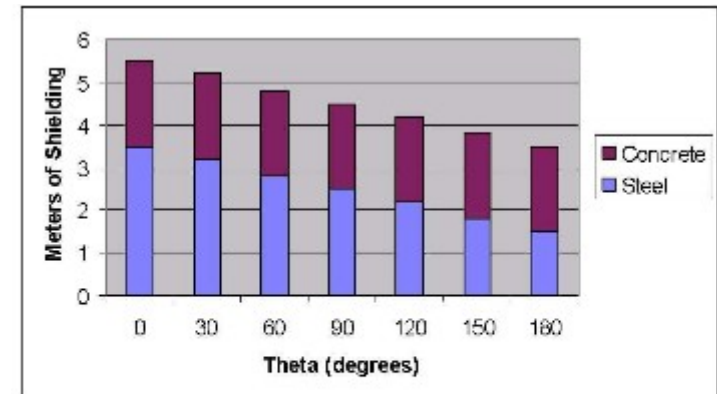
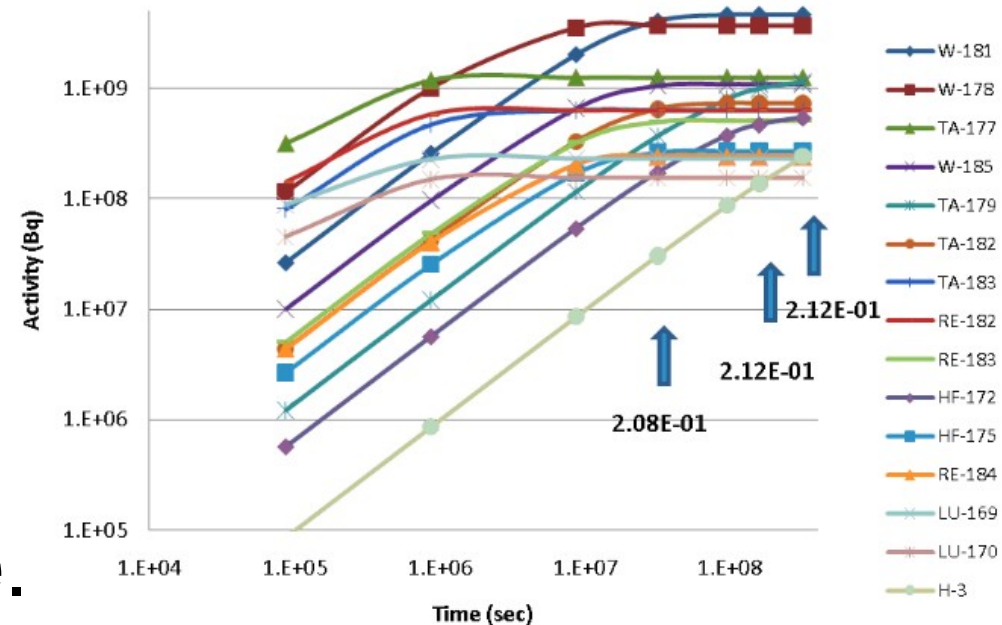


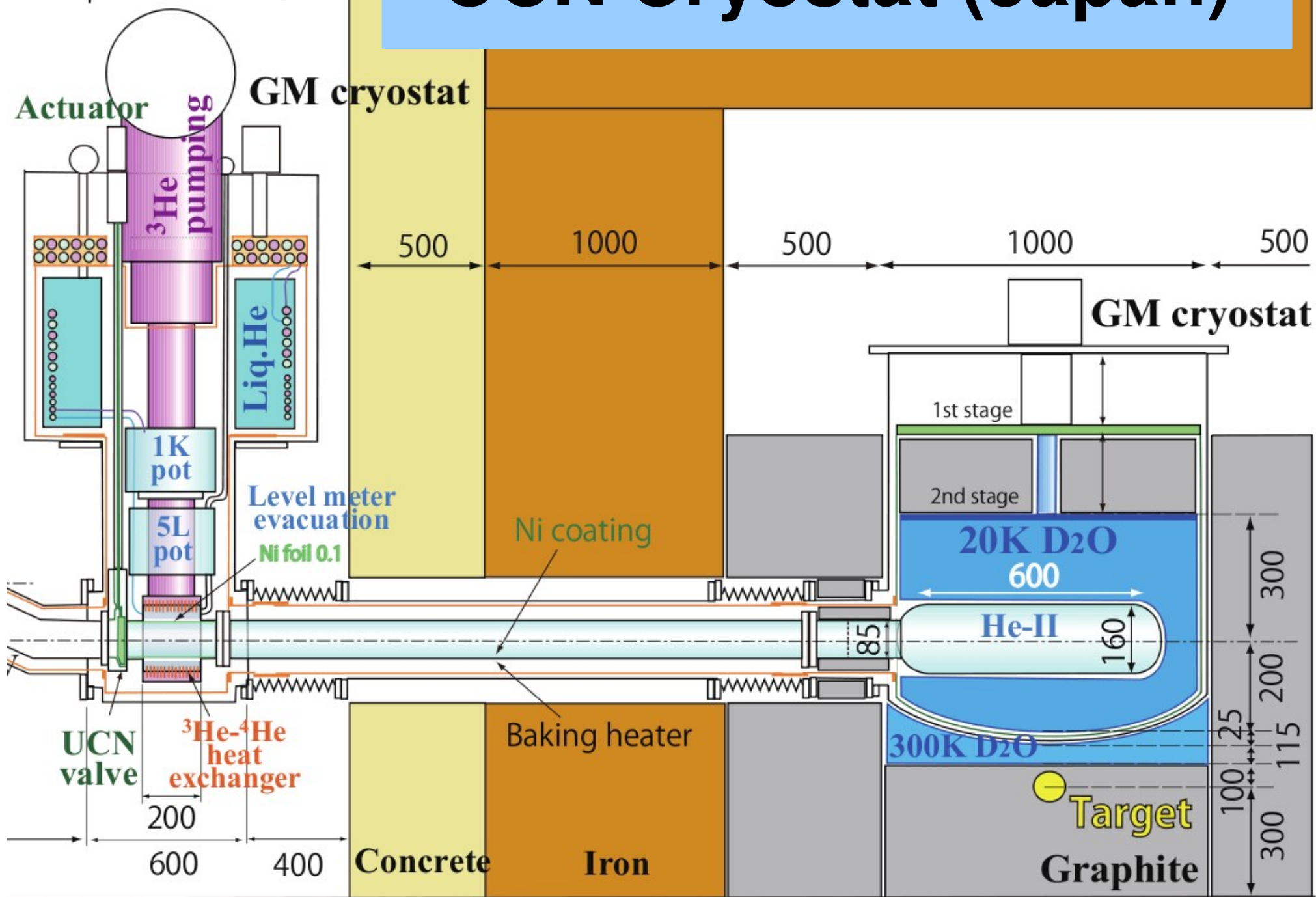
Figure 3: Shielding required for a 40 μ A, 500 MeV proton beam incident on a thick tungsten target. The design dose rate is 3 μ Sv/hr immediately outside the shielding.



He-II cryostat

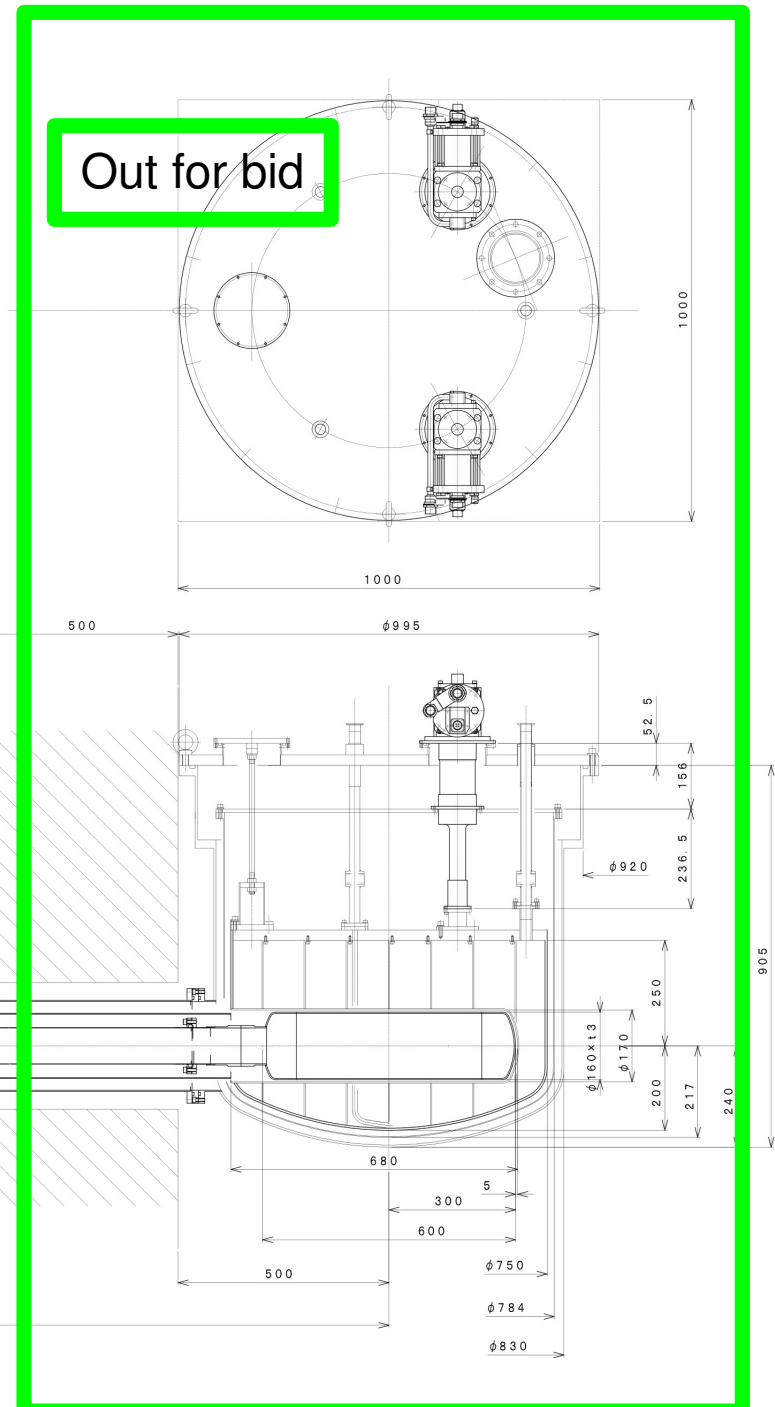
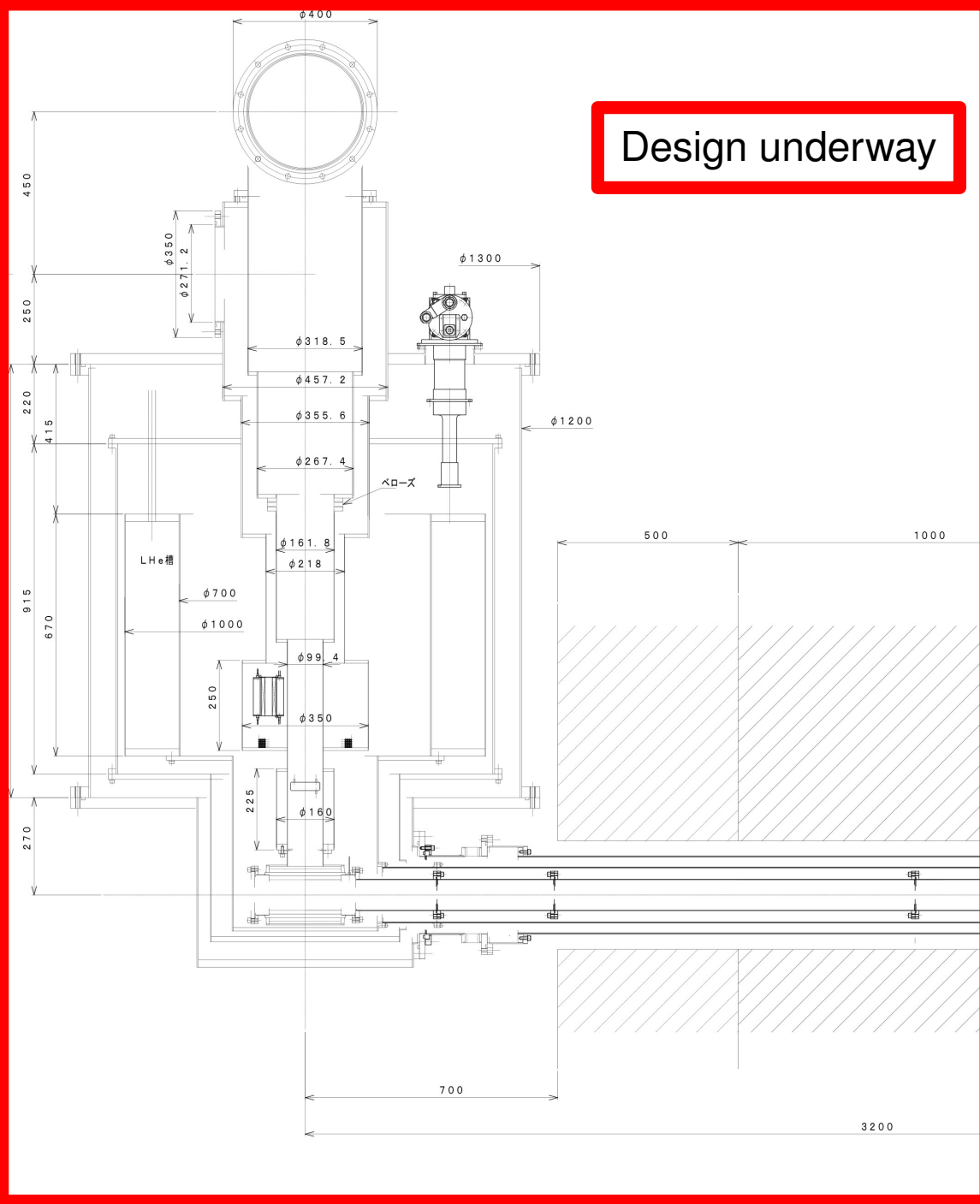
◦ Isopure ^4He ◦ ^3He

UCN Cryostat (Japan)



Design underway

Out for bid



Cryogenics

- Estimated LHe consumption < 1000 LL/day.
- Needs are consistent with liquifier requested in TRIUMF 5YP.
- Locate new liquifier near/in Meson Hall.
 - transfer / warm return lines direct to UCN
 - proposal to alter Japan section cryocoolers and use LHe instead
- Liquifier overhead to support other (μ SR) users with dewars / warm return.

Installation

- Legacy infrastructure removal, followed by installation of key components (e.g. kicker and septum) to be conducted in series of shutdowns in order to minimize impact on cyclotron running (ISAC) and μ SR users (Meson Hall).
- e.g. kicker install requires vault access.
- Draft schedule in development.
- Impact of beamline design on schedule.

**Cost / sched / personnel / MOU's /
reviews**

- Figure 3 is a Gantt chart illustrating the project schedule for the development of the 'Project Phoenix' system. The chart displays tasks, their durations, and dependencies across a timeline from 2019 to 2021. The tasks are organized into a hierarchical structure, with 'Project Phoenix' at the top level, followed by 'Design', 'Development', 'Testing', and 'Deployment'. The chart shows that the project is currently behind schedule, with several tasks delayed and some tasks not yet started. The Gantt chart uses color-coded bars to represent the duration of each task, with red indicating delays and green indicating on-schedule progress. The chart also includes a legend for task status and a summary of the project's overall progress.

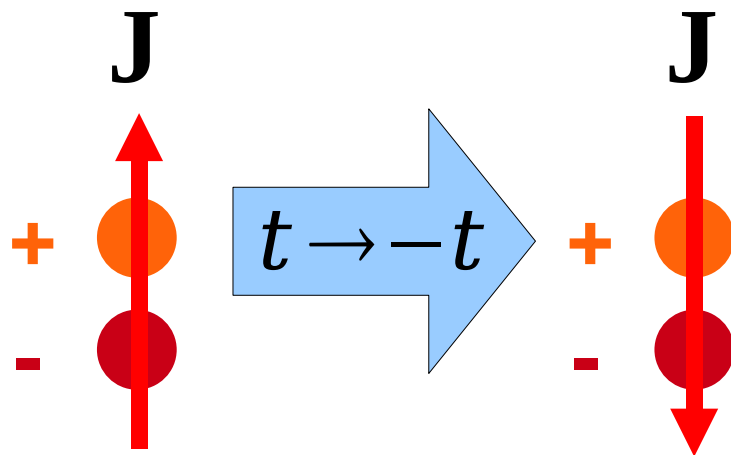
Task Name	Start	End	Duration	Status
Project Phoenix	2019-01-01	2021-01-01	24 Months	On Schedule
Design	2019-01-01	2019-06-01	5 Months	On Schedule
Development	2019-06-01	2020-06-01	12 Months	On Schedule
Testing	2020-06-01	2020-12-01	6 Months	On Schedule
Deployment	2020-12-01	2021-01-01	1 Month	On Schedule

Physics Experiments for the TRIUMF UCN Source

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

All ideas / letters / proposals welcome

Neutron Electric Dipole Moment (n-EDM, d_n)



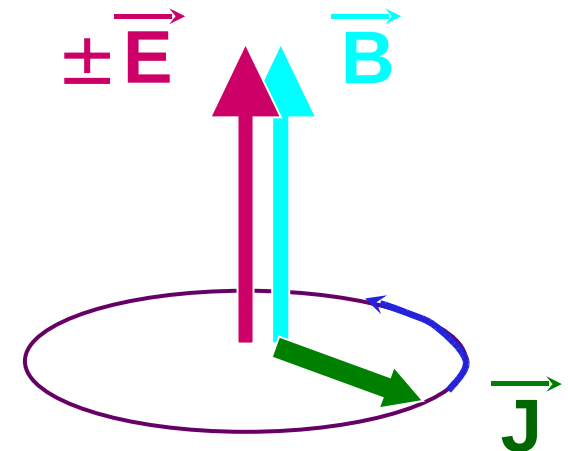
$$d_n \Rightarrow \cancel{T} \Rightarrow \cancel{CP}$$

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

- Complementary to Rn-EDM TRIUMF ISAC.

Experimental technique:

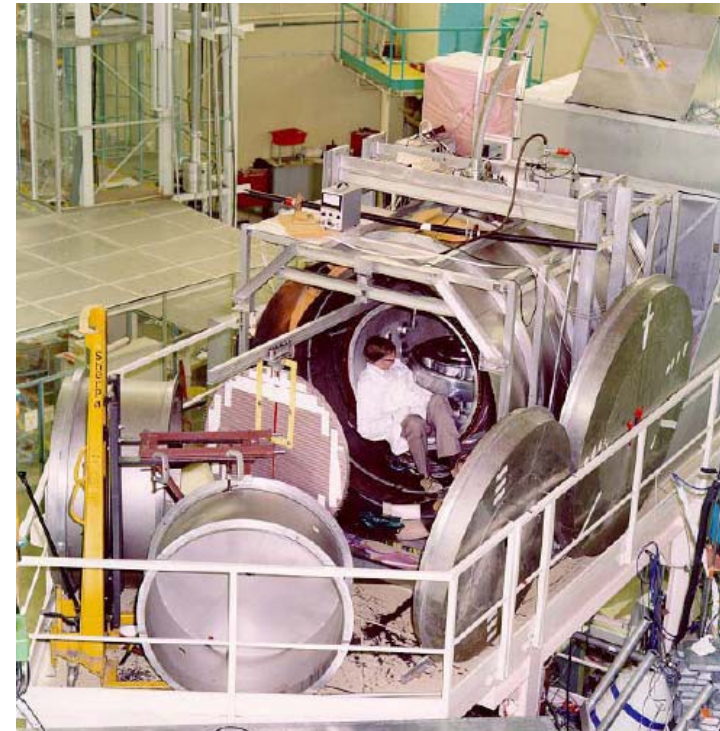
- put UCN in a bottle with E -, B -fields
- search for a change in spin precession frequency upon E reversal.



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

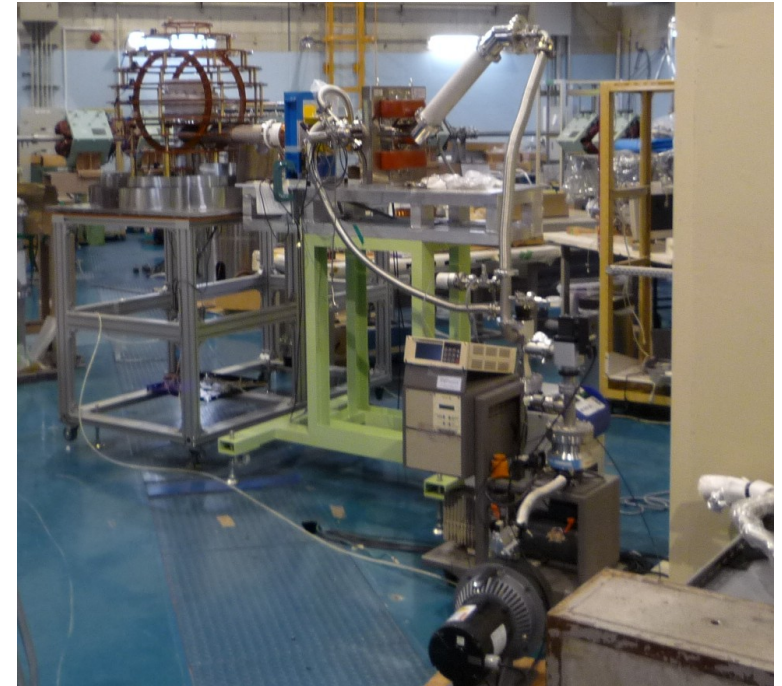
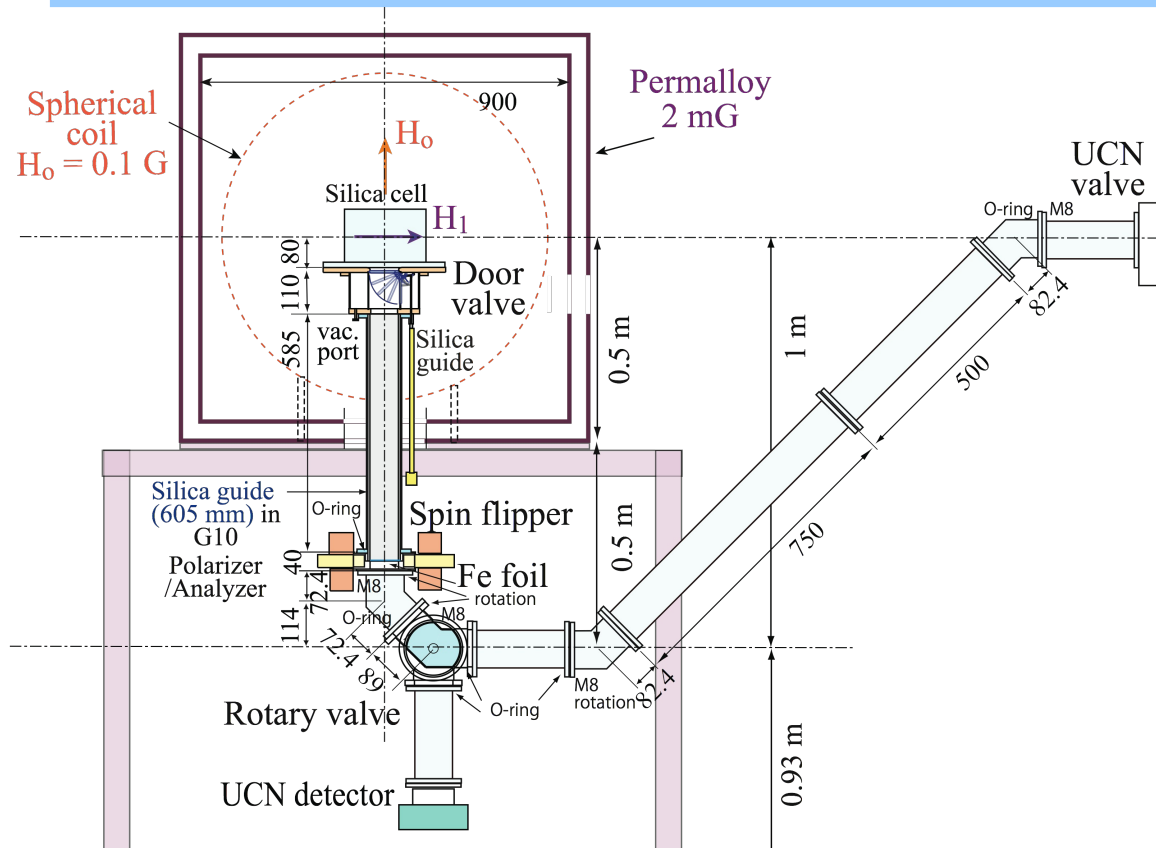
Past and Future n-EDM efforts

- Sussex-RAL-ILL expt. ($d_n < 3 \times 10^{-26}$ 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: 10,000 UCN/cc



Sussex-RAL-ILL experiment

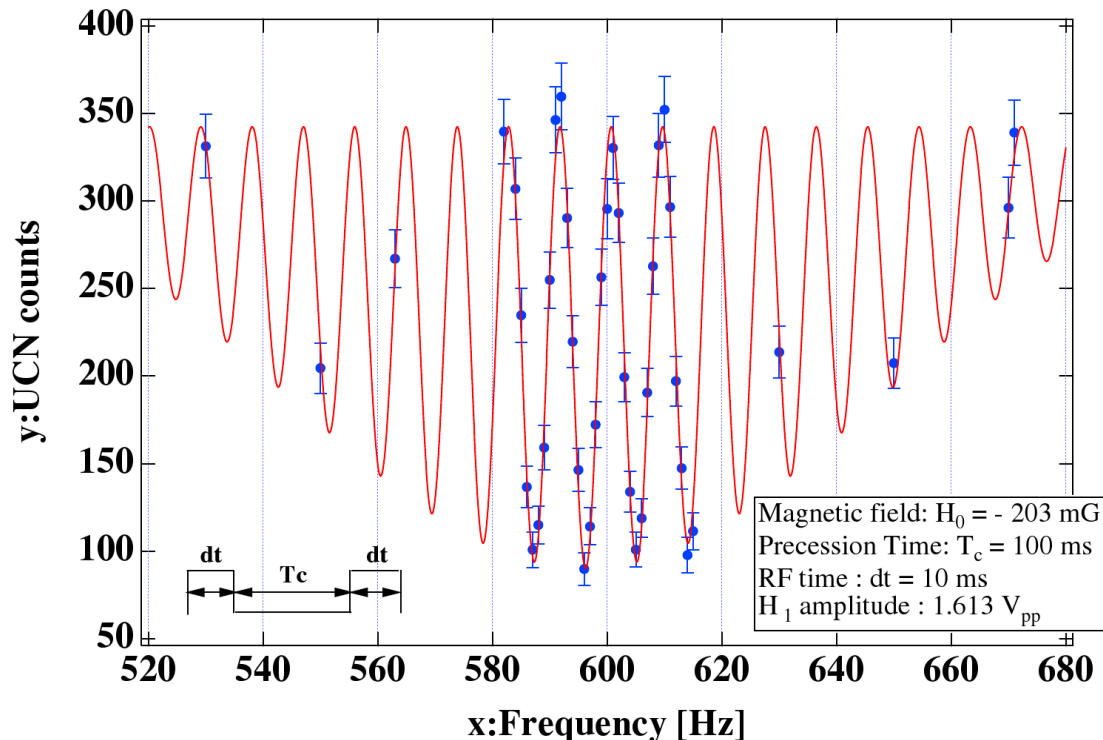
n-EDM development in Japan



- Masuda, et al. Beam tests July 7-16, 2009 and December 8-13, 2009 at RCNP, Osaka.
- Development of:
 - Comagnetometers
 - Ramsey resonance
 - New B-field geometry

Ramsey Resonance Results

Y. Masuda, et al, in preparation



Dec. 12, 2009, achieved:

$$T_2 \sim 300 \text{ ms}$$

Scaling to operating B_0 field:

$$T_2 \sim 300 \text{ ms} * (600/30)^2 = 120 \text{ s}$$

would be competitive with ILL!
(assuming motional narrowing)

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:
$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$
 - $\alpha=0.64$, $\tau=130$ 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 with increased UCN density:
 - 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 at TRIUMF

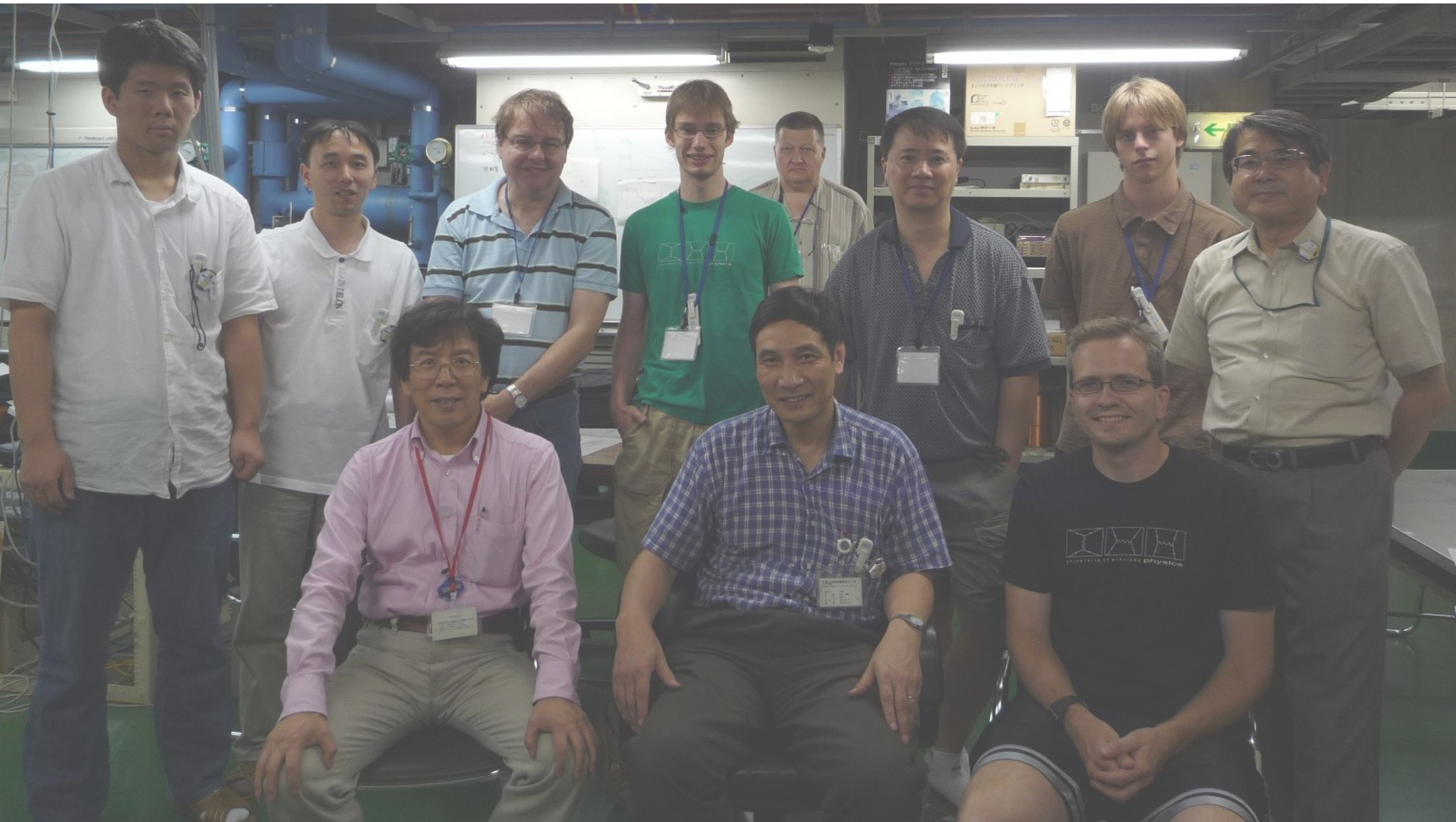
- Complete experiments in Japan, 2009-2012.
- Develop LOI/proposal for TRIUMF ~ 2010-11.
- Unique aspects of the EDM work in Japan:
 - New UCN production mechanism aiming for highest density
 - Higher UCN density allows smaller cell size
 - New DC coil geometry
 - Xe comagnetometer

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

Timeline

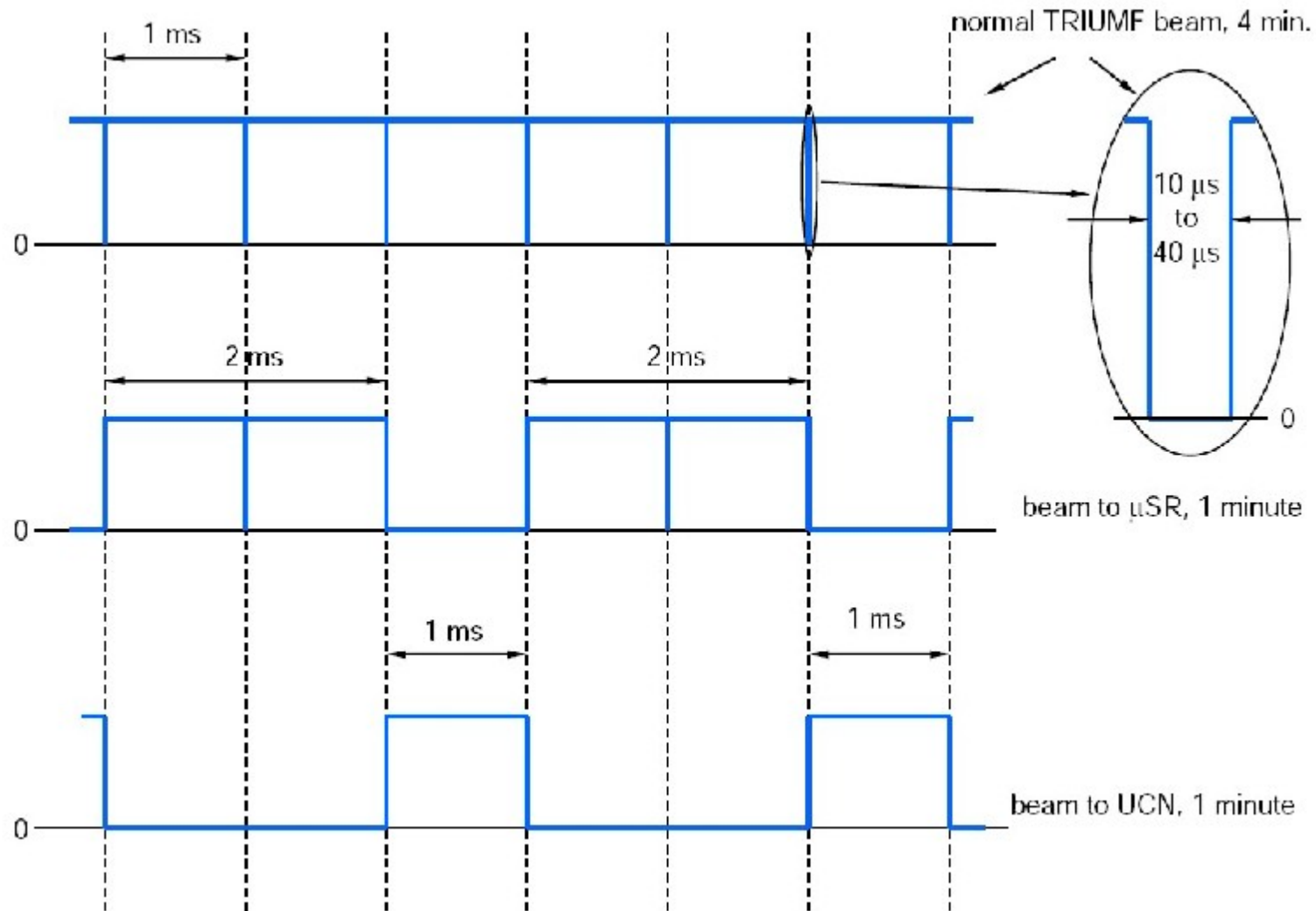
- 2007-8: UCN source supported by TRIUMF committees, included in plan for TRIUMF
- **June 2009: Source funded in Canada and Japan!!!**
 - JSPS, CFI, TRIUMF, Acsion Ind., Govt of MB, UWpg.
- **2009-12:**
 - develop UCN source in Japan, EDM experiment
 - preparations and design at TRIUMF
 - develop collaborations and proposals for experiments
- 2012-13: Install, commission at TRIUMF
- 2013-15: 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