TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

UCN @ TRIUMF: Status and Outlook

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Research Scientist, TRIUMF
for the UCN collaboration

Science Week 2017
July 13

Contents

- UCN?
- Status of ultracold neutrons at TRIUMF
  - Beamline and UCN source installations
  - Beamline commissioning and first neutron experiments
- Ultracold outlook into the next decade
  - Next generation UCN source and EDM experiment
  - TRIUMF ultracold neutron user facility

TRIUMF

Ultracold neutrons (UCN

- Kinetic energies < 300 neV (< 4 mK)
- Can be manipulated by
  - Gravity – $102\,\frac{\text{neV}}{\text{m}}$
  - Strong Interaction – wall potentials < 300 neV
  - Magnetic fields – $60\,\frac{\text{neV}}{\text{T}}$

Kinetic energies < 300 neV (< 4 mK)
Can be manipulated by
Gravity –
Strong Interaction – wall potentials
Magnetic fields –

UCN Transport

NiP coated tube

Polarisation

UCN source

≅

experiment

|B|

polarising magnet

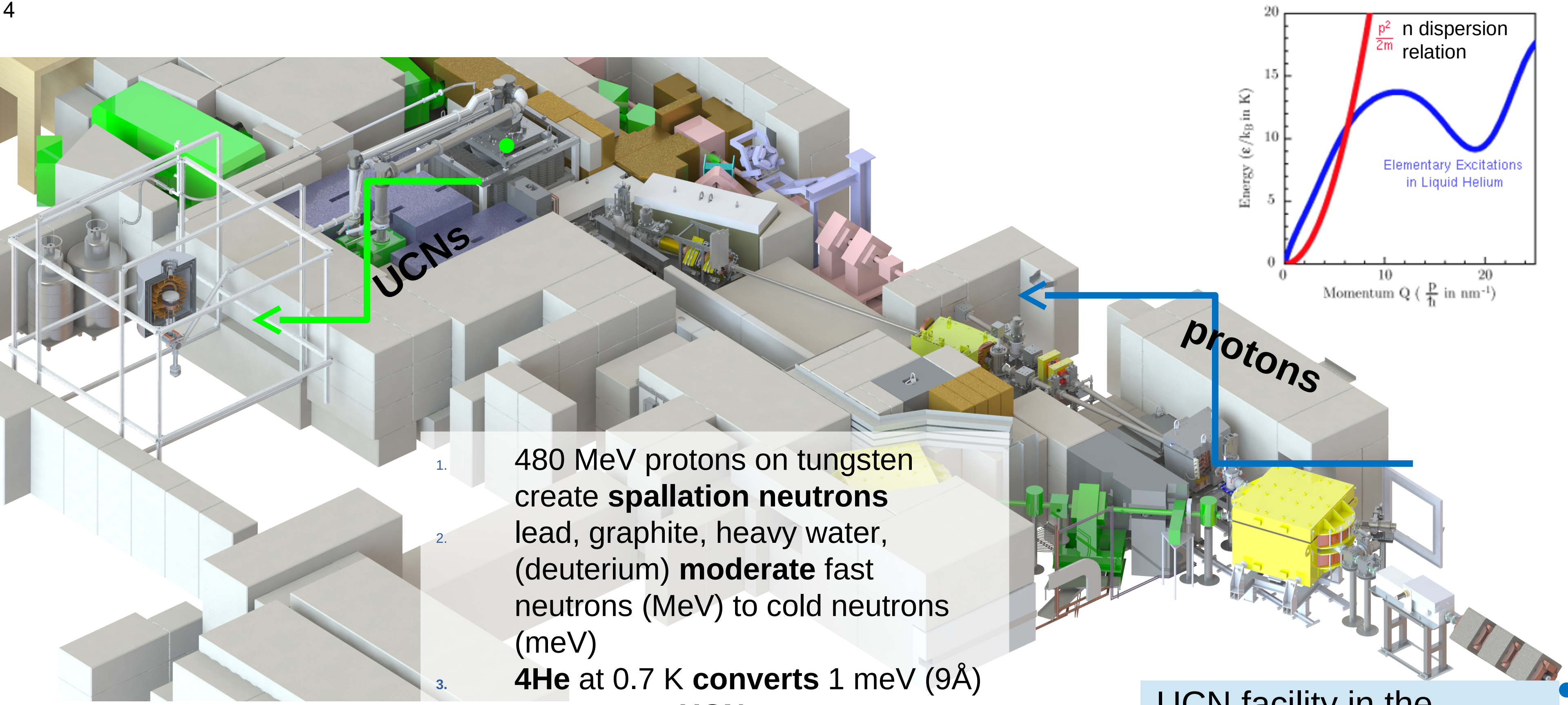
UCN can be …

- observed for 100's of seconds,
- easily polarized to almost 100 %,
- easily manipulated.

Ideal for precision experiments like

The UCN recipe at TRIUM

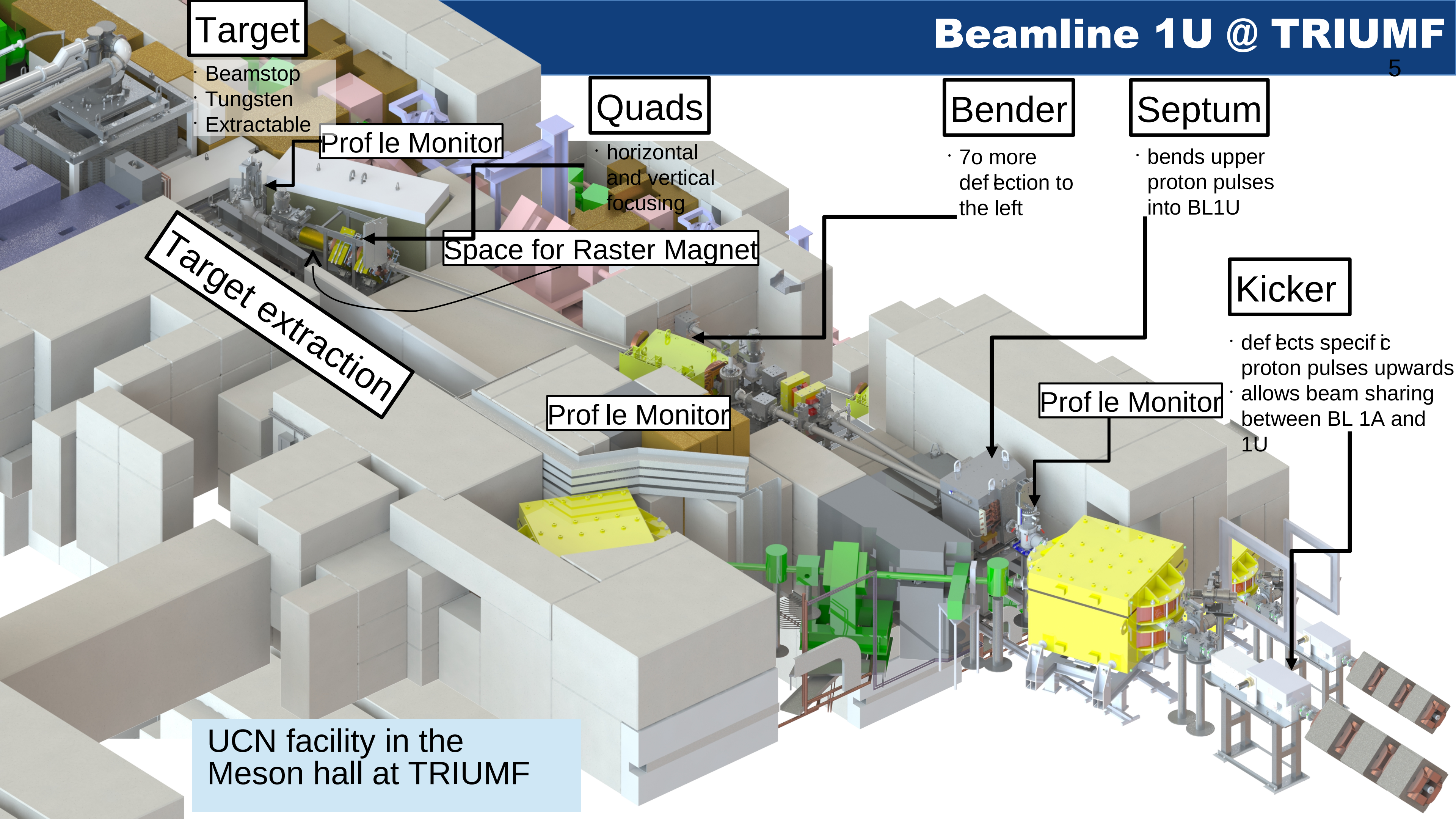
4



1. 480 MeV protons on tungsten create **spallation neutrons**
2. lead, graphite, heavy water, (deuterium) **moderate** fast neutrons (MeV) to cold neutrons (meV)
3. **4He** at 0.7 K **converts** 1 meV (9Å) neutrons **to UCN**
4. **Extraction** to experiments via material guides

UCN facility in the Meson hall at TRIUMF

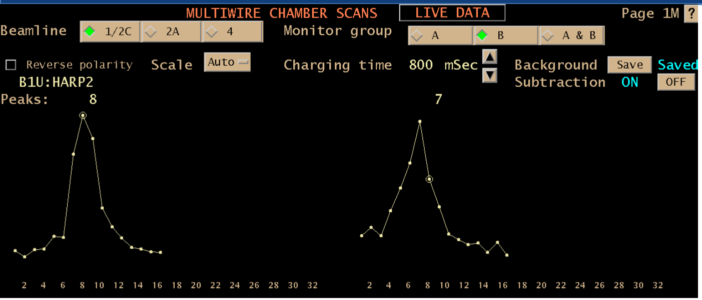
Beamline 1U @ TRIUMF



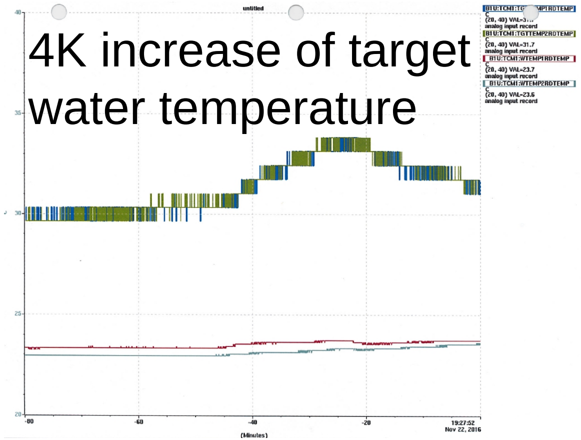
BL1U completion 201(

- After shutdown 2016: all beamline hardware installed (vacuum, optics, diagnostics, target and target extraction)
- Summer 2016: Beamline diagnostics and controls were implemented by Accelerator Division.
- Proton beam times were requested and approved for fall 2016.
- The kicker magnet would be in DC mode.

BL1U commissioning 201



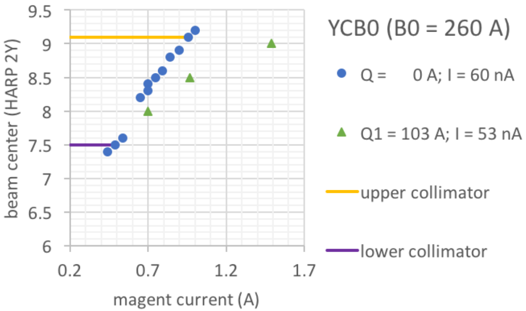
- **Nov 22, 2016: First beam on target and neutron production**
- Only took one hour to reach target and ramp to 1 μA nominal current!



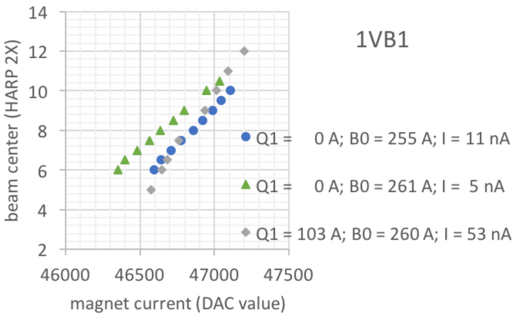
4K increase of target water temperature

Control room celebrations

Magnet scan examples



vertical correction magnet



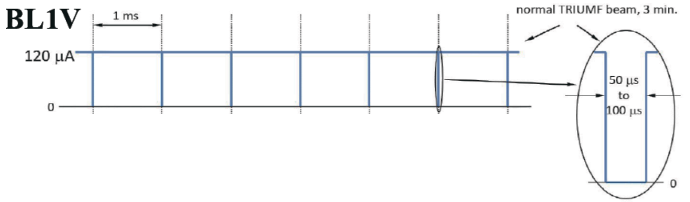
horizontal steering magnet

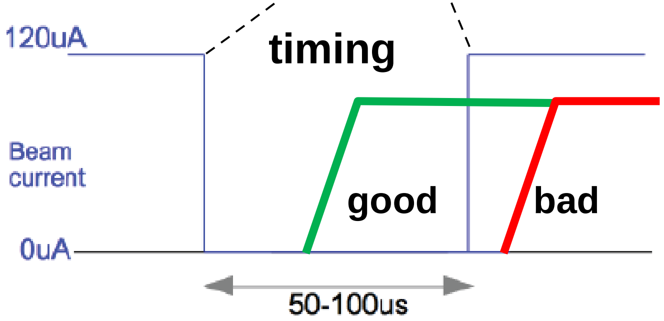
Nov/Dec 2016 and May/June 2017

- Beamline magnets commissioned, kicker tested
- Diagnostic elements have been successfully tested
  - HARP beam profile monitors
  - BSM beam spill monitors
  - Collimator thermo couples
- Target water cooling system fully online
- Beamline is pretty well understood from various magnet scans

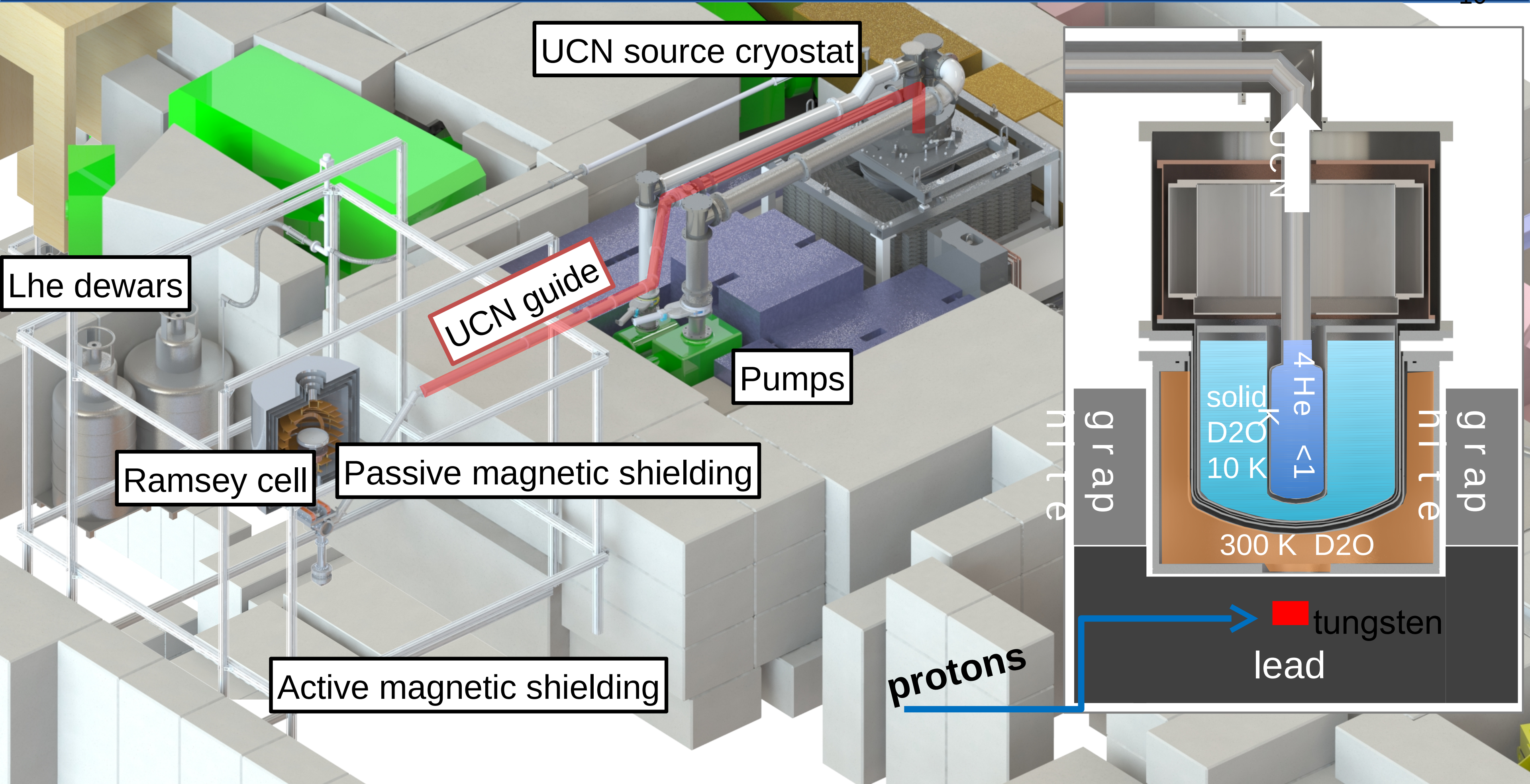
- **Beam sharing** between BL1A and 1U possible because of beam notches
- Need good timing of kicks
- First tests at lower injection current: kicker works like a charm!
- Commissioning at full current planned for July 18

Next: UCN production!





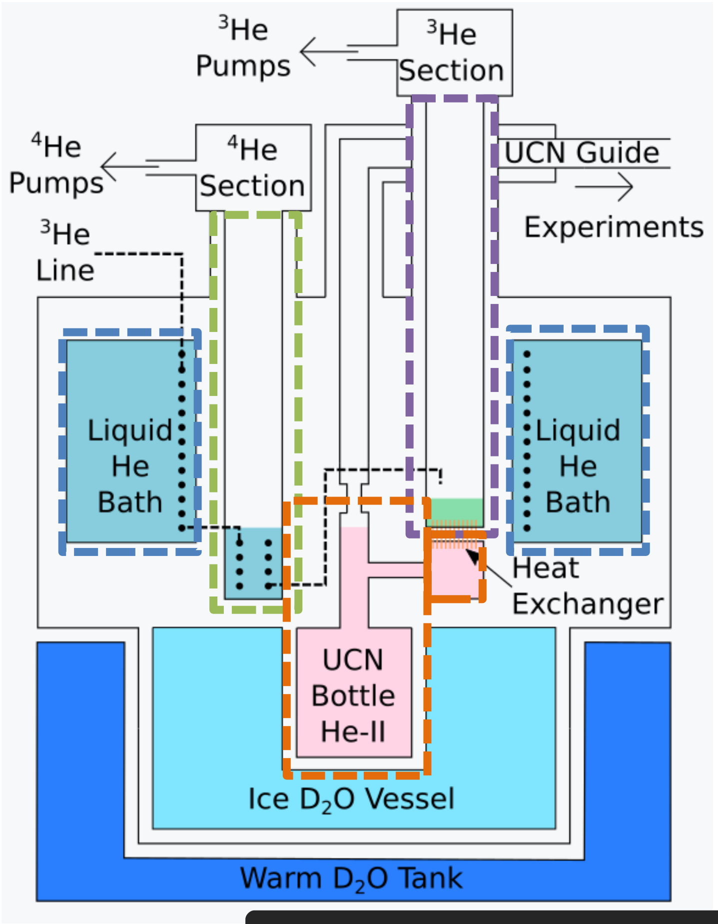
The Ultracold Neutron Source @ TRIU



3 cooling stages, heat exchanger to isopure 4He

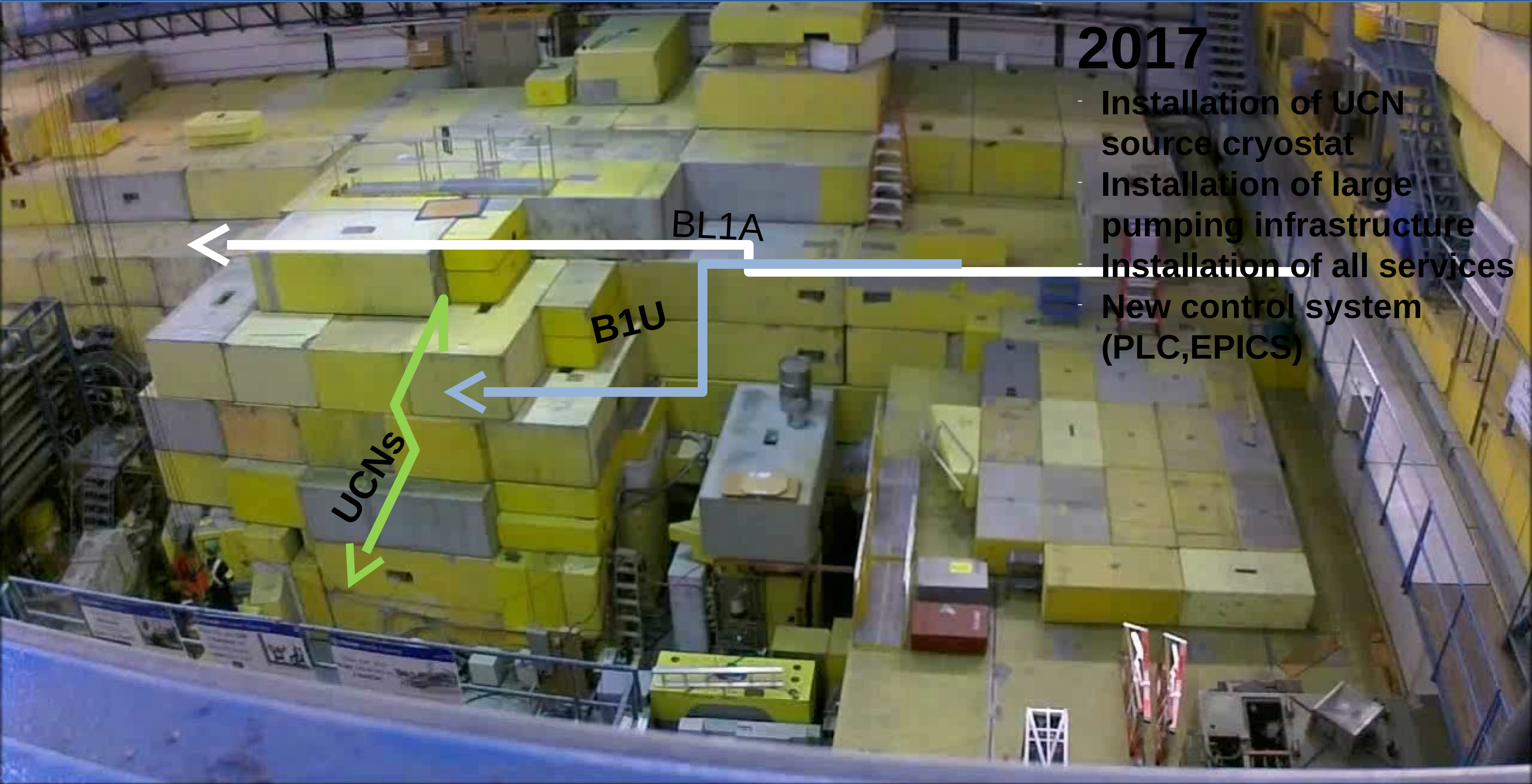
- lHe bath cryostat
- 4He pumping section (1.4 K)
- 3He pumping section (down to 0.8 K)
- Isopure 4He UCN converter cooled via heat exchanger

Running at 1 µA beam current to start with (as at RCNP).



Ryohei Matsumiya, Shinsuke Ka

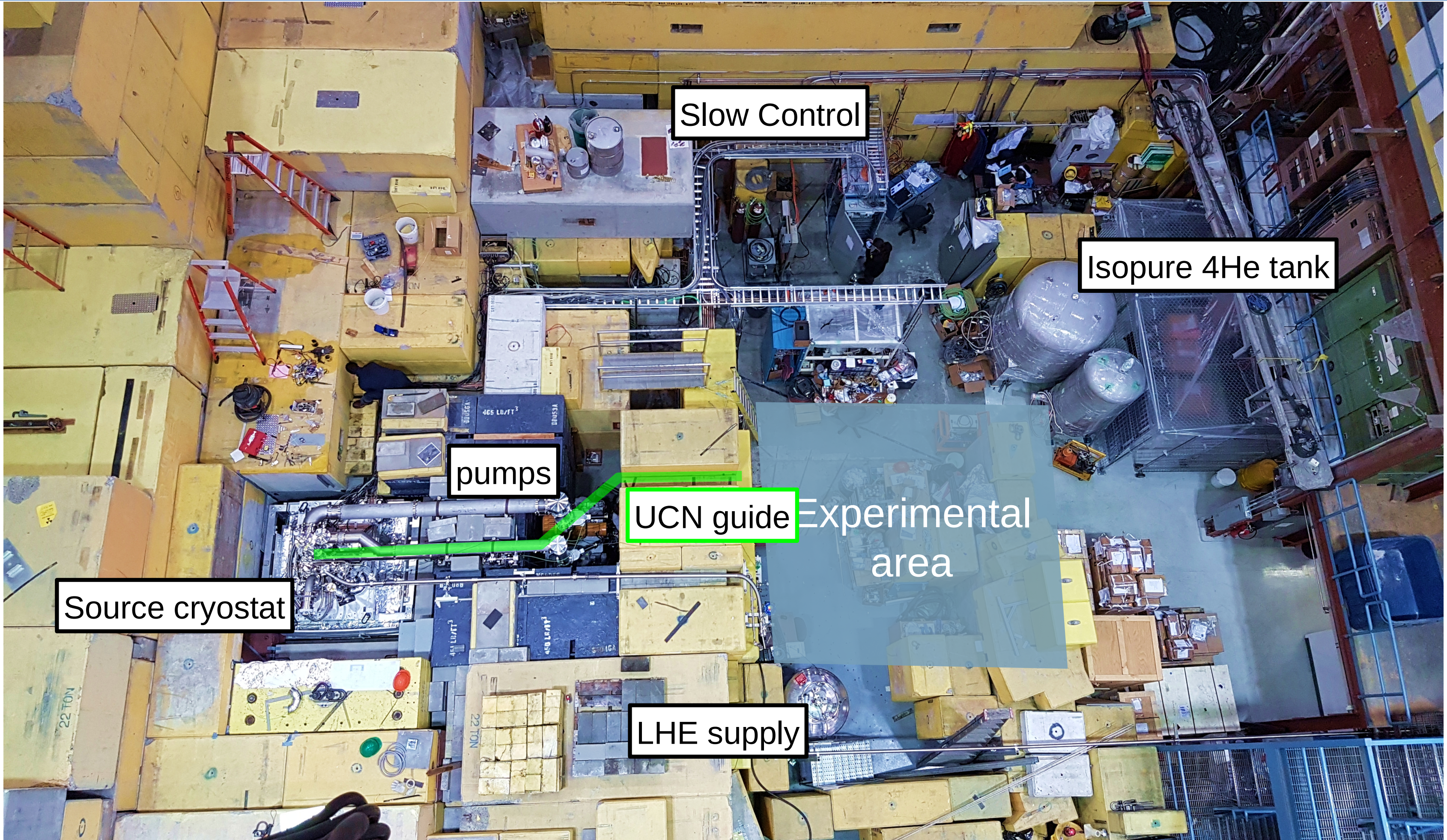
UCN shutdown work 201



2017

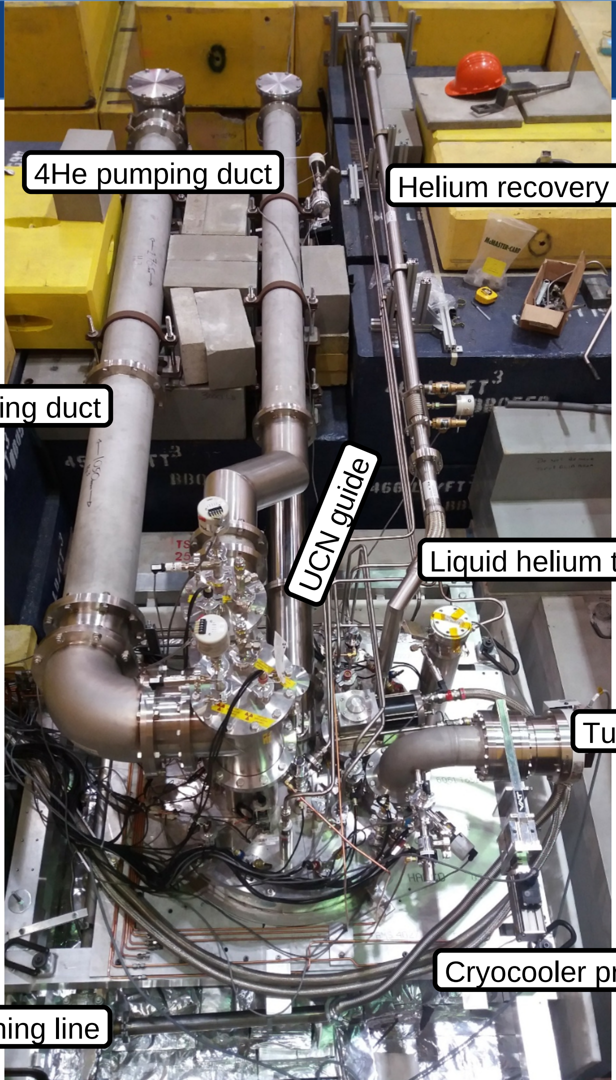
- Installation of UCN source cryostat
- Installation of large pumping infrastructure
- Installation of all services
- New control system (PLC,EPICS)

UCN area layout 2017 without shiel

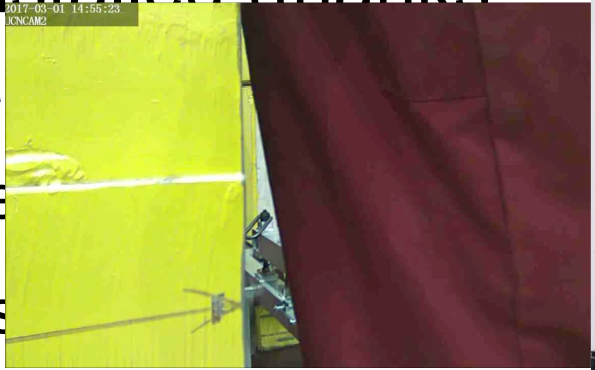


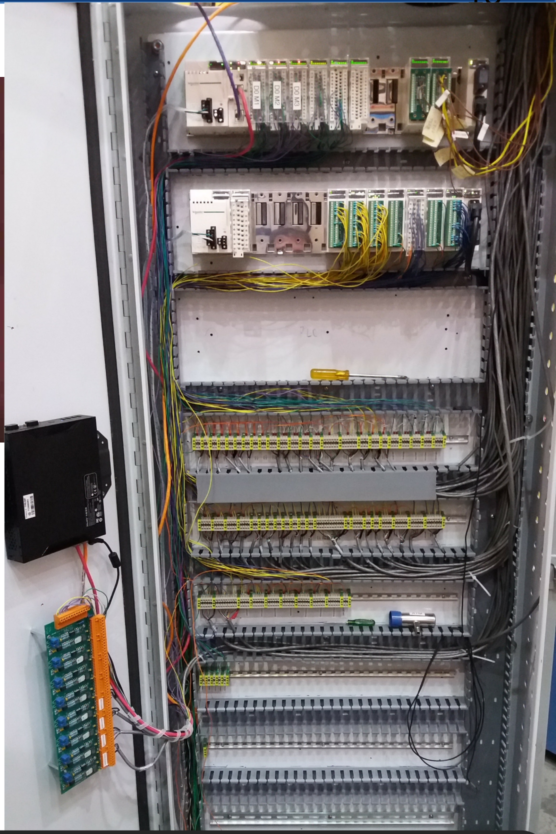
UCN source installed

N



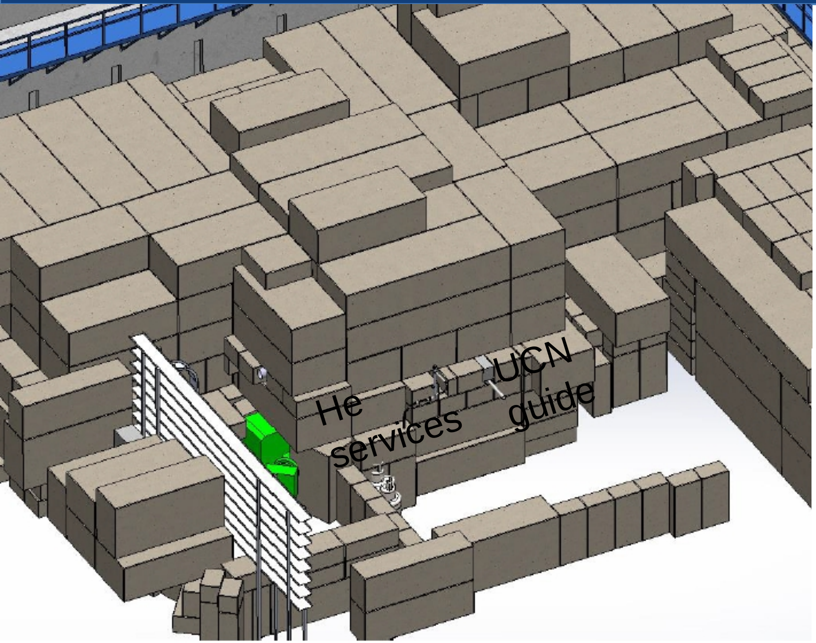
- Services had to be installed (thanks to the TRIUMF elect
  - 50 kW electrical powe
  - Ca 15 vacuum pumps
  - Pressurized air, cooling water
  - Helium recovery line
  - Stationary liquid helium dewar
  - New ca 10 m liqu
- Graphite stacking



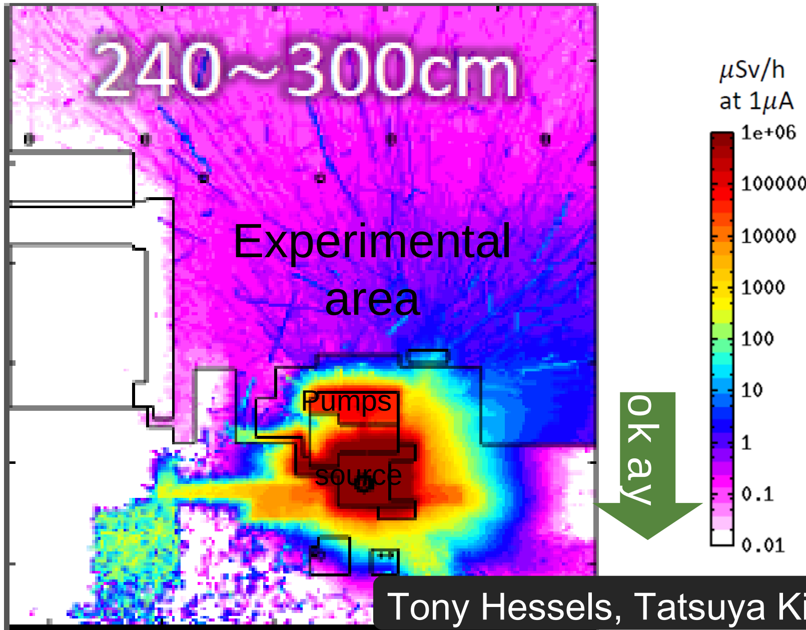


Taraneh Andalib, Beryl Bell, Beatrice Franke, Tony Hessels, Shinsuke Kawasaki, Tatsuya Kikawa, Florian Kuchler, Thomas Lindner, Cam Marshall, Ryohei Matsumiya, Matthew Palmer, Ruediger Picker, Steve

- Economical: no custom shielding required
- Pumps inside shielding

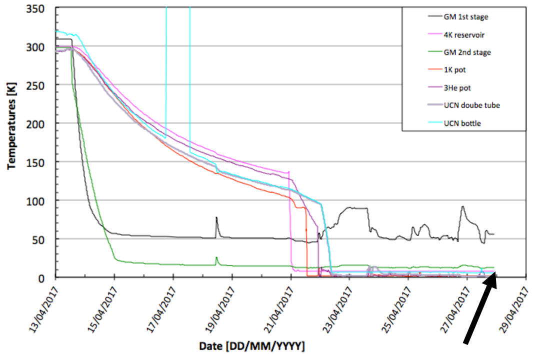


- Experimental area accessible with beam on

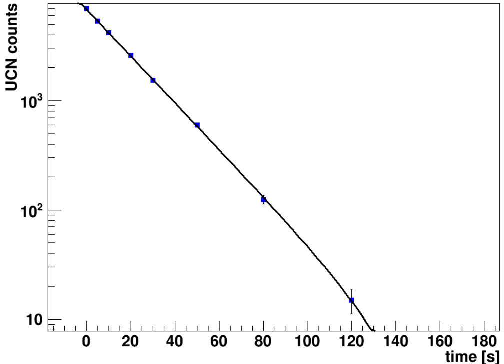


Status

- All infrastructure has been installed (total ca $15M invest)
- Full cooldown test was successful: 0.92 K in the isopure helium
- D2O has been frozen and is at 20 K
- UCN guides and detectors ready for first UCN counting
- Liquid nitrogen cooling of the Meson

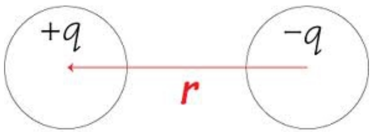


He-II in the UCN bottle 0.92K



Neutron EDM?

electric dipole moment (EDM)
charge separation

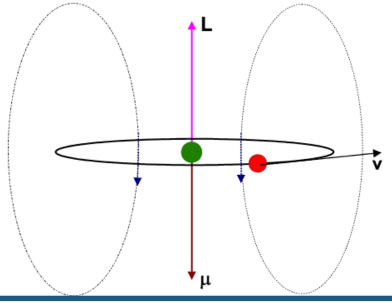


$\mu = q r$[e≅ cm]

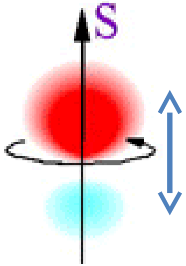
Experimental limit today:

dn < 2.9 • 10-26 e·cm (PDG 90% conf.)

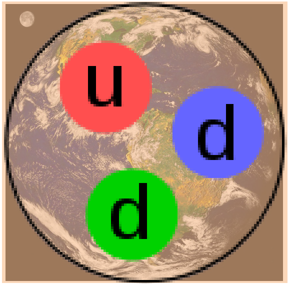
neutron case



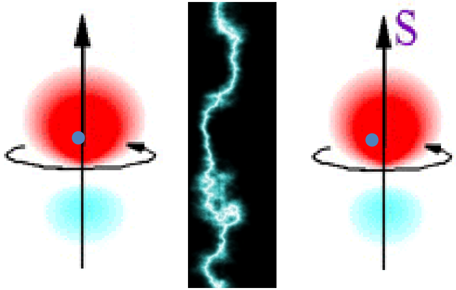
slight separation of the positive and negative **charge cloud** along the axis of the magnetic moment

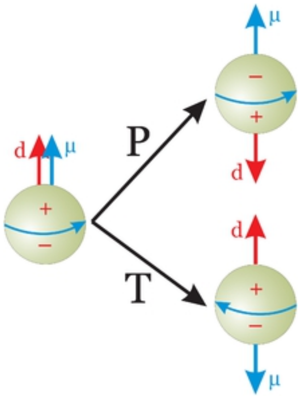


2 μm
for earth sized neutron



Why is it special?
Time reversal violation
 CP violation
(if CPT holds)



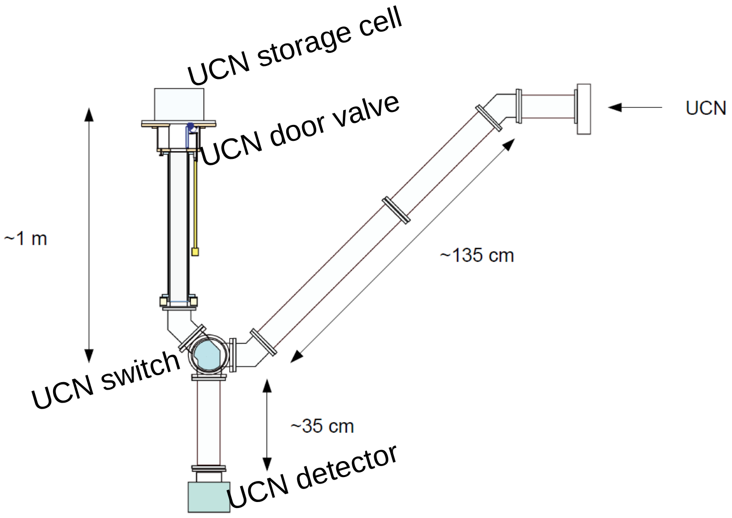


 need more CP violation to explain matter domination

Using the existing EDM apparatus from R

- No competitive EDM measurement possible mainly due to magnetic field limitations
- Good for neutron storage and handling development for next generation apparatus (Phase 2)
- Good training platform for students (and ourselves)

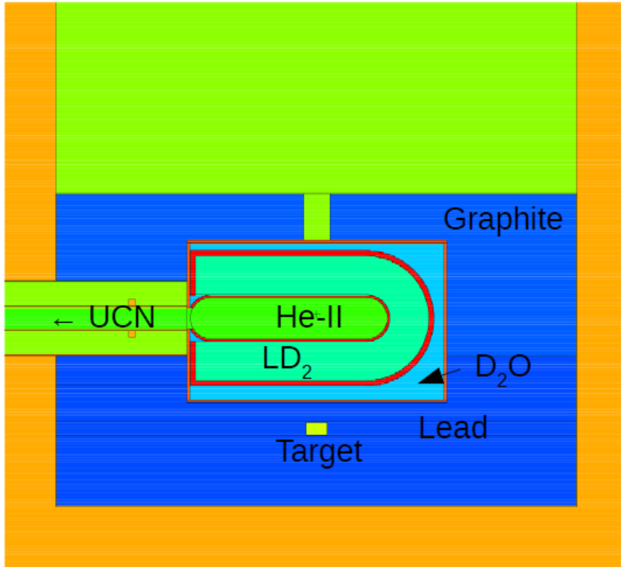
Will be exploited to benefit Phase 2



UCN source

- Superfluid helium source with liquid deuterium moderator
- Goal: world leading UCN density/flux
- Capable for 40 µA proton beam
- Two experimental ports

Shall be ready 2019

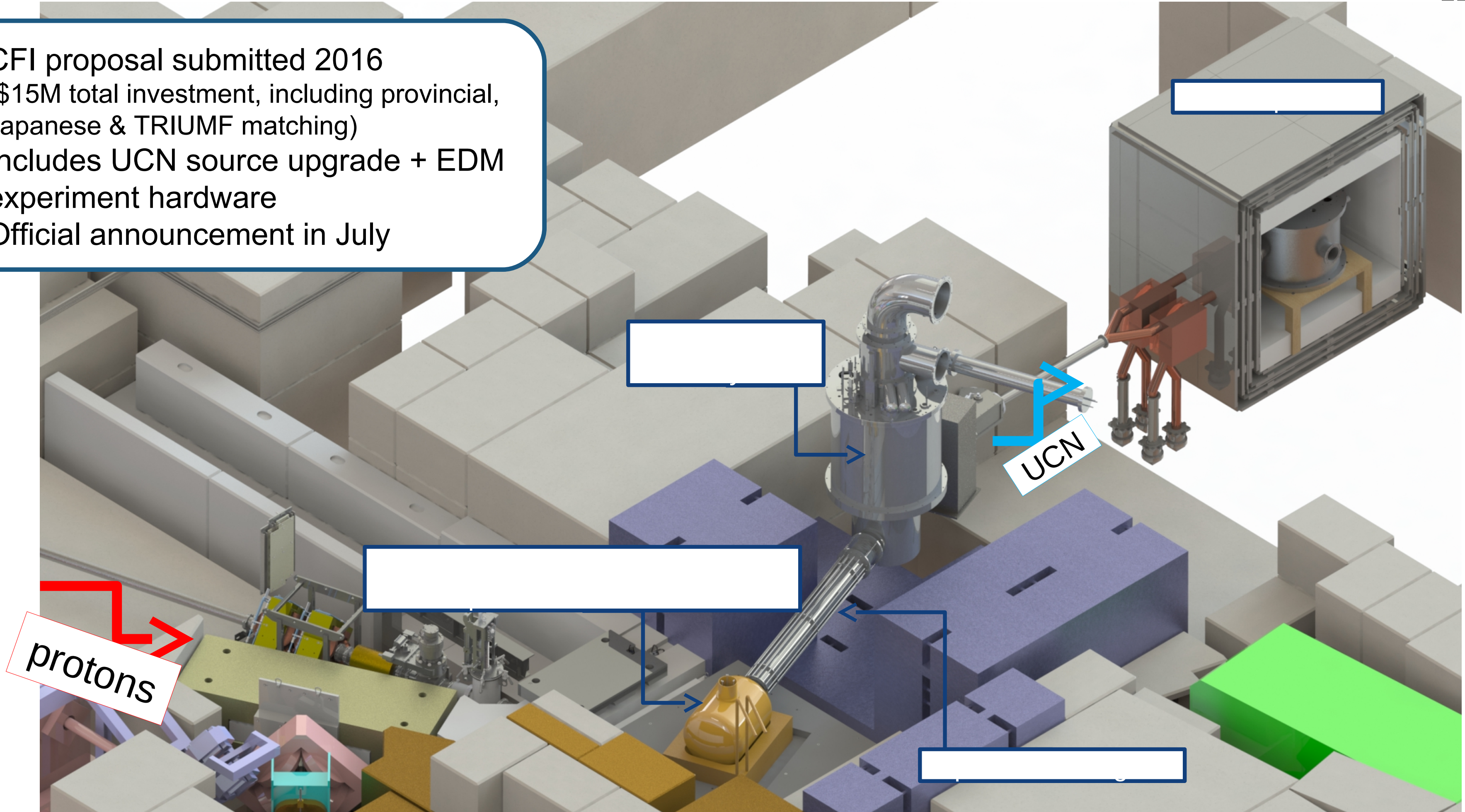


Neutron EDM experiment

- Ramsey technique at room temperature

Layout of Phase 2 UCN facili

- CFI proposal submitted 2016
  ($15M total investment, including provincial, Japanese & TRIUMF matching)
- Includes UCN source upgrade + EDM experiment hardware
- Official announcement in July

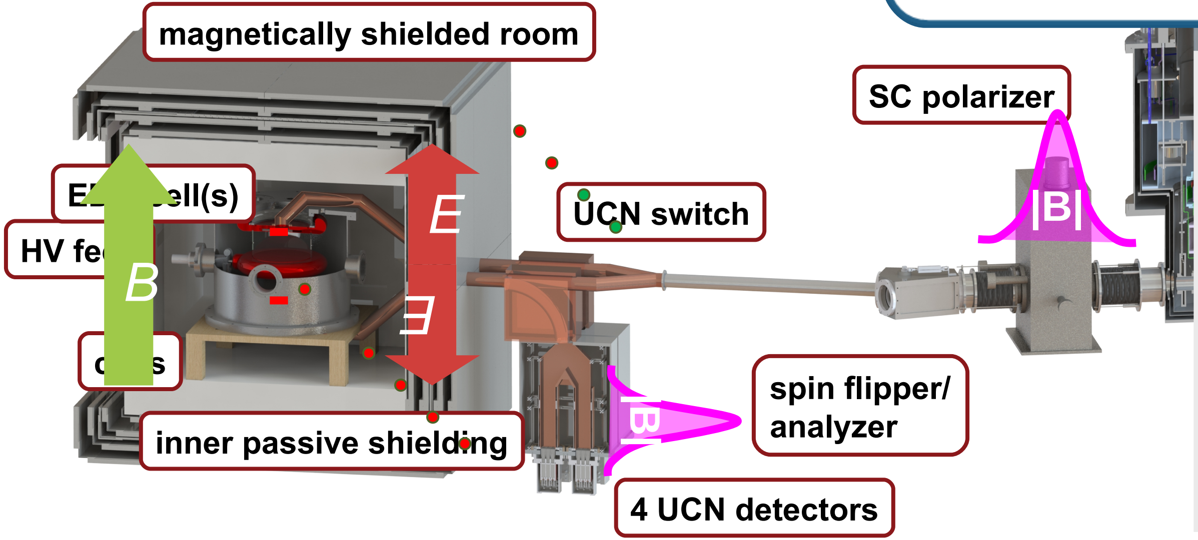


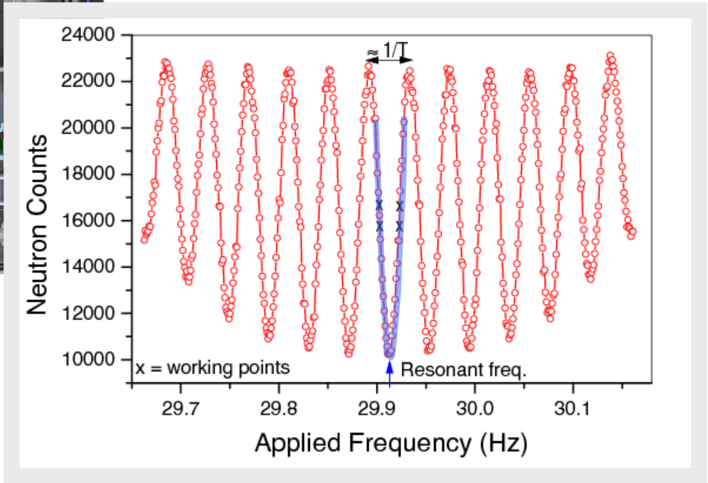
(1) Polarization:

- 4 T magnet creates 240 neV barrier for one spin species of UCN

(2) Ramsey cycle:

- two π/2 spin flips turn a larmor precession change into a polarization change
- $H_{\mathrm{int}} = -\mu_{\mathrm{n}} \cdot \vec{\sigma}\vec{H} \pm d_{\mathrm{n}} \cdot \vec{\sigma}\vec{E}$





(3) Analysis:

- spin sensitive neutron counting

⇒polarization measurement

- fit the Ramsay curve to determine larmor frequency
- change in frequency under field reversal?

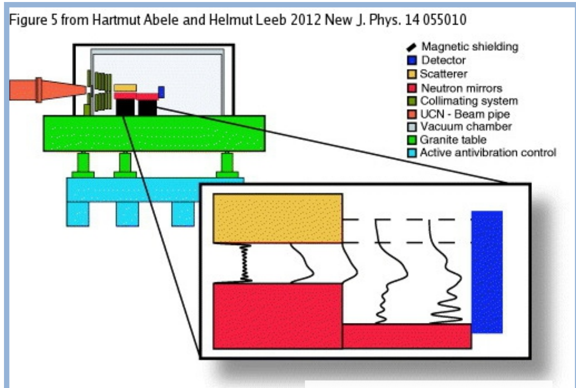
$$\Delta\epsilon = \hbar|\Delta\nu| = 4E\, d_{\mathrm{n}}$$

BINGO!

fit the Ramsay curve to determine larmor frequency

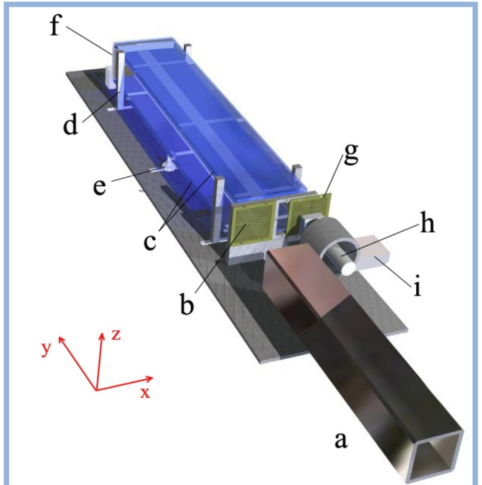
- EDM experiment will probably take 5 years+
- Second port shall be available for other experiments
  - Neutron decay
  - Gravity

- EDM experiment will probably take 5 years+
- Second port shall be available for other experiments
  - Neutron decay
  - Gravity
  - Charge
  - NN oscillations
  - …

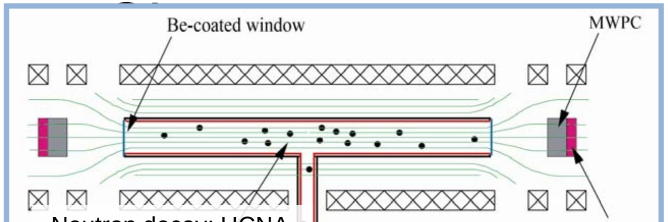


Gravity: Q-Bounce


Lifetime: PENeLOPE



Neutron charge



Neutron decay: UCNA

- CKM matrix

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

- neutron lifetime

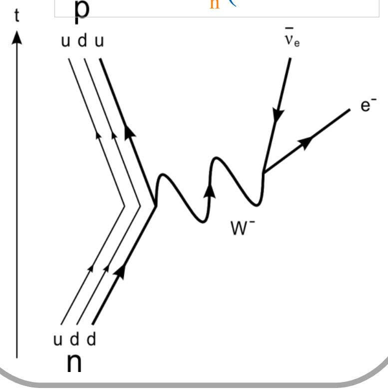
$$\tau_n \approx 880\, s$$

- ratio of coupling constants

$$\lambda = G_A / G_V = -1.2695(0.00\ldots)$$

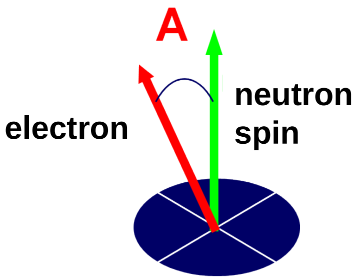
- neutron decay

$$|V_{ud}|^2 = \frac{4908.7(1.9)}{\tau_n(1+3\lambda^2)}$$



- neutron decay correlation A
- „beta-asymmetry“

$$A = -2\frac{|\lambda|^2 + \ldots}{1+3|\lambda|^2}$$



© Hartmut Abele

- PERKEO,UCNA,PERC

- Big storage volume to maximize time between wall interactions
- Surrounded by magnetic shield
- Surrounded by track detector, calorimeter, cosmic veto
- Current limit 8 x 107 s

- Sensitivity reach up to 109 s Fomin '17

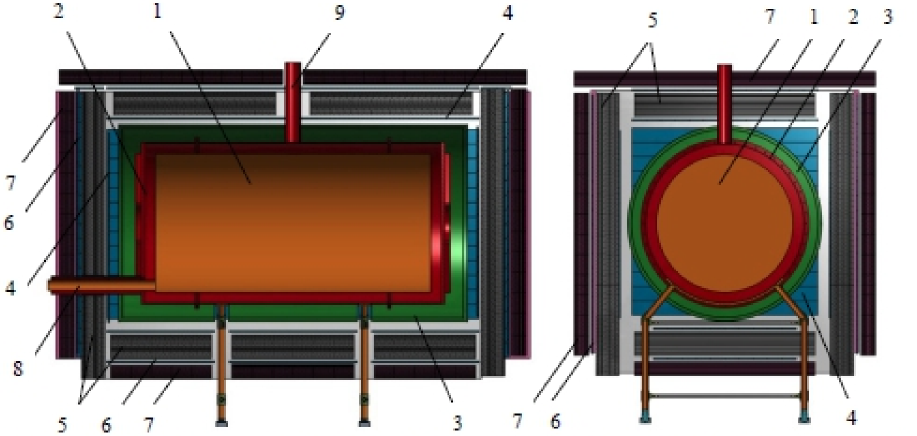


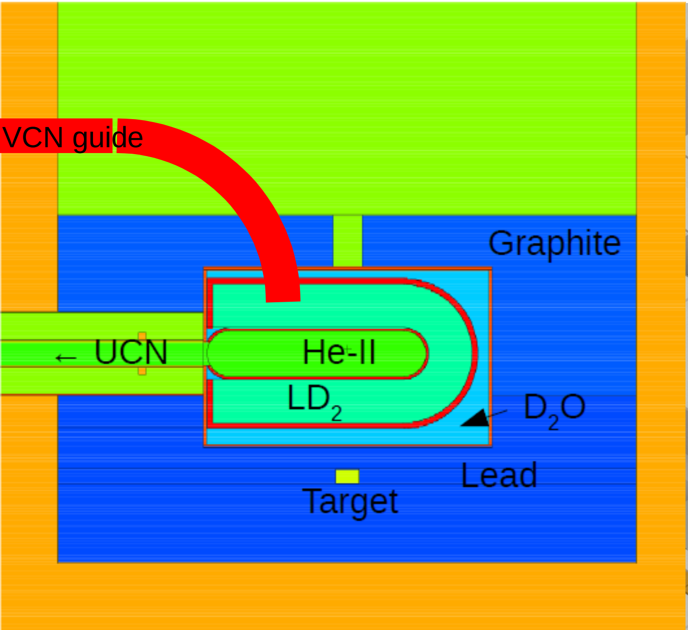
Figure 3. General scheme of experimental setup: 1 - UCN trap, 2 - vacuum chamber, 3 - magnetic shield, 4 - hodoscope (internal part), 5 - trek detector, 6 - hodoscope (external part), 7 - calorimeter, 8 – neutron guide, 9 - pumping outlet.

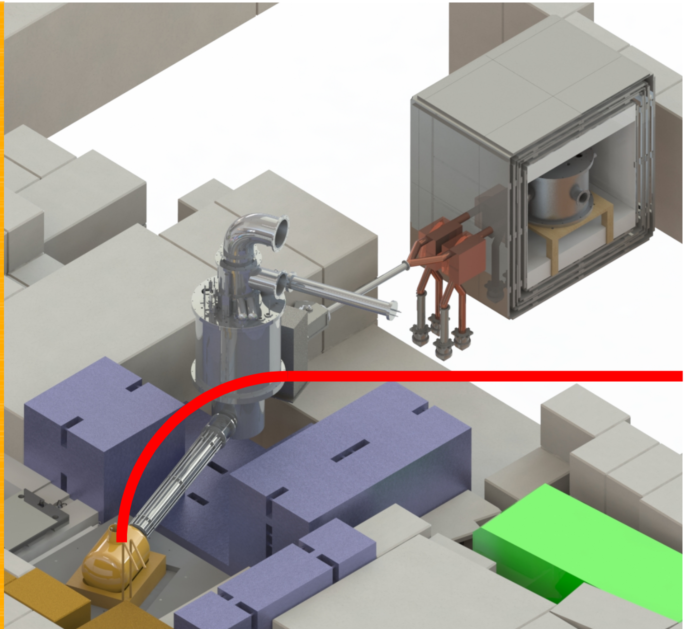
Very cold neutrons (VCN)

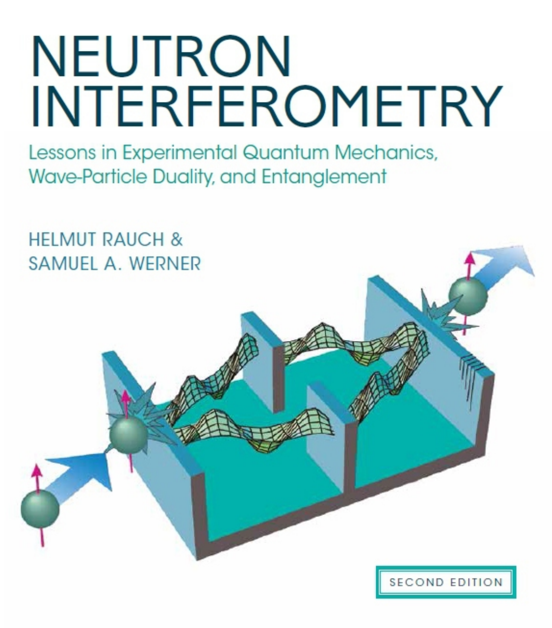
- 15 m/s, 1 ueV
- VCN guide points to cold source
- Vertical extraction ideal
- Interest in Japan

- 15 m/s, 1 ueV
- VCN guide points to cold source
- Vertical extraction ideal

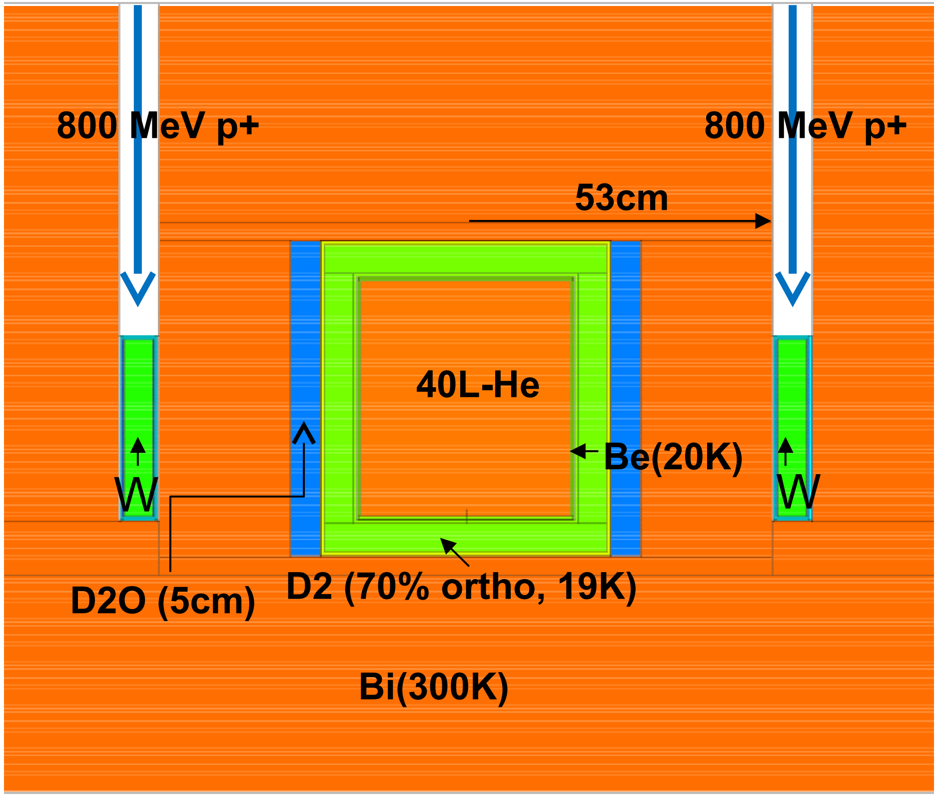
- Experiments:
  - Neutron radiography (imaging) — Bates '74, Kawabata '04
  - Neutron interferometry (quantum effects, gravity) — Klepp '14, Rauch '15
  - VCN-SANS (soft matter experiments)
  - $N\bar{N}$ oscillations — Shimizu '09, Yamada '16







Interesting geometries for higher UCN de



Surround source by target:

1.0*108 UCN/s/100I A (compare to 1.0*107 UCN/s/40I A for our source)

Heat load @ 100I A ≡ 80KW

Total heat: 13.9 W

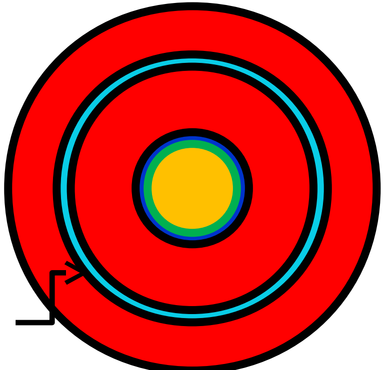
Neutron heat: 10.8 W

Photon heat: 2.4 W

Proton heat: 0.7 W

7.14*108 UCN/s/100W (heat in the He)

Track detector, calc



Young,

Cylindrical proton target (beam rastered around circumference)

Conclusion

- Phase 1 of the UCN facility is ready for operation

  First UCN this summer!

- Phase 2 planning is in its hot phase
- nEDM will be the first experiment
- Second port shall come online during the next 5YP
- Additional possibilities exist (CN, VCN…)

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Thank you!

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EDM development groups

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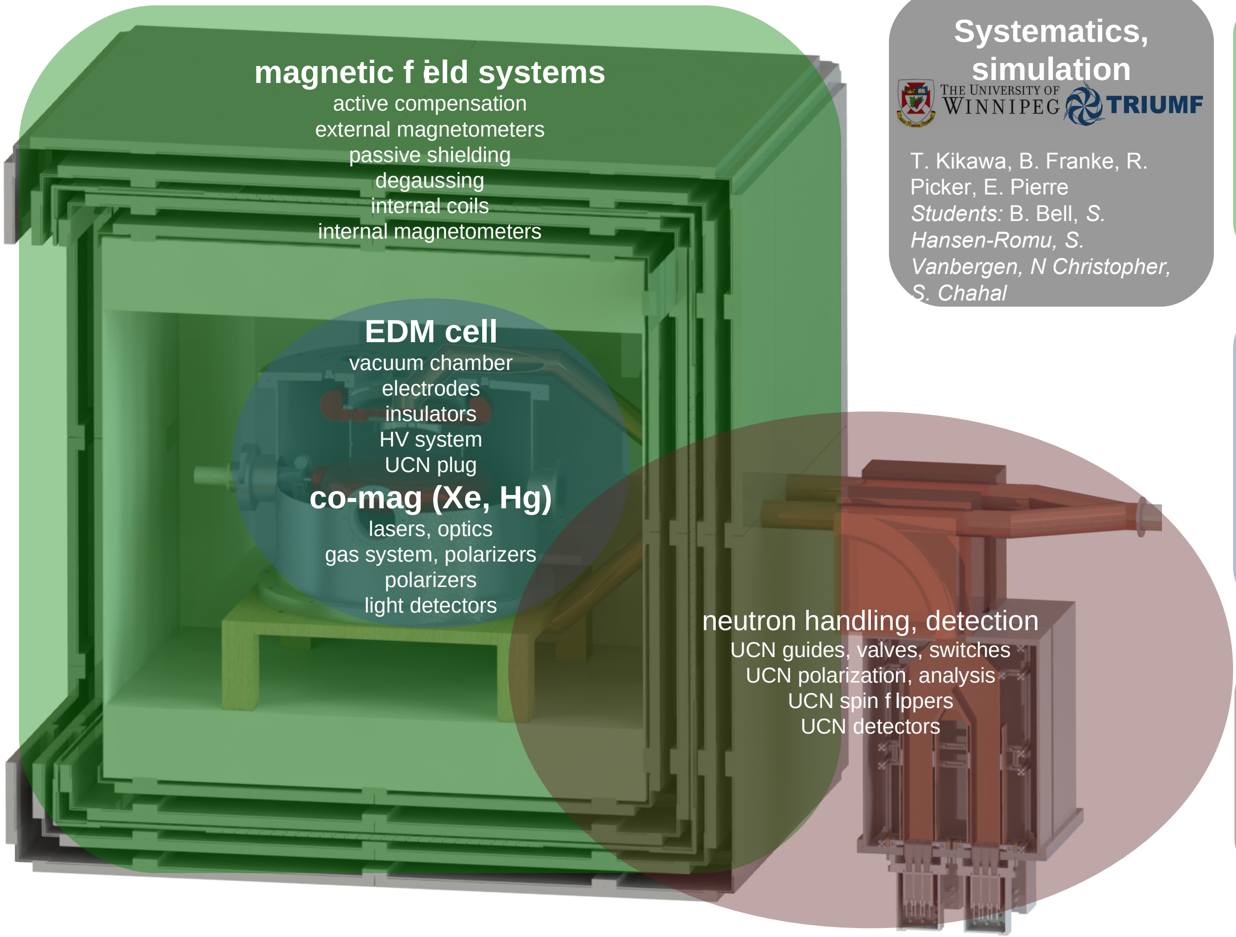


Systematics, simulation

T. Kikawa, B. Franke, R. Picker, E. Pierre
Students: B. Bell, *S. Hansen-Romu, S. Vanbergen, N Christopher, S. Chahal*

magnetic field systems

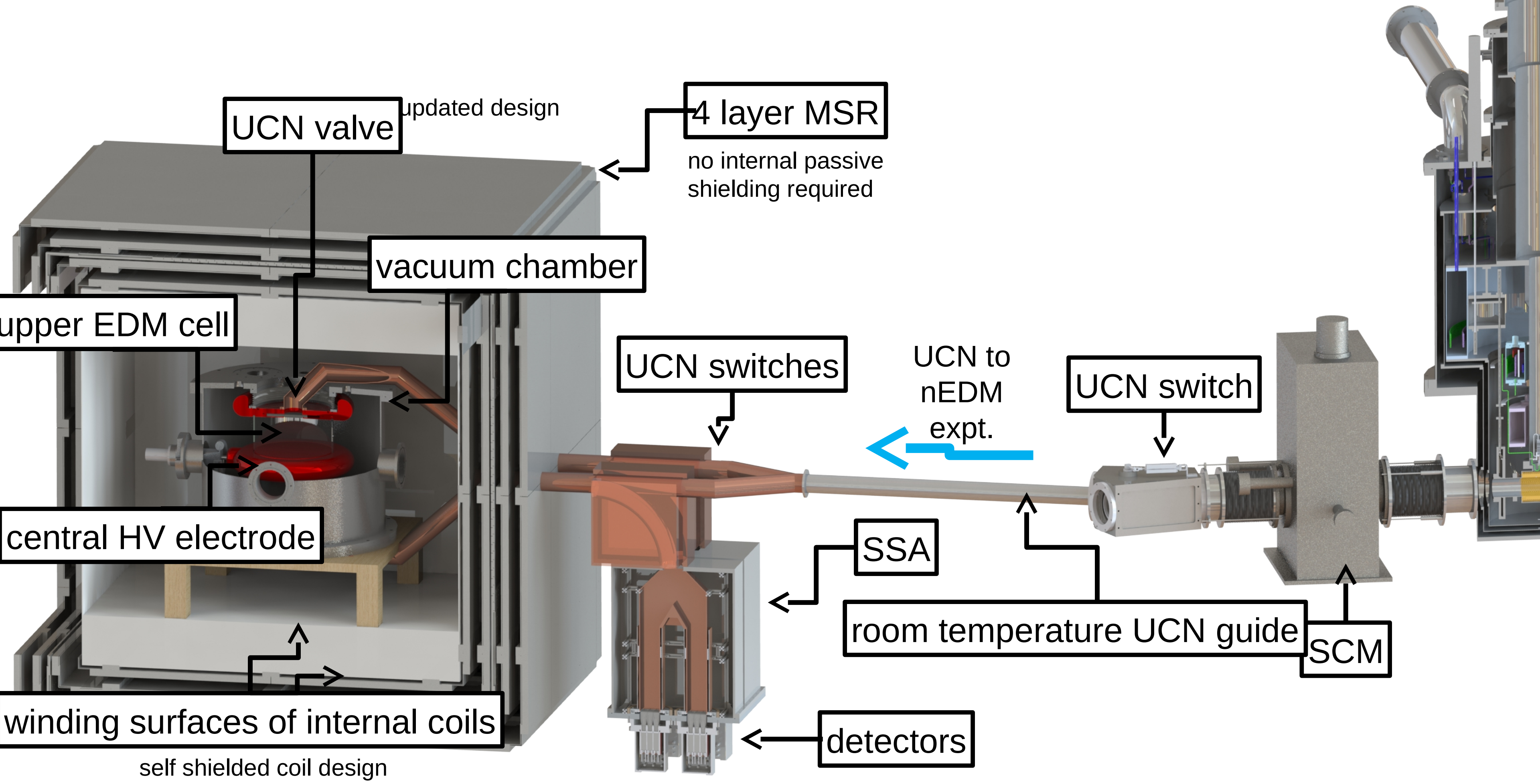
C. Bidinosti, B. Franke, S. Kawasaki, R. Mammei, J. Martin, E. Pierre
Students: S. Ahmed, T. Andalib, M. Das, S. Hansen-Romu, W. Klassen, M. Lang, B. Bell, Junyao Pu, Rosie Burrough
Theses: T. Andalib (B.Sc.), M. Lang (M.Sc.), C. Cerasani (B.Sc.), C. Loftson (B.Sc.)

EDM cell, co-magnetometer

C. Bidinosti, D. Jones, K. Katsika, S. Kawasaki, F. Kuchler, K. Madison, J. Martin, R. Matsumiya, T. Momose, D. Ostapchuk, R. Picker, W. Schreyer, J. Sonier
Students: E. Altiere, M. Lang, E. Miller, J. Weinands, S. Sidhu
Theses: T. Dawson (M.Sc.), M. Losekamm (B.Sc.), J. Wiebe (B.Sc.)

UCN handling, detection

M. Gericke, B. Jamieson, S. Kawasaki, C. Marshall, E. Pierre, R. Mammei, R. Matsumiya, S. Page, R. Picker, W. Schreyer
Students: F. Doresty, L. Rebenitsch


UCN valve
updated design
4 layer MSR
no internal passive
shielding required
vacuum chamber
upper EDM cell
UCN switches
UCN to
nEDM
expt.
UCN switch
central HV electrode
SSA
room temperature UCN guide
SCM
winding surfaces of internal coils
self shielded coil design
detectors

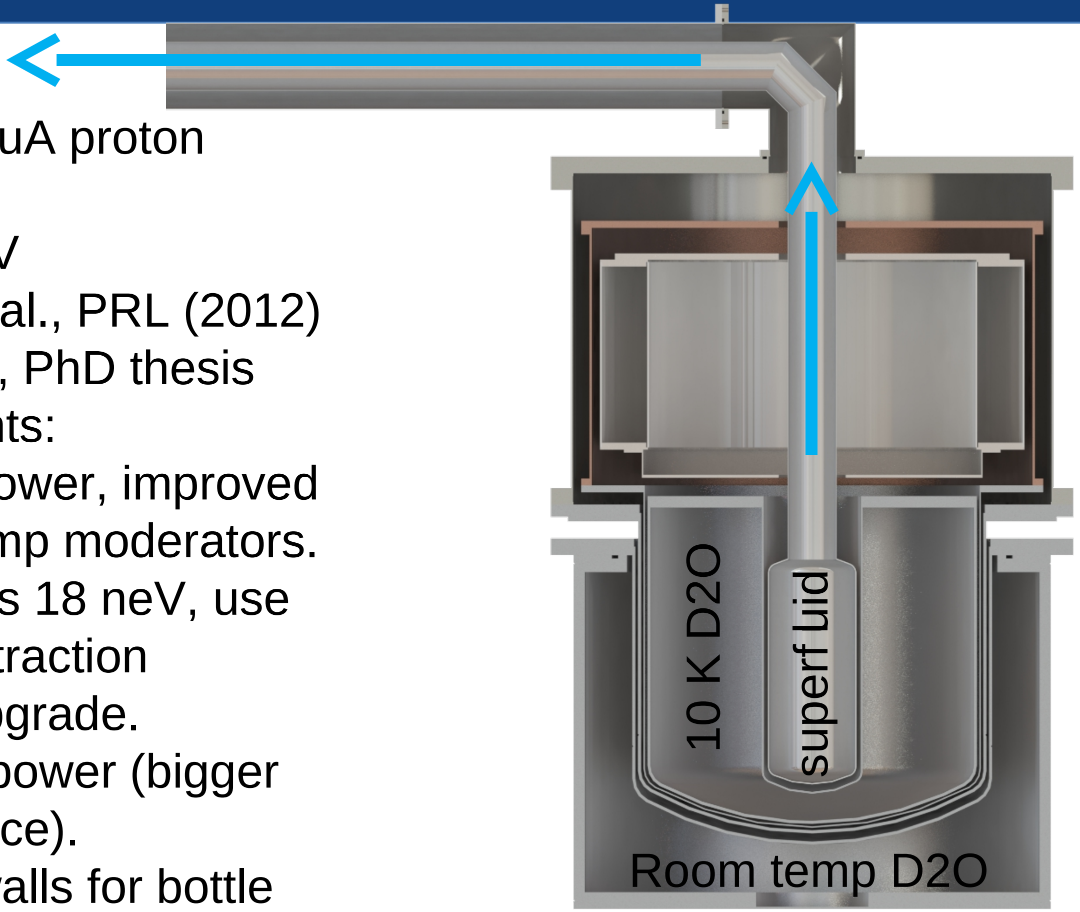
Vertical superfluid He cryos

Key results:

- 26 UCN/cm3 @ 1 uA proton current
- Spectrum < 90 neV
  - Y. Masuda et al., PRL (2012)
  - R. Matsumiya, PhD thesis

Possible improvements:

- Increased beam power, improved targeting, room temp moderators.
- Material potential is 18 neV, use near-horizontal extraction
- Cold moderator upgrade.
- Improved cooling power (bigger pumps, conductance).
- Thinner Al or Be walls for bottle (beta and gamma heating)



Surrounding graphite, steel not shown

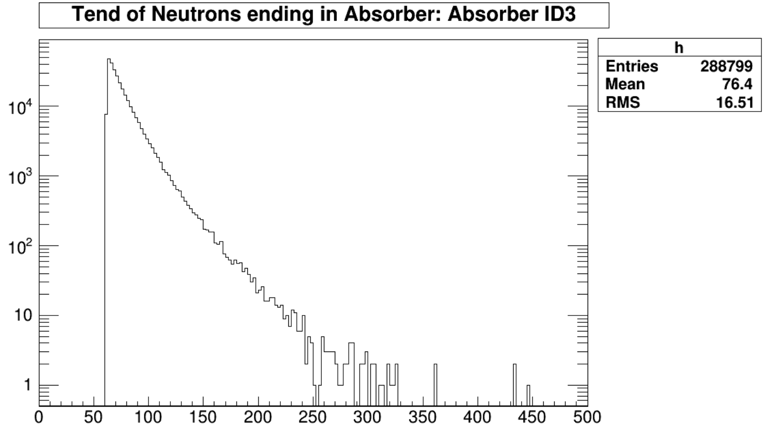
Spallation target

MCNP parameters

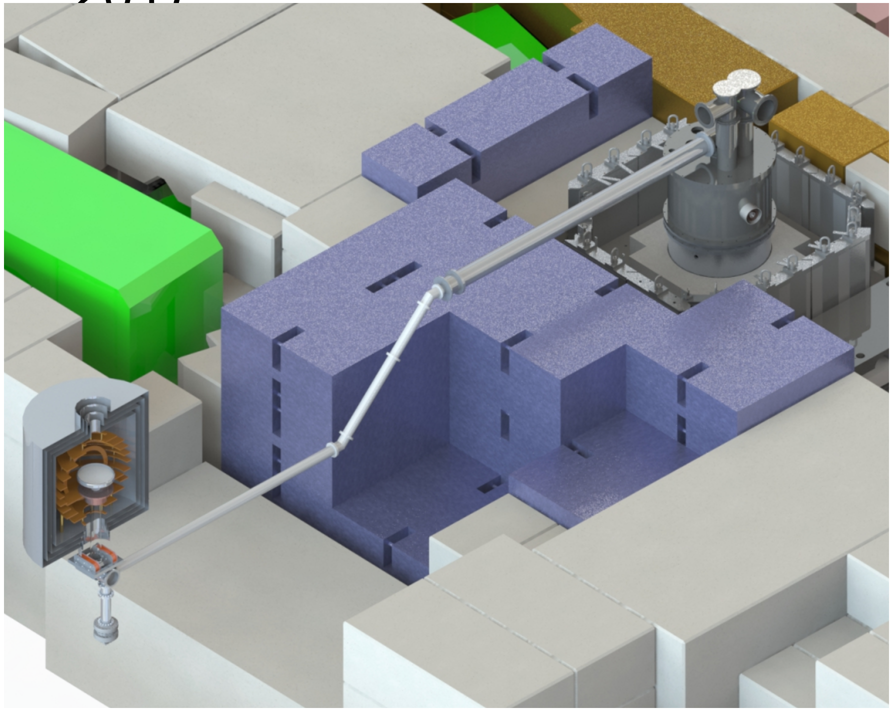
- 1 μA proton beam on realistic target geometry
- 80 K free gas model for 20 K D2O

PENTrack parameters

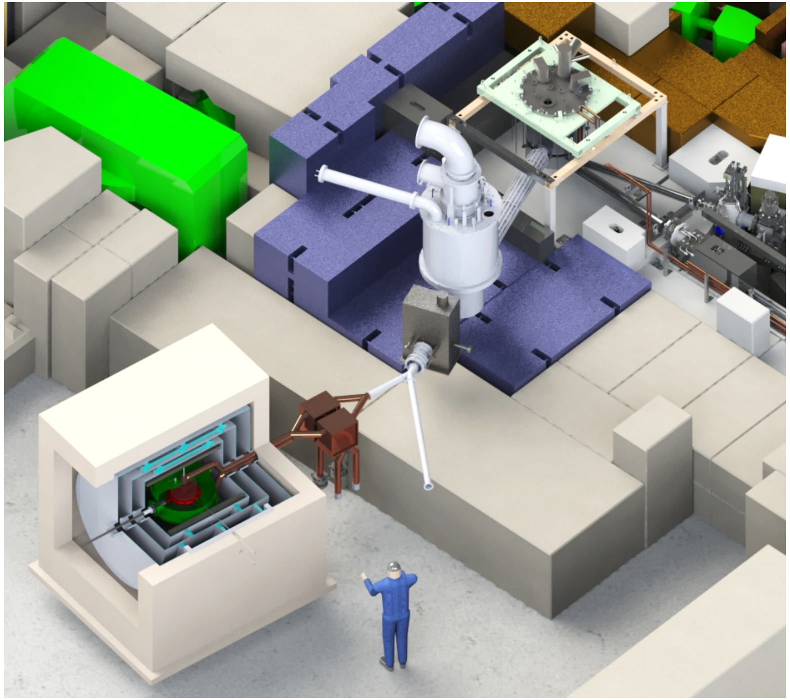
- 60 s proton irradiation
- 60 s ?? storage lifetime in the source
- Realistic geometry
- Li detector



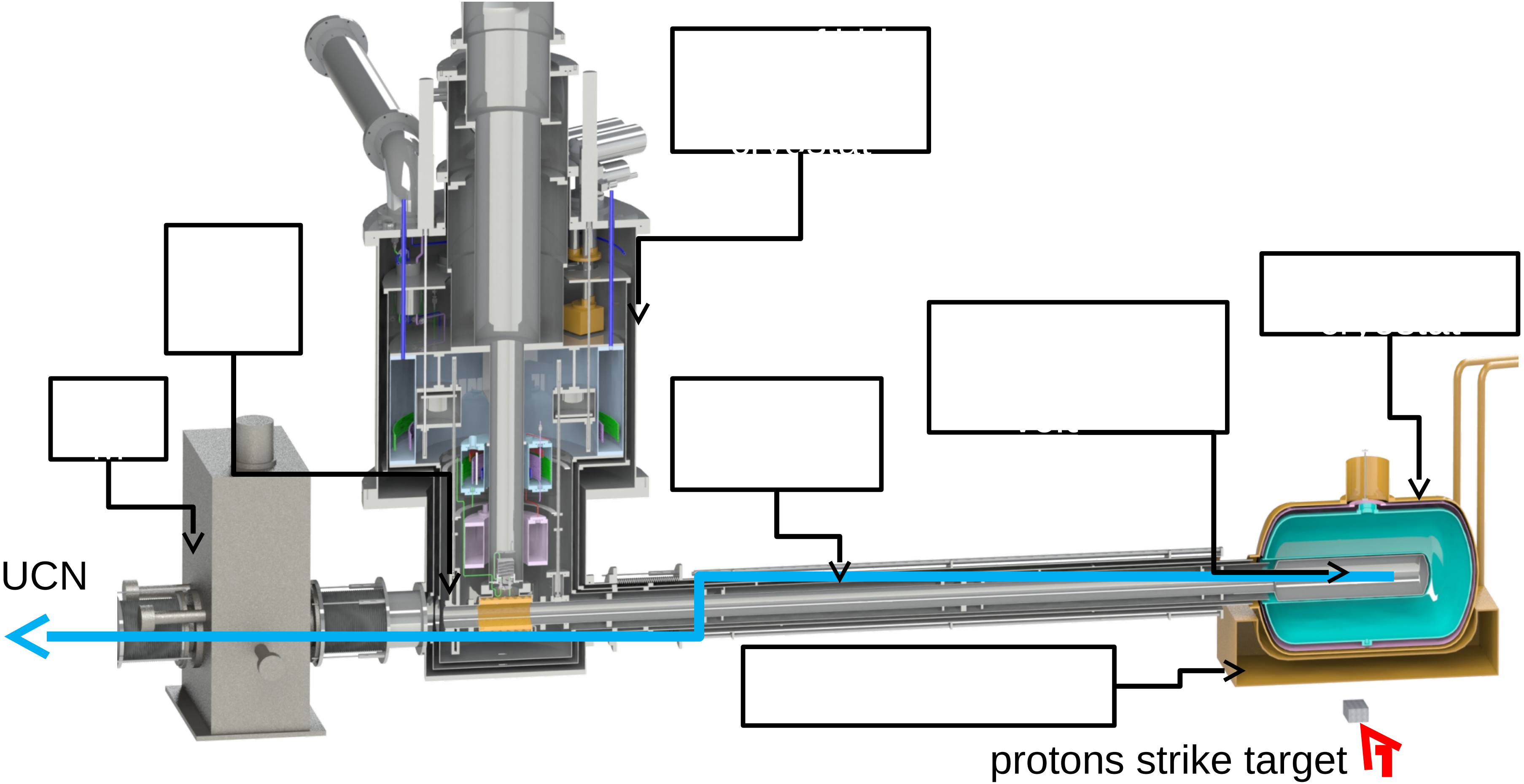
- Helium cryostat will be installed and UCN production to start in 2017



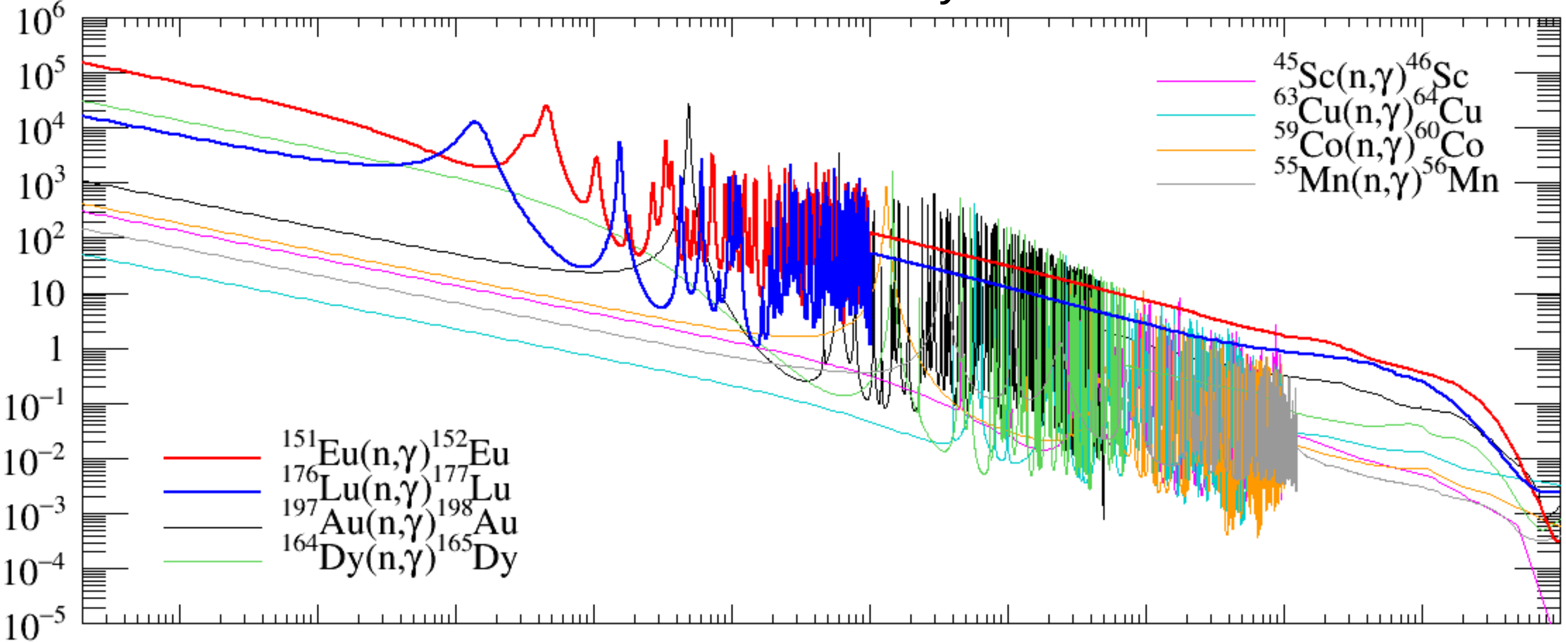
RCNP Vertical cryostat for phase 1



Horizontal cryostat for phase 2


UCN
protons strike target

Activation cross section by neutron



- **Neutron cross section below 1eV is generally** 1/v.
- $^{151}Eu(n,\gamma)^{152}Eu$ and $^{176}Lu(n,\gamma)^{177}Lu$ cross sections deviate from 1/v even below 1eV.
- If they are used as sample, cold/thermal neutron spectrum will be able to be measured. First attempt ever.

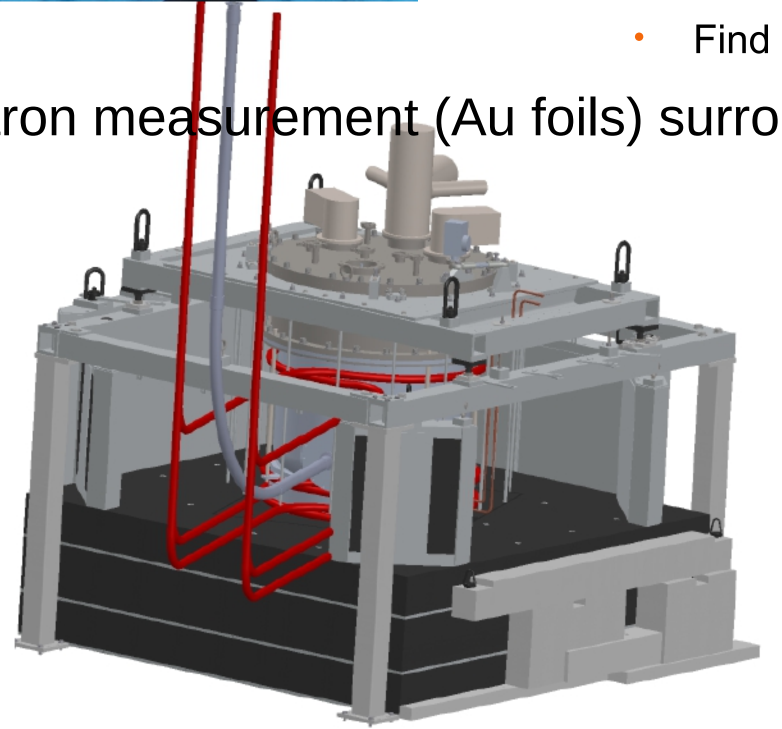
Thermal measuremen

- Measure thermal and colder neutron flux outside cryostat
- Calculate total neutron flux for bare and Cd-covered 197Au

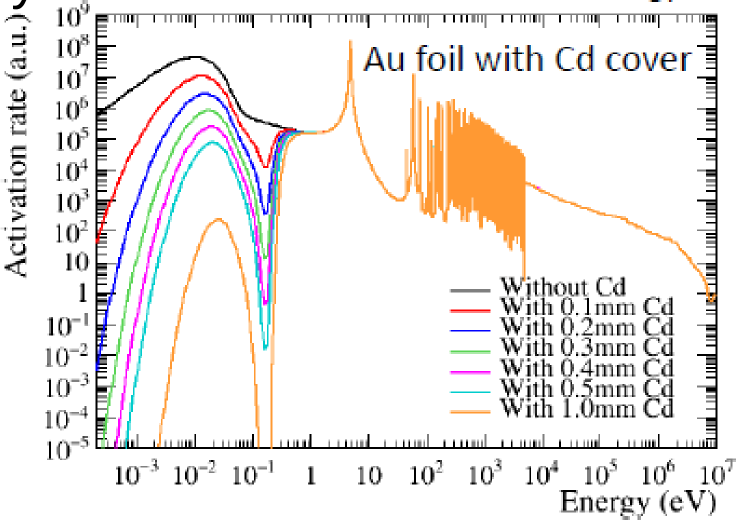
$$\phi_{th} = \phi_b - \phi_c$$

- Find thermalizing effect of graphite reflectors

neutron measurement (Au foils) surrounding cryostat



Activation rate as a function of energy



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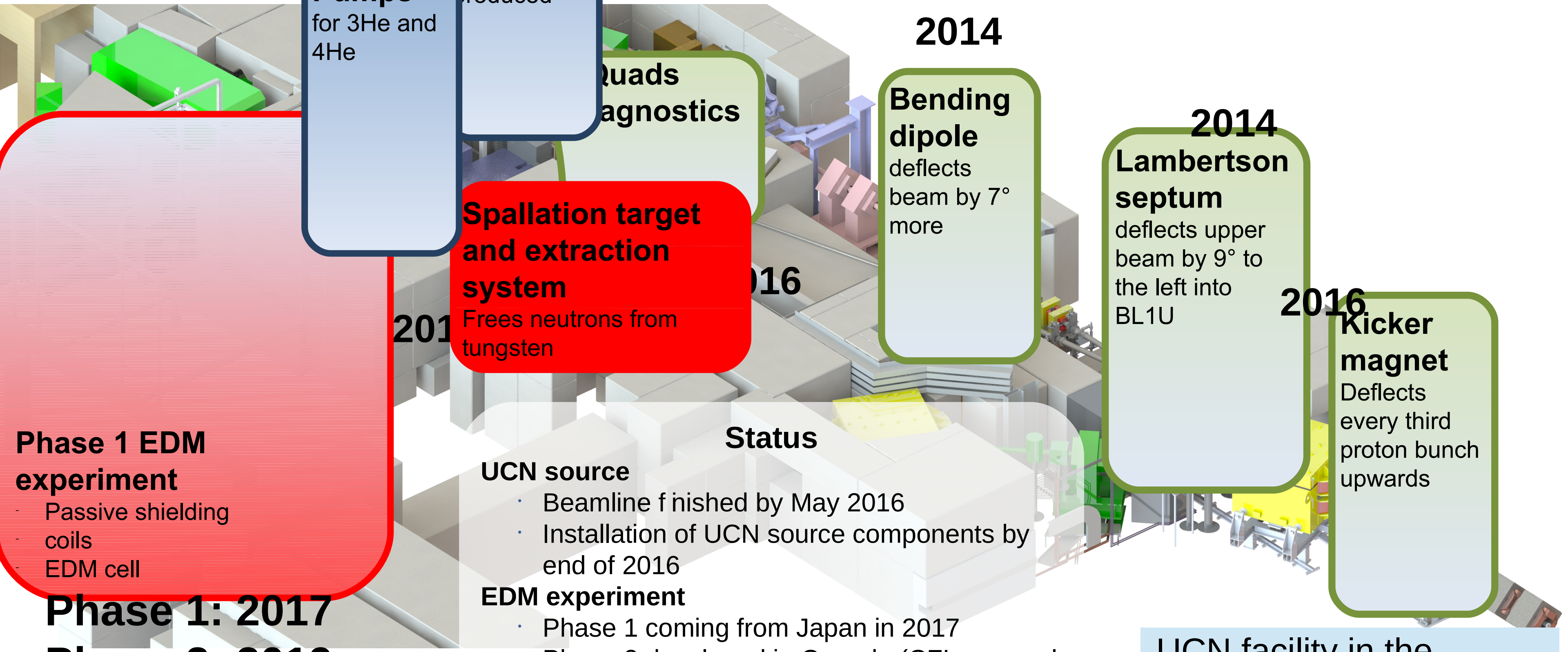
UltraCold N… Electric Dipole Moment



Phase 1: 2017
Phase 2: 2019

Status

UCN source

- Beamline finished by May 2016
- Installation of UCN source components by end of 2016

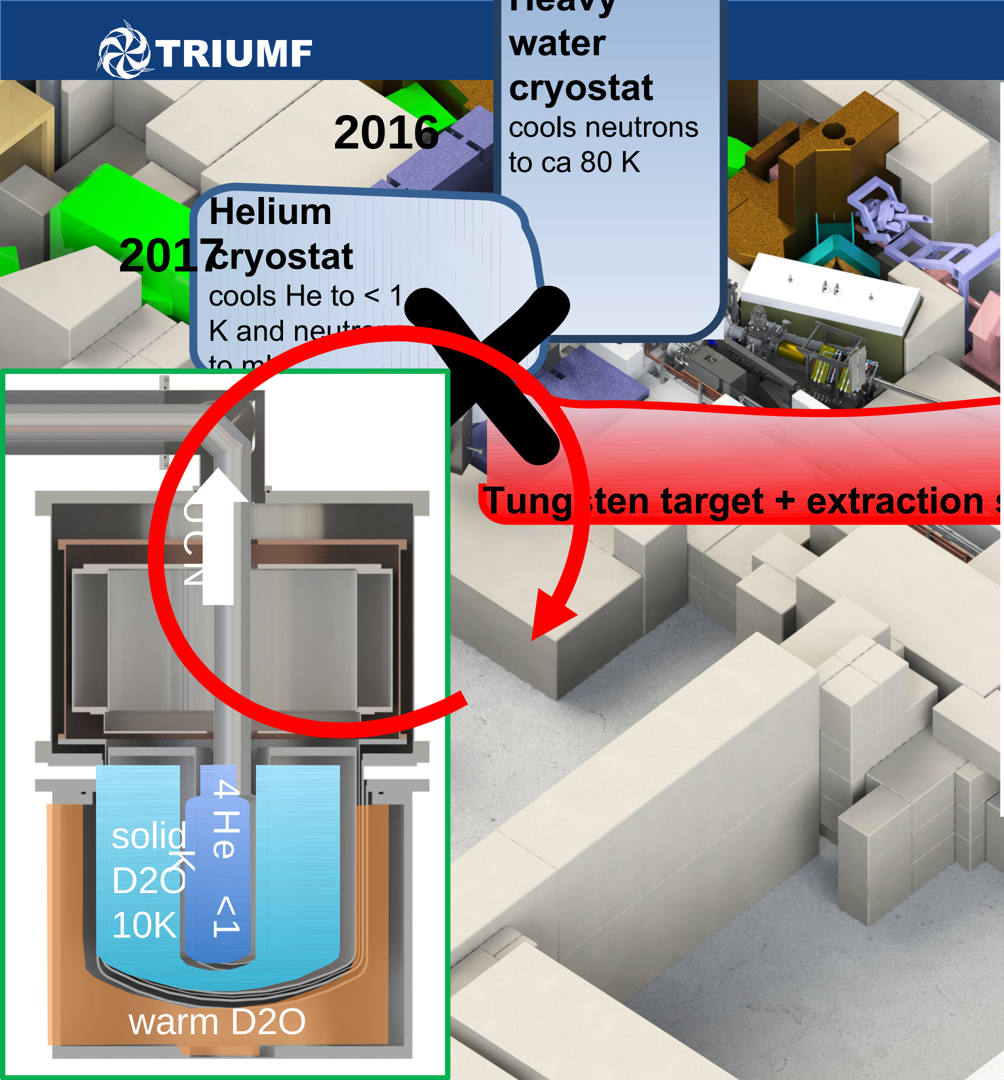
EDM experiment

- Phase 1 coming from Japan in 2017
- Phase 2 developed in Canada (CFI proposal this year) for 2019

UCN facility in the Meson hall at TRIUMF

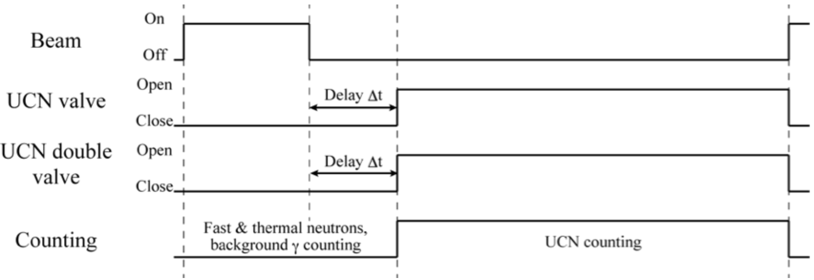
Change of plans 201

- Mid 2016: horizontal source (HS) cryostat became unavailable
- Vertical source (VS) from RCNP tested and available *PRL 108, 134801 (2012)*
- Similar techniques to horizontal source (warm D2O and D2O ice cryostat surrounding superfluid 4He UCN converter)
- Main difference: gravitational extraction vs 3 foils for horizontal source (limiting UCN phase space)
- Maximum current: a few µA (compared to 40 µA)
- Collaboration decision to install it during shutdown 2017

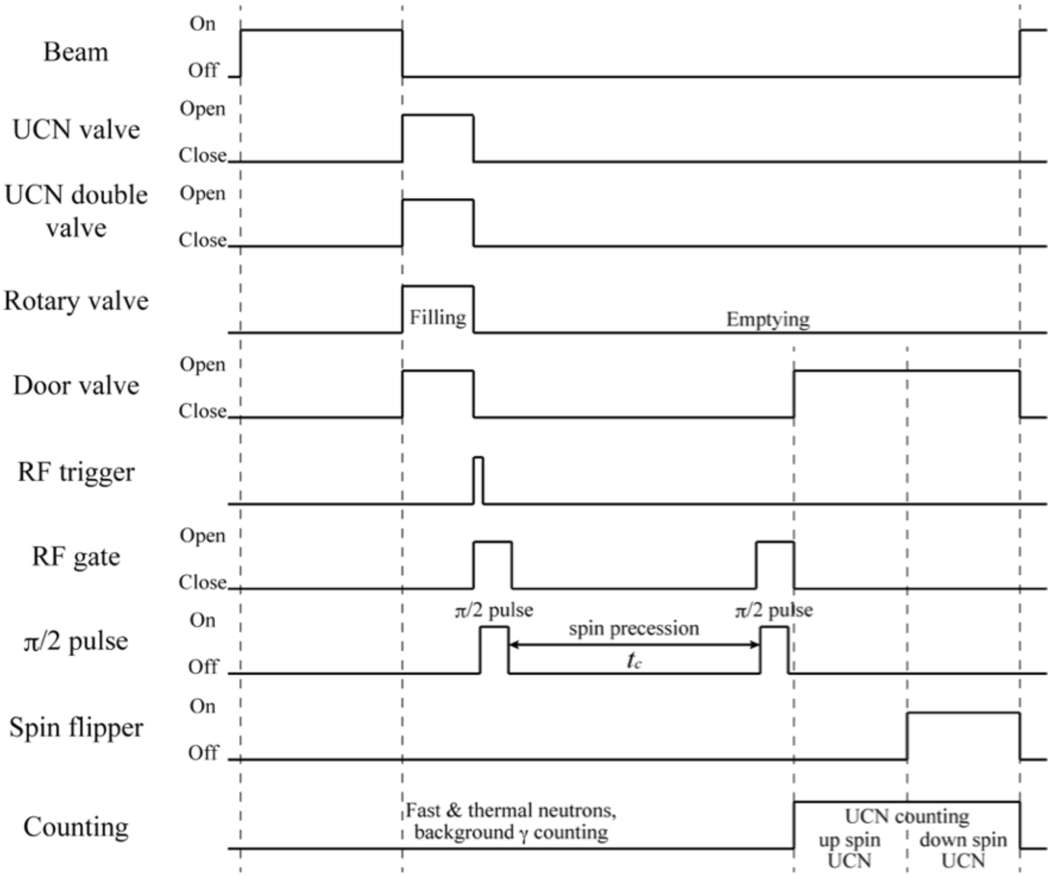


UCN facility in the Meson hall at TRIUMF

Sequence for UCN experimen



Simple counting or storage lifetime measurement



Ramsey cycle

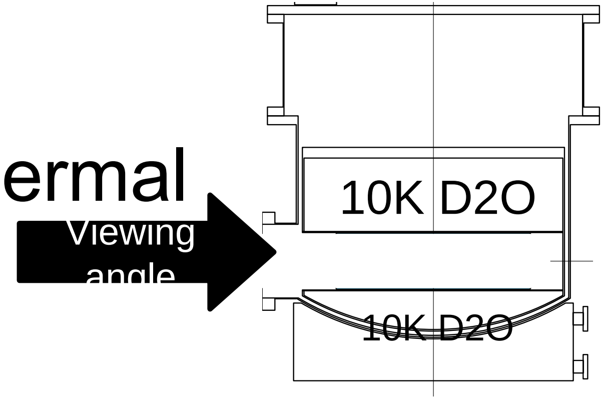
Possible flexible realisati

Name	Duration [s]	Beam request [out]	Beam on [in]	UCN source valve open [out]	UCN detection on [out]	Rotary Valve position 1 [out]	TTL 1 [out]	TTL 2 [out]
Beam on	60	X	X	0	0			
Delay	0, 5, 10, 20, 30, 50, 80, 120, 170	0	0	0	X			
Detection		0	0	X	X			
Waiting	as long as there is no beam	X	0	X	X			

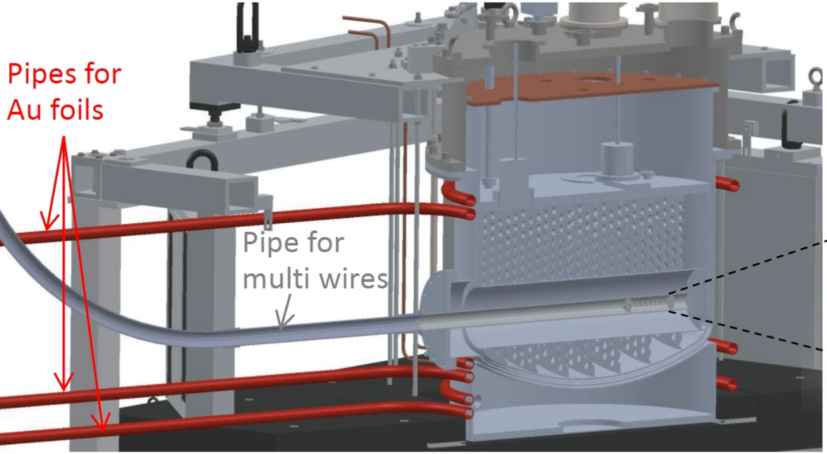
Don't know whether this is possible. Might have to have to submit beam request to Cyc ops and follow it

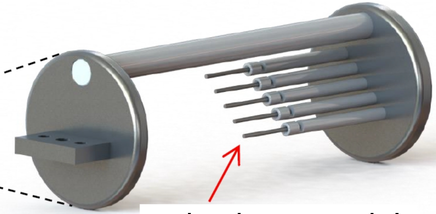
First neutron measuremen

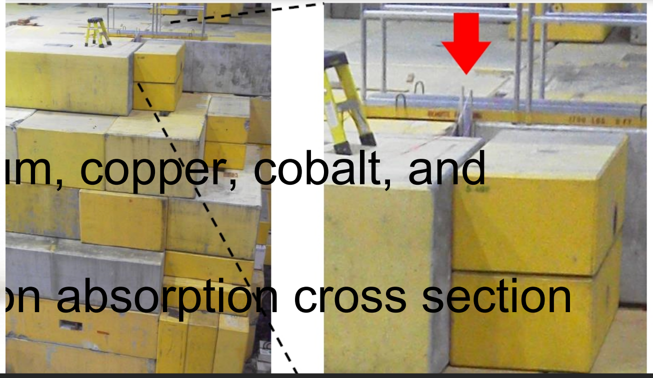
- Want to benchmark cold/thermal neutron production with simulations (FLUKA, MCNP)
- Hard to measure cold neutron spectrum using TOF measurement in our geometry
- Gold foil activation widely used for thermal neutrons
- Want to extend this to cold neutrons



- **thermal neutrons (proven technique, e.g. used at PSI UCN source):**
  - place **Au foils**, some covered with **neutron absorber Cd**, at strategic positions around our thermal moderators
  - measure **gamma rays**oming from nuclei that have absorbed a neutron (Ge detector)
  - subtracting both yields **thermal flux**







um, copper, cobalt, and

on absorption cross section

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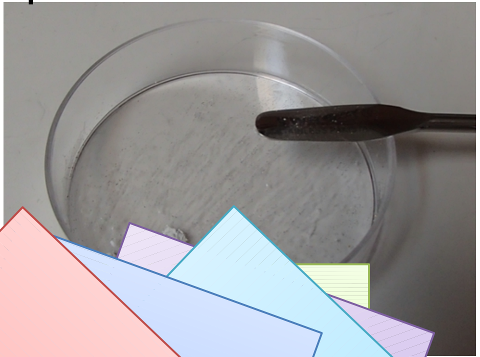
Cold neutron activation measuren

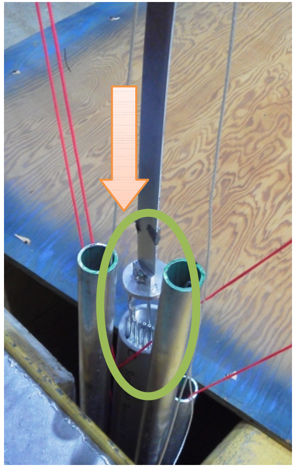
- Each material is sensitive to different energy of neutron.
- Install sample with five materials to D2O cryostat.
- Measure activity with Ge detector after beam.

Mix powder of five materials

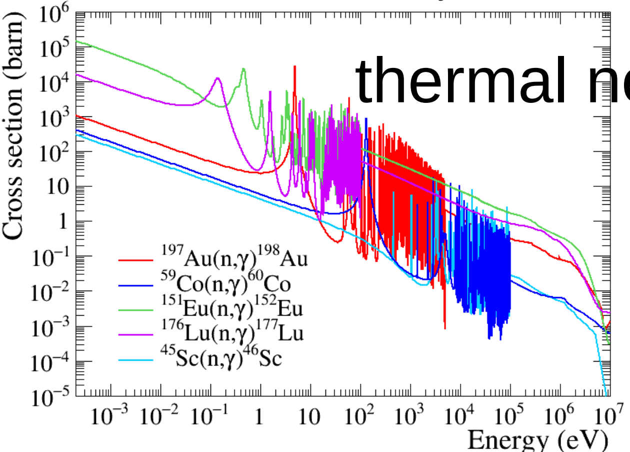


Fill in Al cell

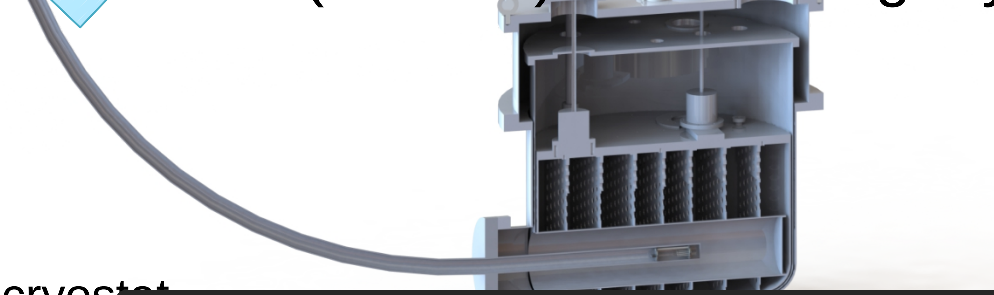
Installation



Activation cross section by neutron



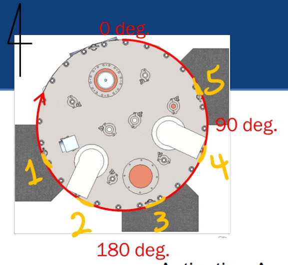
thermal neutron measurement (Au foils) surrounding cry



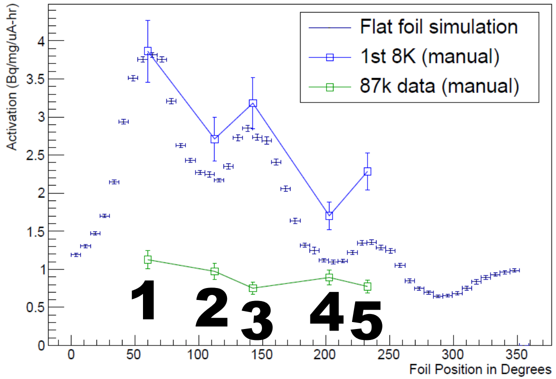
D2O cryostat

Blair Jamieson, Tatsuya Kikawa, Edgard Pierre, Lori

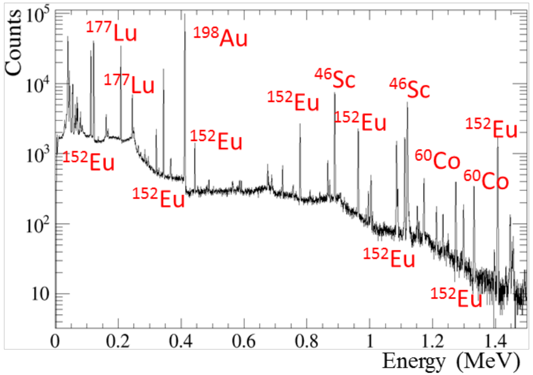
- We took 10 data points at different temperatures and saw **plenty of (cold) neutrons**
- Large **data-MC difference in 46Sc (n cross section measure**

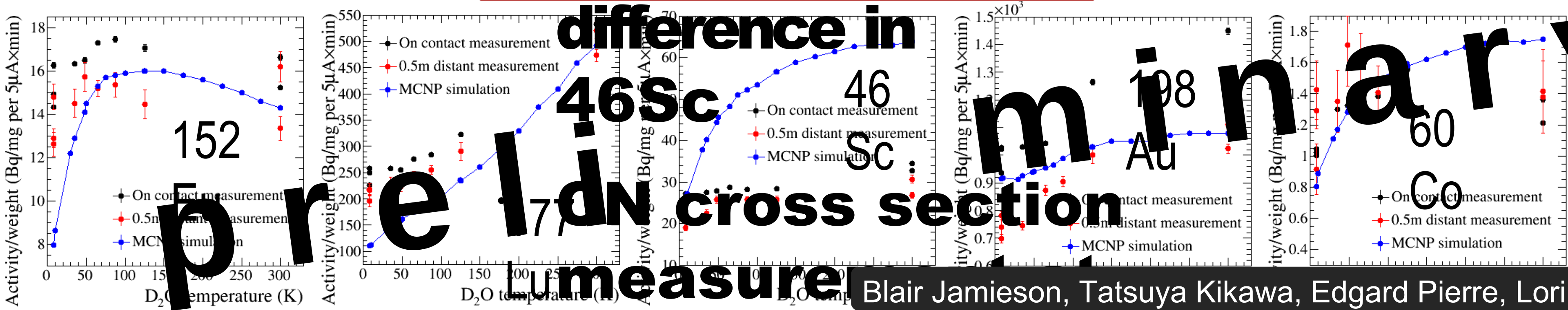


Activation According to Position



γ-ray spectrum measured by Ge detector





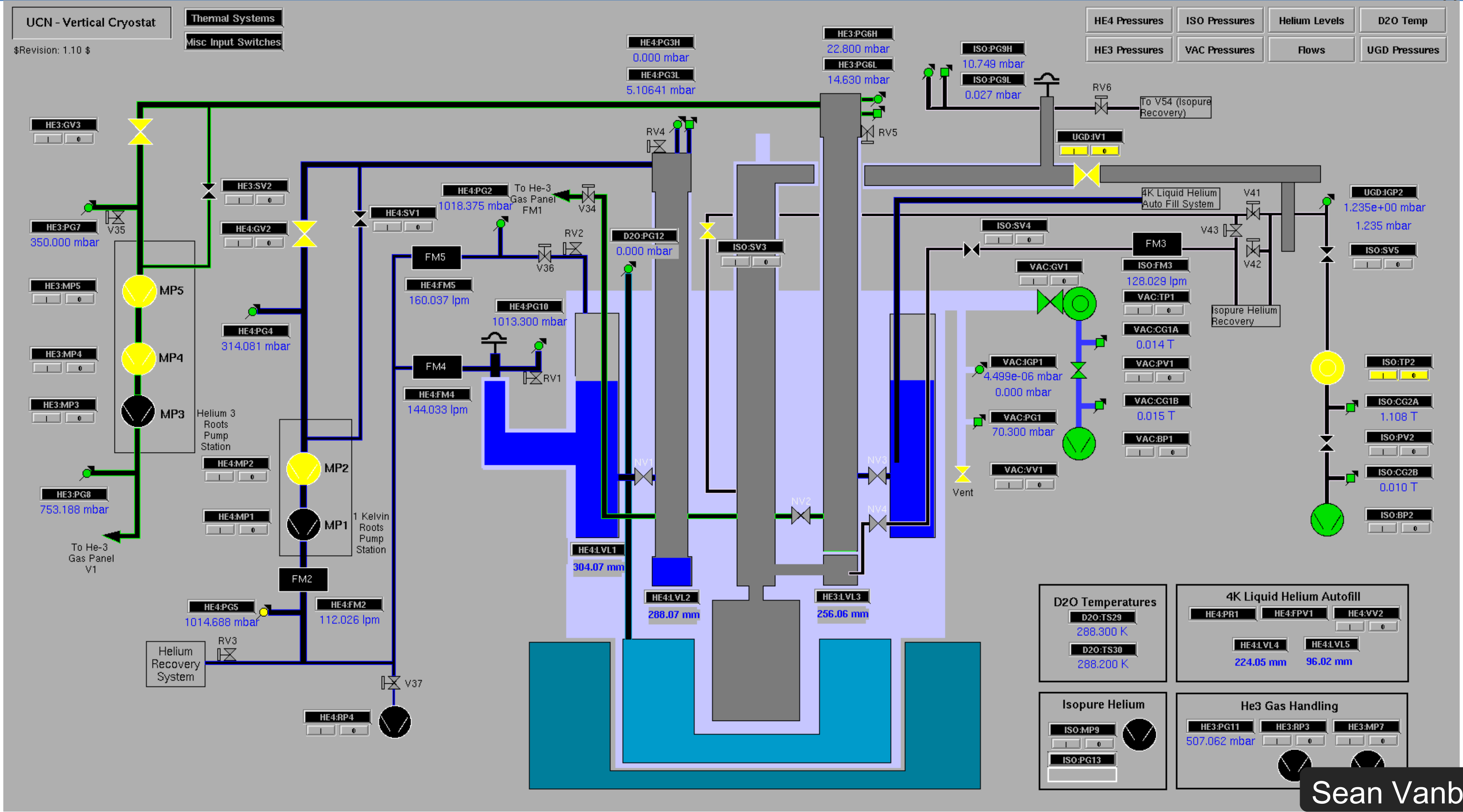
Beamline to do list

- Commission TNIM non-intercepting current monitor (monitors our 1 μA operating licence when kicking)
- Commission kicker
- Read out BPM beam position monitors
- Read out TPM target protect monitor

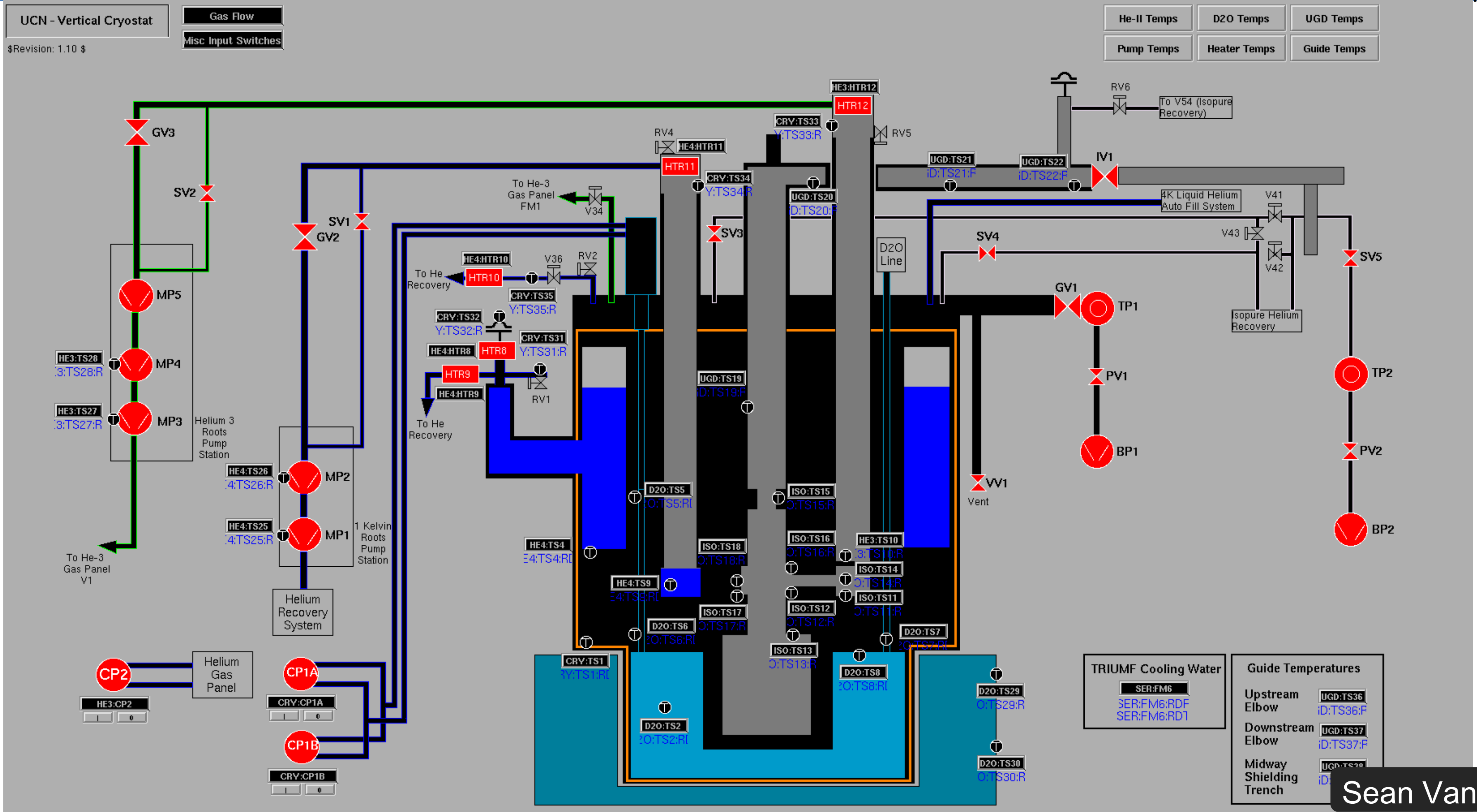
Thomas Lindner's presentation!

- Hand over beamline to accelerator division and

EPICS pressure screen



EPICS thermal screen

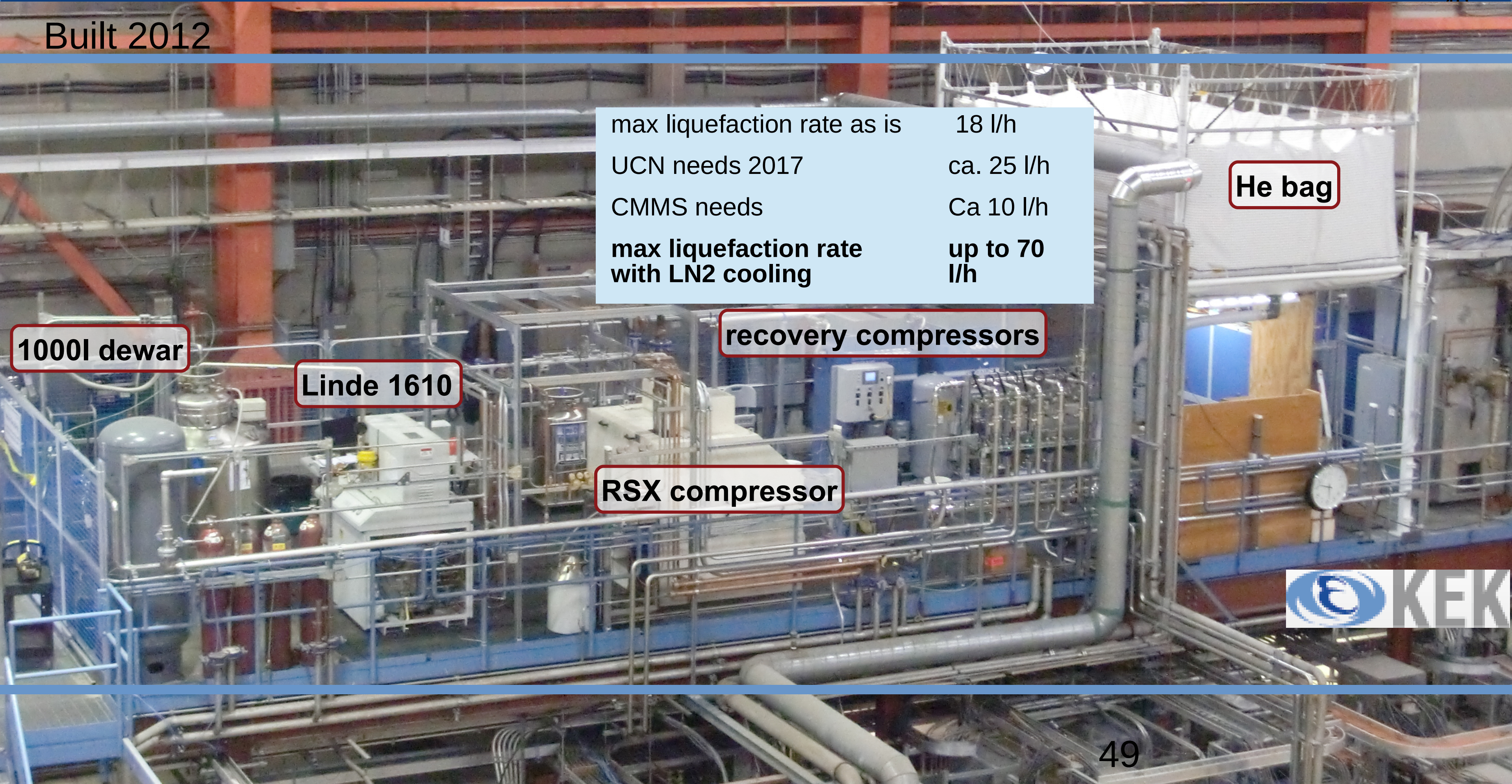


Sean Vanberg

Meson hall He liquefie

Built 2012

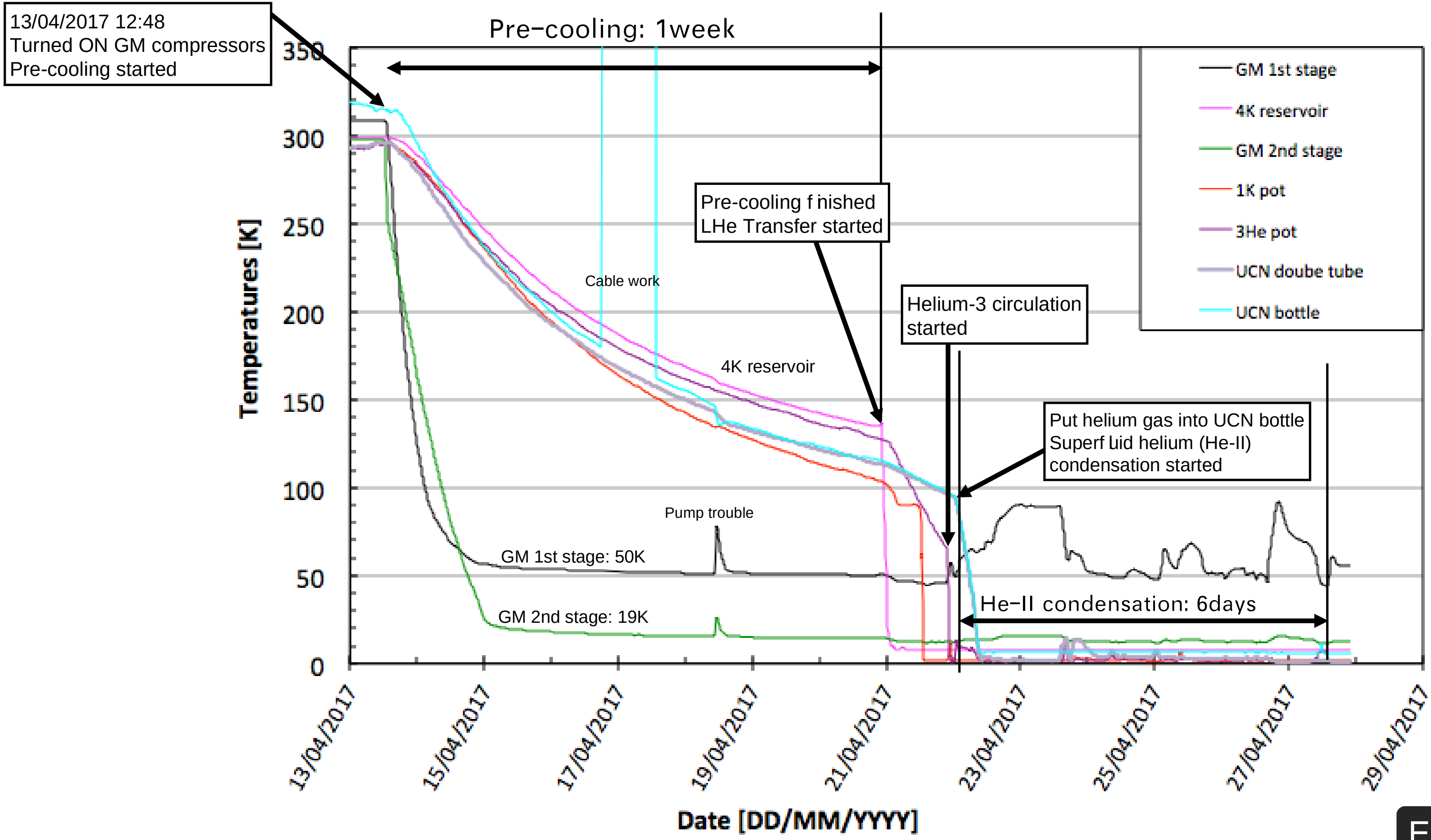
max liquefaction rate as is	18 l/h
UCN needs 2017	ca. 25 l/h
CMMS needs	Ca 10 l/h
max liquefaction rate with LN2 cooling	**up to 70 l/h**



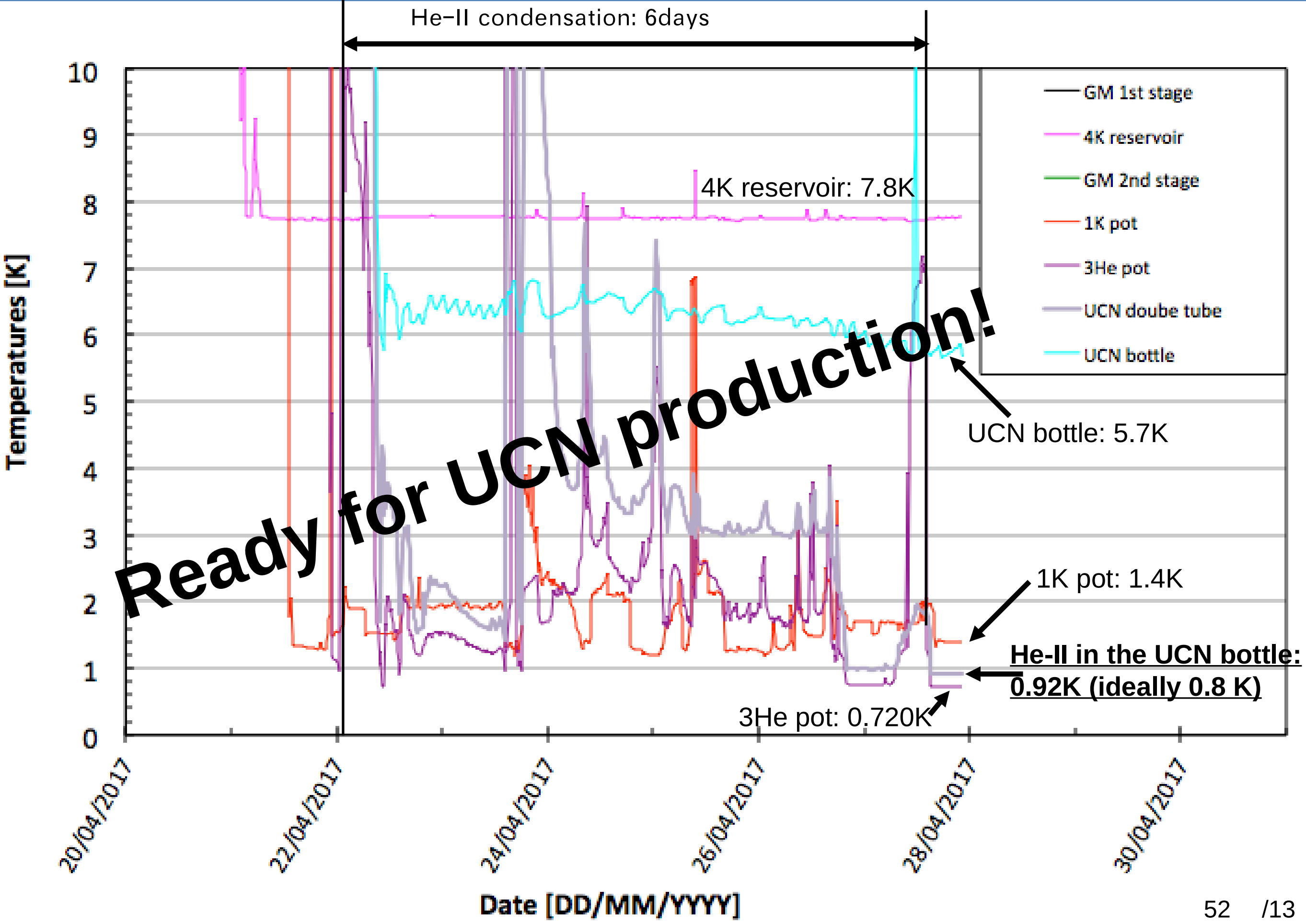
IN2 cooling

- Praxair will take over IN2 delivery to TRIUMF (next 6 months)
- Use new cyclotron IN2 tank
- No new tank & pad necessary
- Routing along IN2 supply for M15 and He recovery of M15
- Installed spring 2017
- First test next week

UCN source cooldown test April 2017



Isopure helium condensation per



He upscattering lifetime

K. K. H. Leung et al., Phys. Rev. C 93, 025501

- $\tau_{0.8K} = 366\ s$
- $\tau_{0.92K} = 186\ s$

Assuming 80 s wall storage time:

- $\tau_{0.8K+W} = 66\ s$
- $\tau_{0.92K+W} = 56\ s$

Why? Speculation…

- Heat bridge because something shifted during transport or reassembly
- D_2O vessel not filled

He upscattering lifetime
Assuming 80 s wall storage time:
Why? Speculation…
- Heat bridge because something shifted during transport or reassembly
- D2O vessel not

Heater tests during cooldo

- Heat input of 1 μA : 70 mW (MCNP benchmarked with PHITS simulations at RCNP)
- 20% smaller than at RCNP
- Superfluid helium temperature rise during heater tests

Heater power (mW)	Current equivalent (μA)	Duration (s)	Temperature increase (K)
75	1	60	0.01
250	3.5	60	0.027
1000	14	60	0.062

T [K]	τ (B=8.8x10^{-3})	τ (B=7.6x10^{-3})
0	880	880
0.5	826	833
0.7	540	567
0.8	334	365
0.9	187	210
1.0	100	114

- RCNP results with vertical source
  - ca 105 UCN for 40 s proton irradiation with 1 µA (400 MeV)
- MCNP simulations: expect 20% more production (480 vs 400 MeV)