A Quasi-Monoenergetic Neutron Beam for Calibrating Dark Matter Detectors

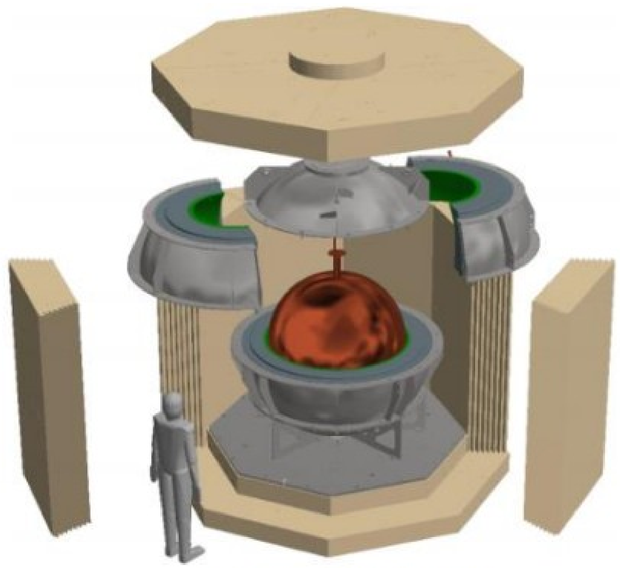
CPAD Instrumentation Frontier Workshop 2021
Thursday March 18^{th}
Jean-François Caron

NEWS-G: New Experiments with Spheres - Gas

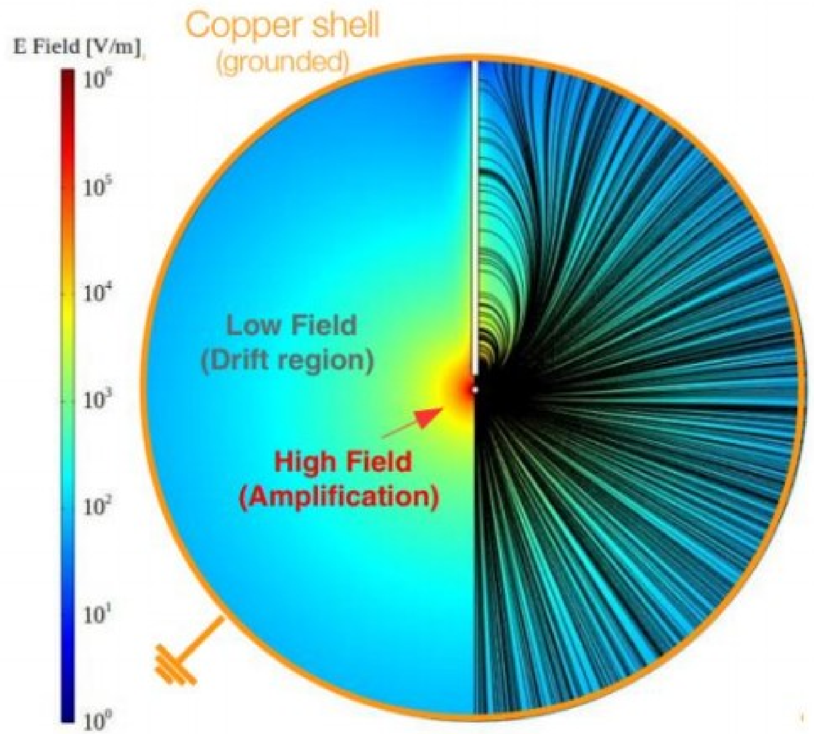
Such a detector is being installed at SNOLAB as I speak!

Videos and photos:
https://news-g.org/news/

140 cm diameter low activity copper (C10100) SPC
7 - 25 µBq/kg ^{232}Th
1 - 5 µBq/kg ^{238}U
Electropolishing and electroplating



Compact Shielding (35 t)
40 cm borated PE
22 cm low activity Pb (3 cm archeological Pb)
SS enveloppe flushed with pure N (radon mitigation)



In the *Gaseous Detectors* track:

- 108: NEWS-G: Search for Light Dark Matter with Spherical Proportional Counters - Konstantinos Nikolopoulos 3/18/21, 1:20 PM (Already Finished)
- 71. Detecting neutrinos and measuring nuclear quenching factors with spherical proportional counters - Marie Vidal 3/18/21, 2:00 PM (Already Finished)
- 110: Recent advancements on the spherical proportional counter instrumentation for NEWS-G - Ioannis Katsioulas 3/18/21, 2:20 PM ← Right now!

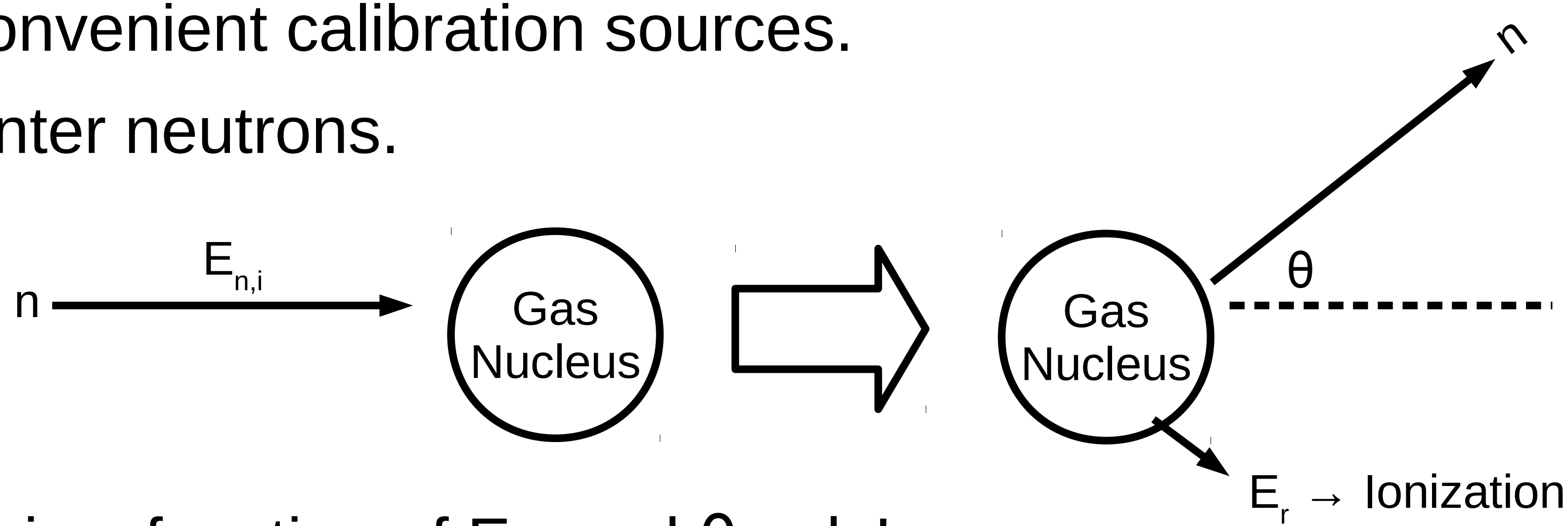
Calibrating

- We need a mapping between detector amplitude and energy deposited by a dark matter particle.
- Convenient sources interact with the electrons around atoms (laser, X-rays, α, β, cosmic μ).[1]
- Dark matter sought by NEWS-G will interact with the nucleus!
  - The nucleus ionizes the gas, releasing electrons.
  - We only "see" the effect on the electrons.
- The ratio of amplitudes from nuclear and electronic recoils is called the ***quenching factor*** (QF).

[1] radioactive neutron sources are ~MeV and thus unsuitable for the ~keV recoils relevant to NEWS-G

Measuring Quenching Factors

- If we can hit a nucleus with a few known energies, we can determine the quenching factor/function and use our convenient calibration sources.
- Enter neutrons.

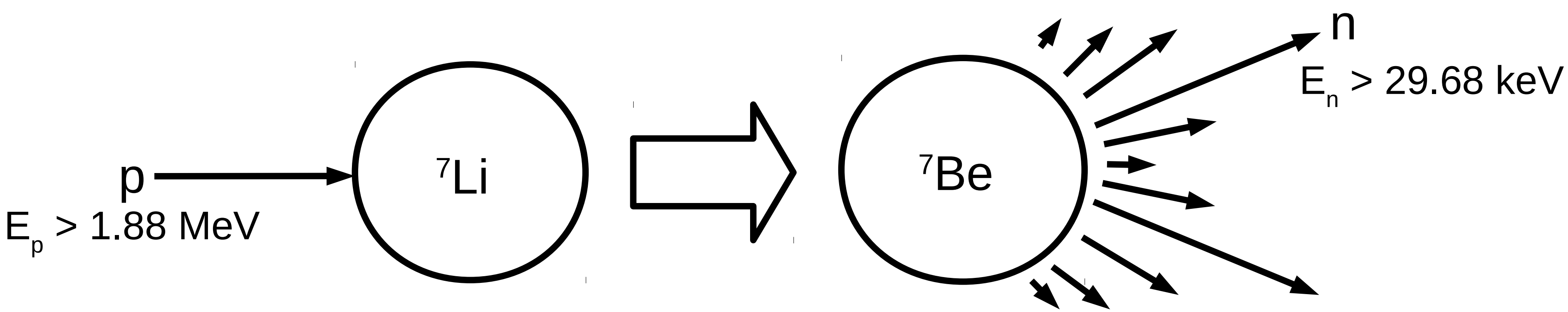


- E_r is a function of $E_{n,i}$ and θ only!
- What remains is to make a beam of quasi-monoenergetic neutrons with a suitable energy.

Quenching factors are actually energy-dependent functions, and different for each material.

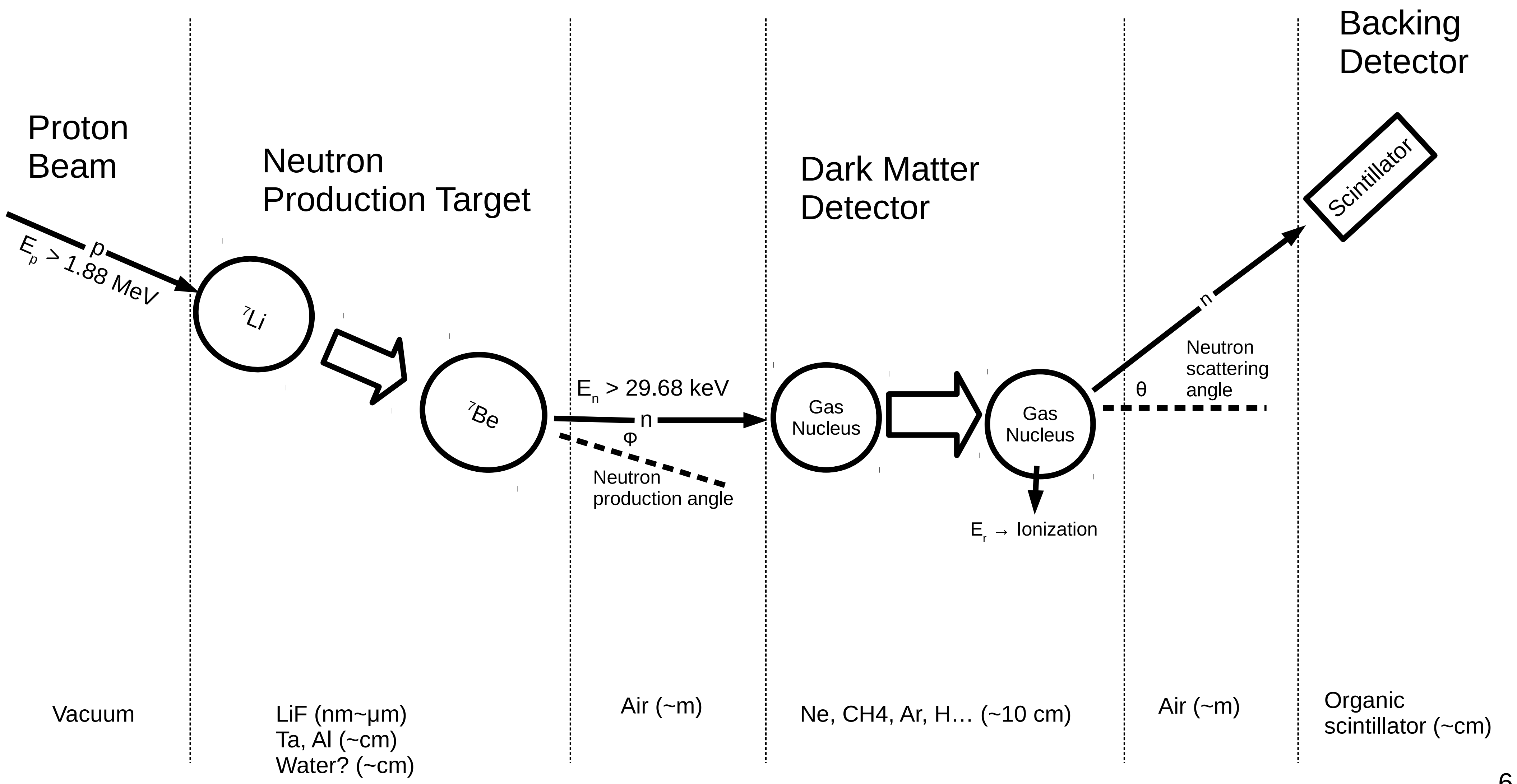
Other approaches include shooting ions directly into gas (COMIMAC): https://doi.org/10.1051/epjconf/201715301014 and using the nuclear recoil from neutron capture (D. Durnford M.Sc. thesis): http://hdl.handle.net/1974/24878

How to Make Neutrons



- In nuclear lingo this is $^7Li(p,n)^7Be$.
- Li metal is very reactive, so LiF is used for stability.
- LiF is hygroscopic, but manageable.
- At a specific neutron production angle, the neutrons are monoenergetic → detector angle selects for energy.

Measuring Quenching Factors 2

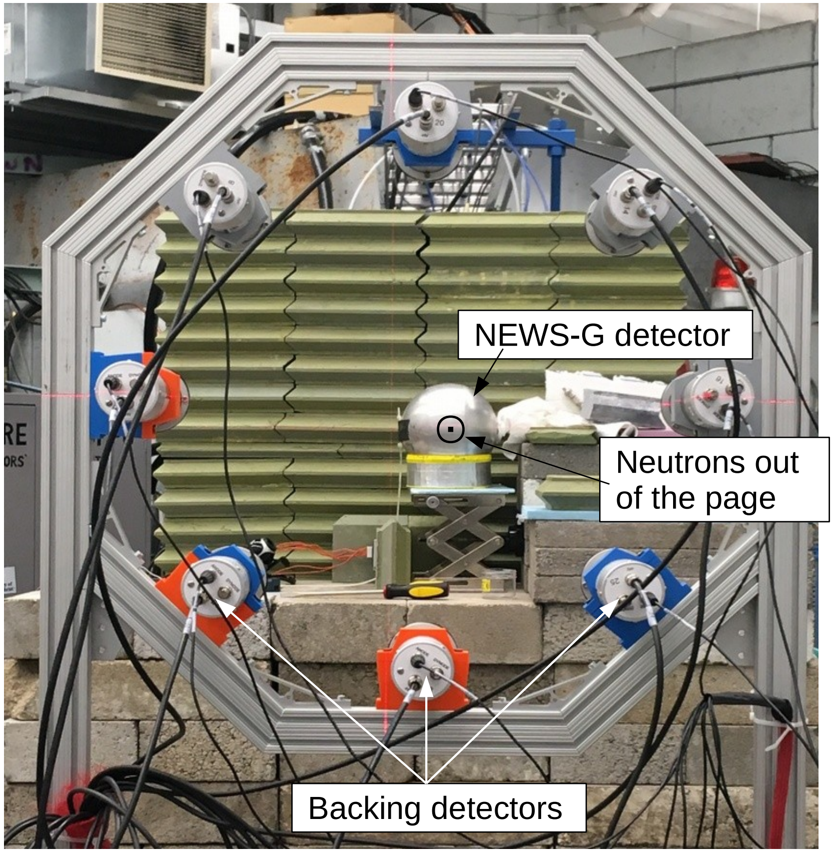


Crappy art credit: me

Prior/Ongoing Work

- QF experiments were done at TUNL in North Carolina.
- QF were measured in neon with a 545 keV neutron beam.
- Nuclear recoil energies down to 0.35 keV obtained by moving the backing detectors to select neutron scattering angle θ.
- Paper by Marie Vidal *et al.* in preparation.

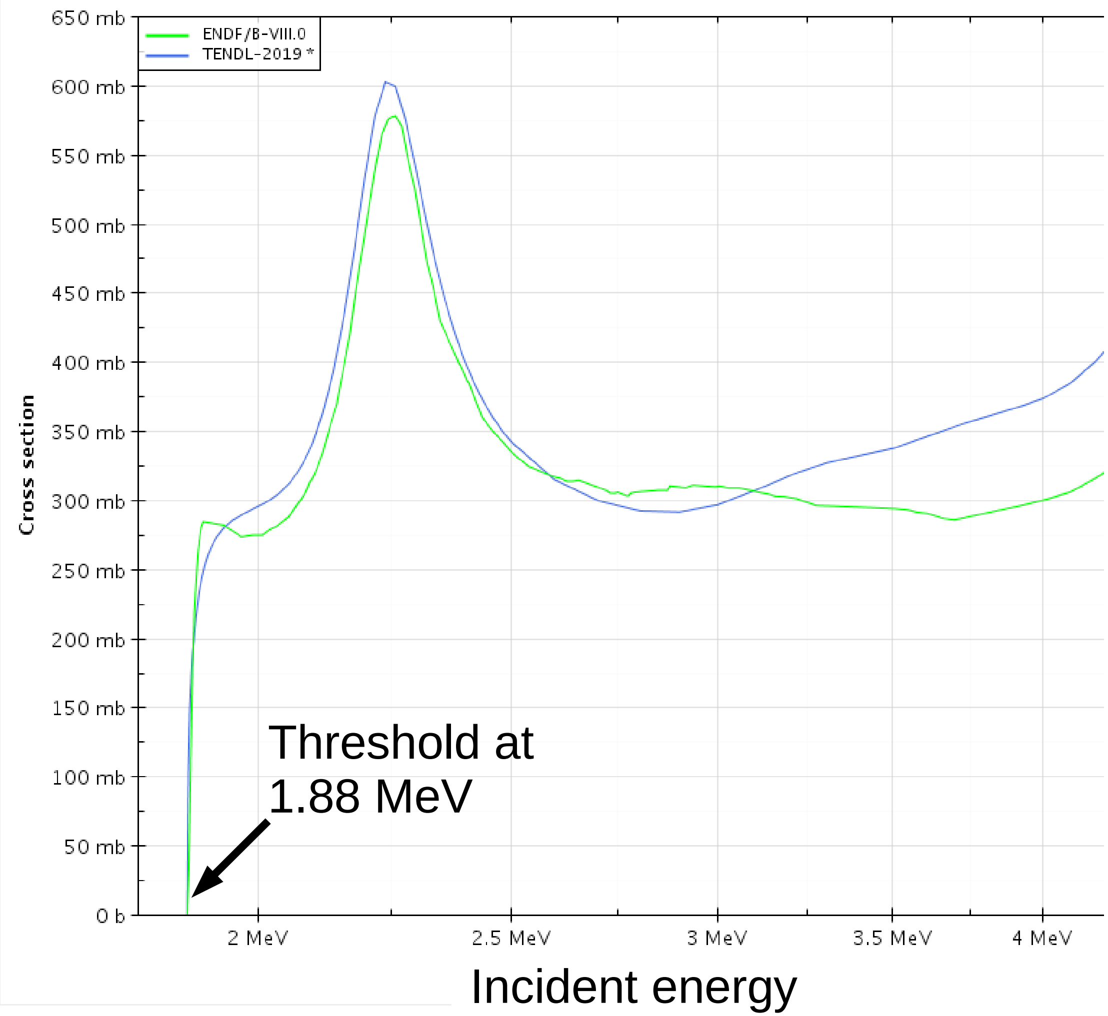
TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY



Lower Recoil Energies

- Lower energy neutrons (~30 keV) are desired to reach even-lower nuclear recoil energies.
- LiF neutron production drops dramatically as you approach the threshold.
- Higher beam current can compensate, but TUNL's tandem accelerator is limited to ~1 μA pulses.

$^{7}Li\ (p,n)\ ^{7}Be$

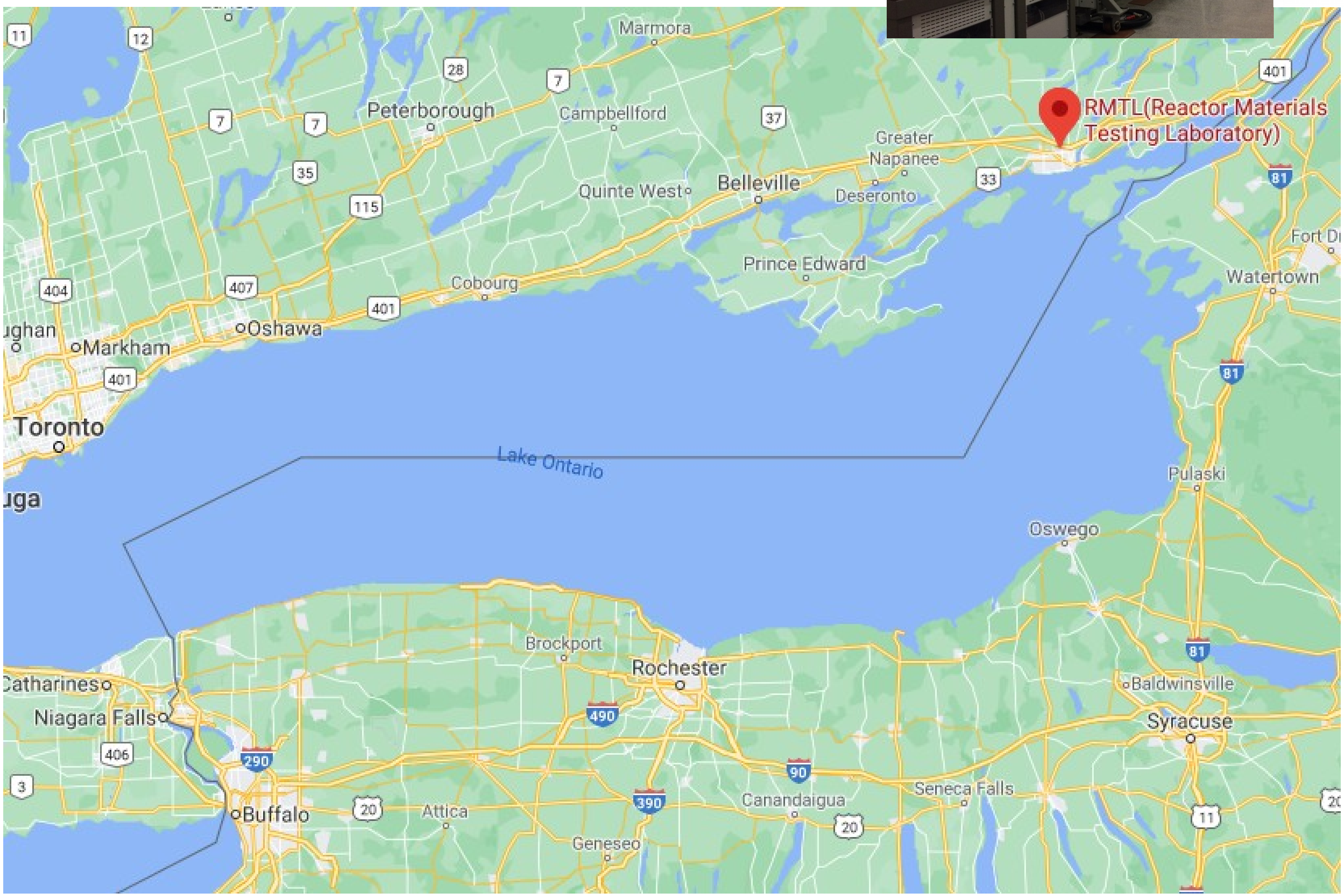


From JANIS (https://www.oecd-nea.org/janisweb/) reaction MT4 on Li7.

Moving to Kingston, ON

- Reactor Materials Testing Laboratory (RMTL) in the Queen’s University Mechanical and Materials Engineering Department.
- Maximum proton current is 45 μA (~50x higher than TUNL), allowing us to get closer to the threshold while maintaining a usable neutron flux.
- Much easier access to the beam than TUNL.
- Caveat: as a nuclear irradiation facility, RMTL lacks some instrumentation taken for-granted at a particle physics lab - notably the proton beam spectrum.

Where is Kingston?



2019 RMTL
Neutron Experiment Goals

- Commission the LiF target for safety. 
- Make some neutrons. 
- Measure neutron spectra. 
- Measure neutron angular distribution. 
- Quantify proton beam spread by scanning across production threshold. 

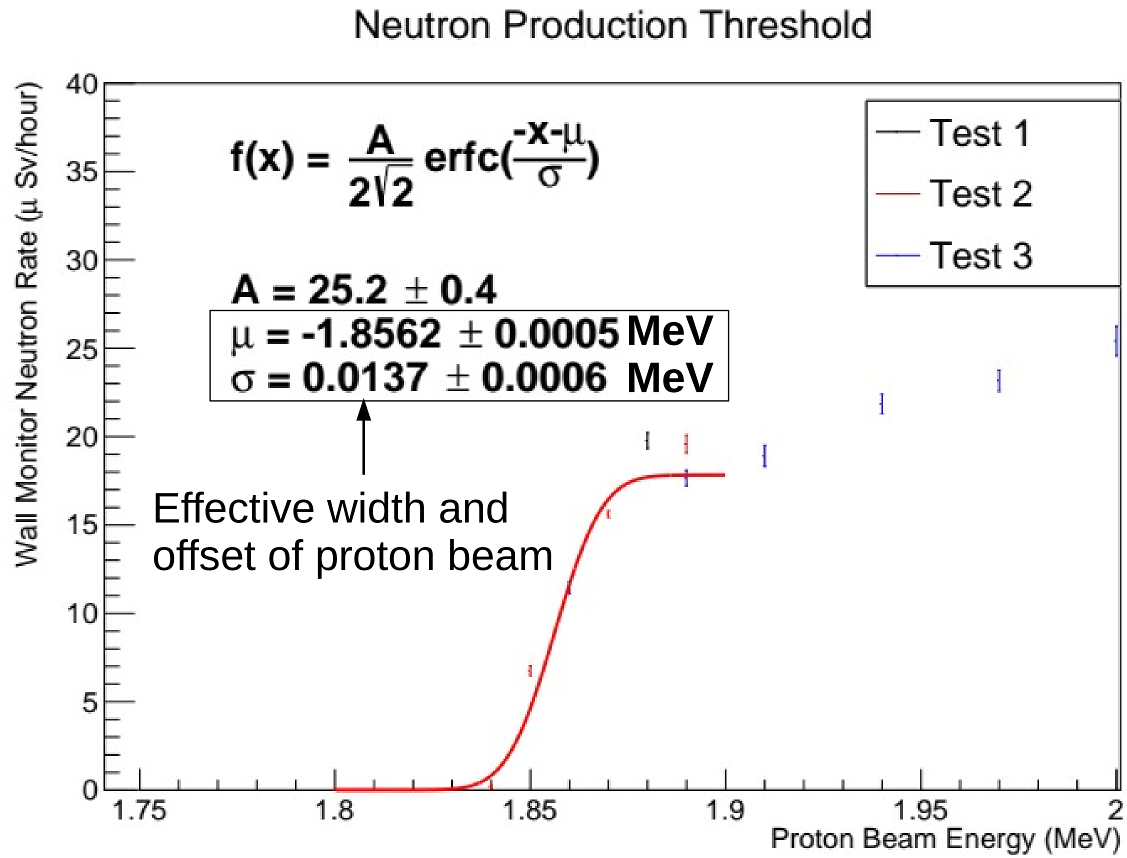
2019 Results

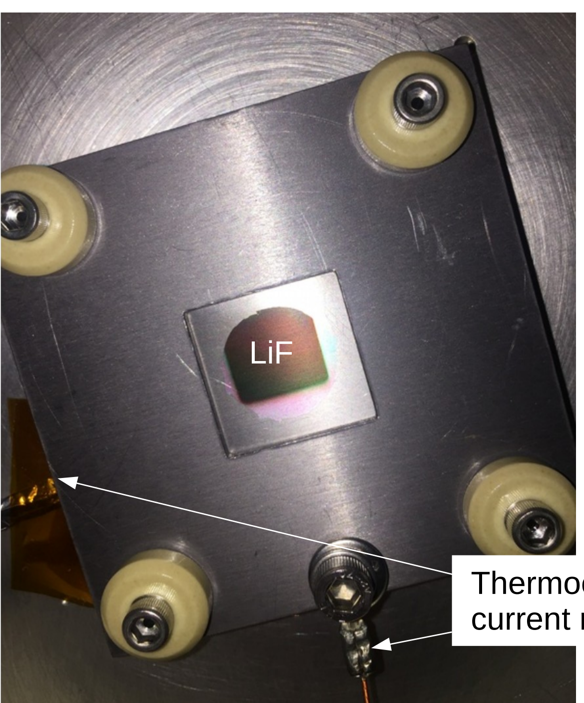
Lessons: need to reduce smearing from:

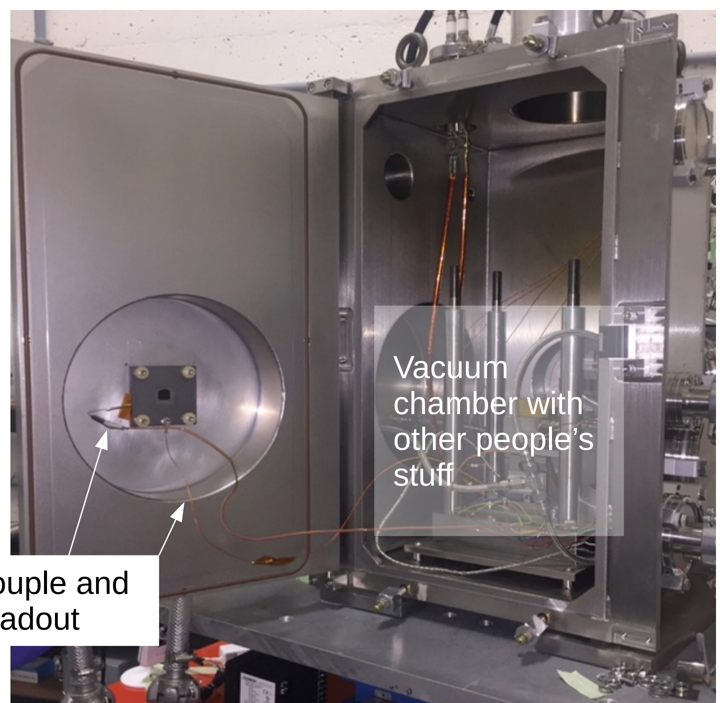
- LiF target itself (~1 µm)
- cooling system (~cm H_2O, Al)
- detection of reflected neutrons

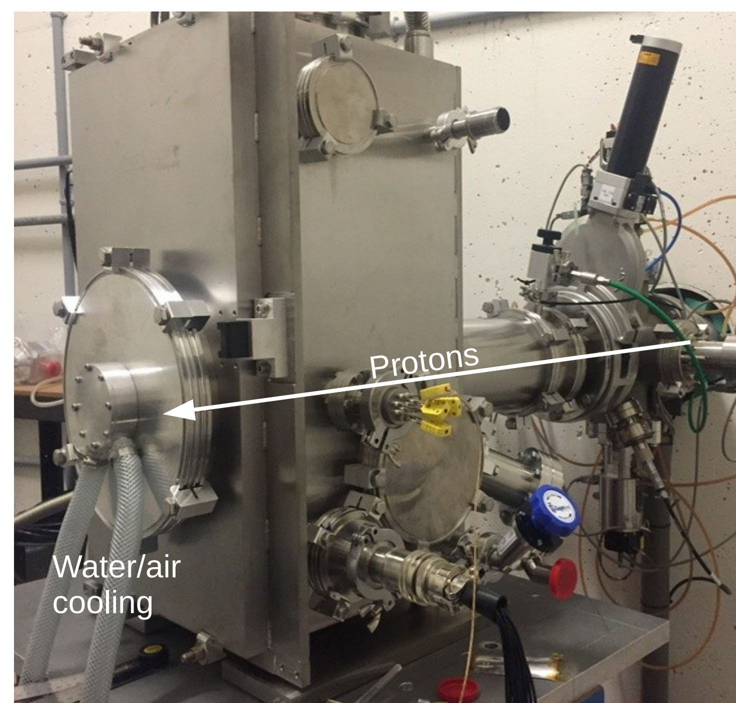
Inconclusive results with:

- angular distribution of neutrons
- neutron spectrum

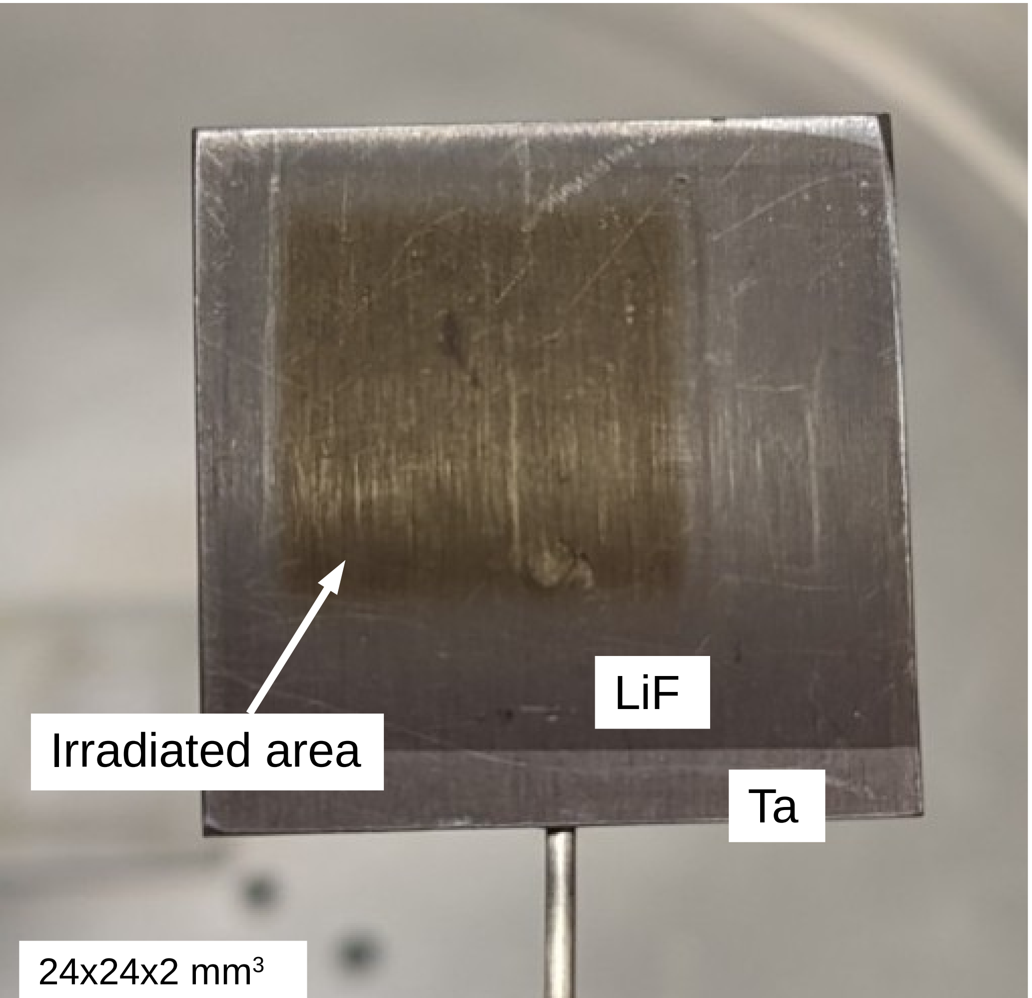








2020: New Targets



Thermocouple

Three new targets were made by Université de Montréal.

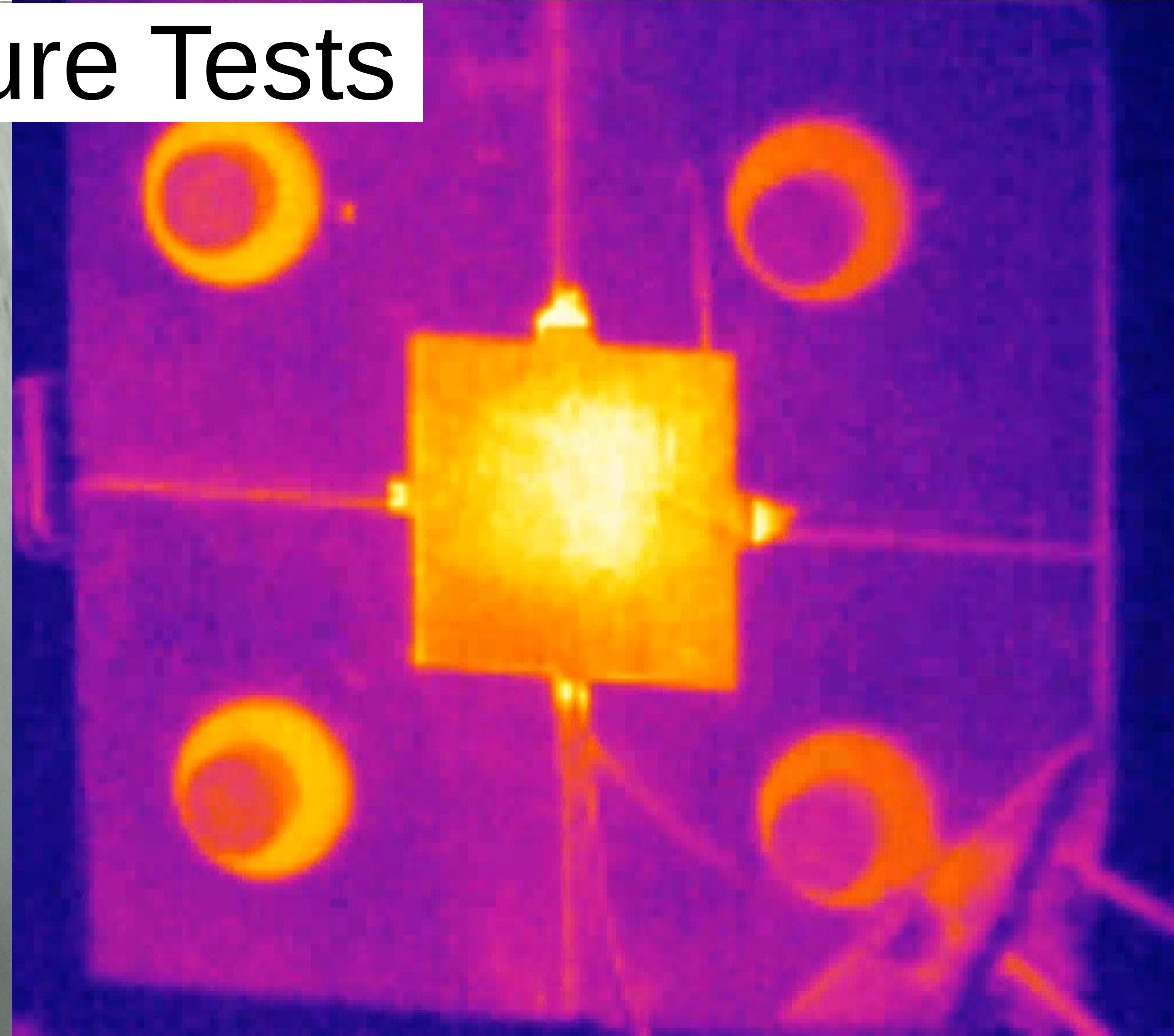
The new targets have **direct thermocouple measurement**, allowing tests with reduced cooling.

Thinner LiF means less proton energy smearing.

- LiF-A: 250 nm 10 keV
- LiF-B: 120 nm 5 keV
- LiF-C: 38 nm 1.5 keV
- Old target: ~1 μm 30 keV

Note: no independent verification of thickness & smoothness.

2020 Temperature Tests



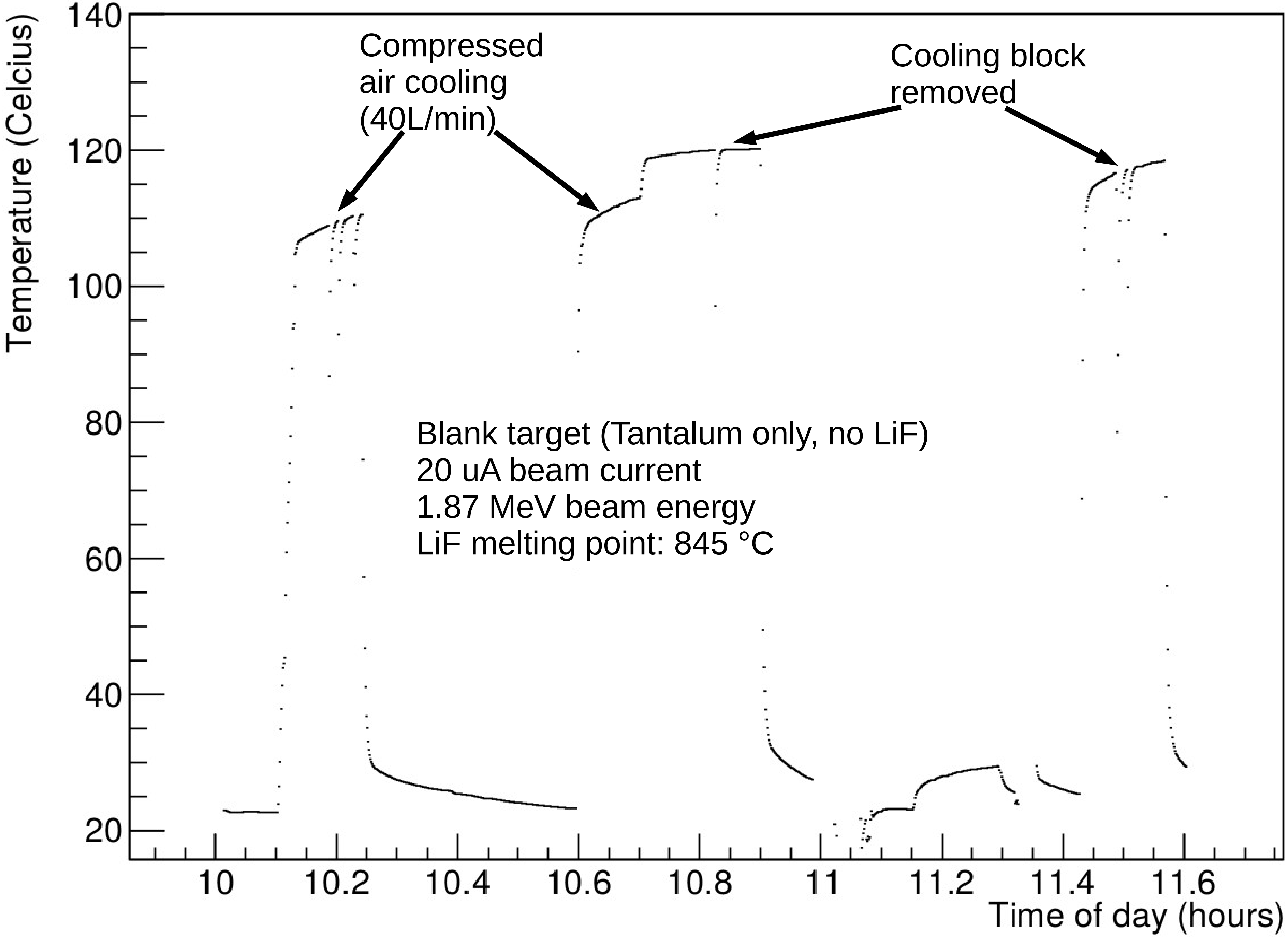
LiF is deposited on a Ta backing plate.

Ta backing plate is held down by W flange.

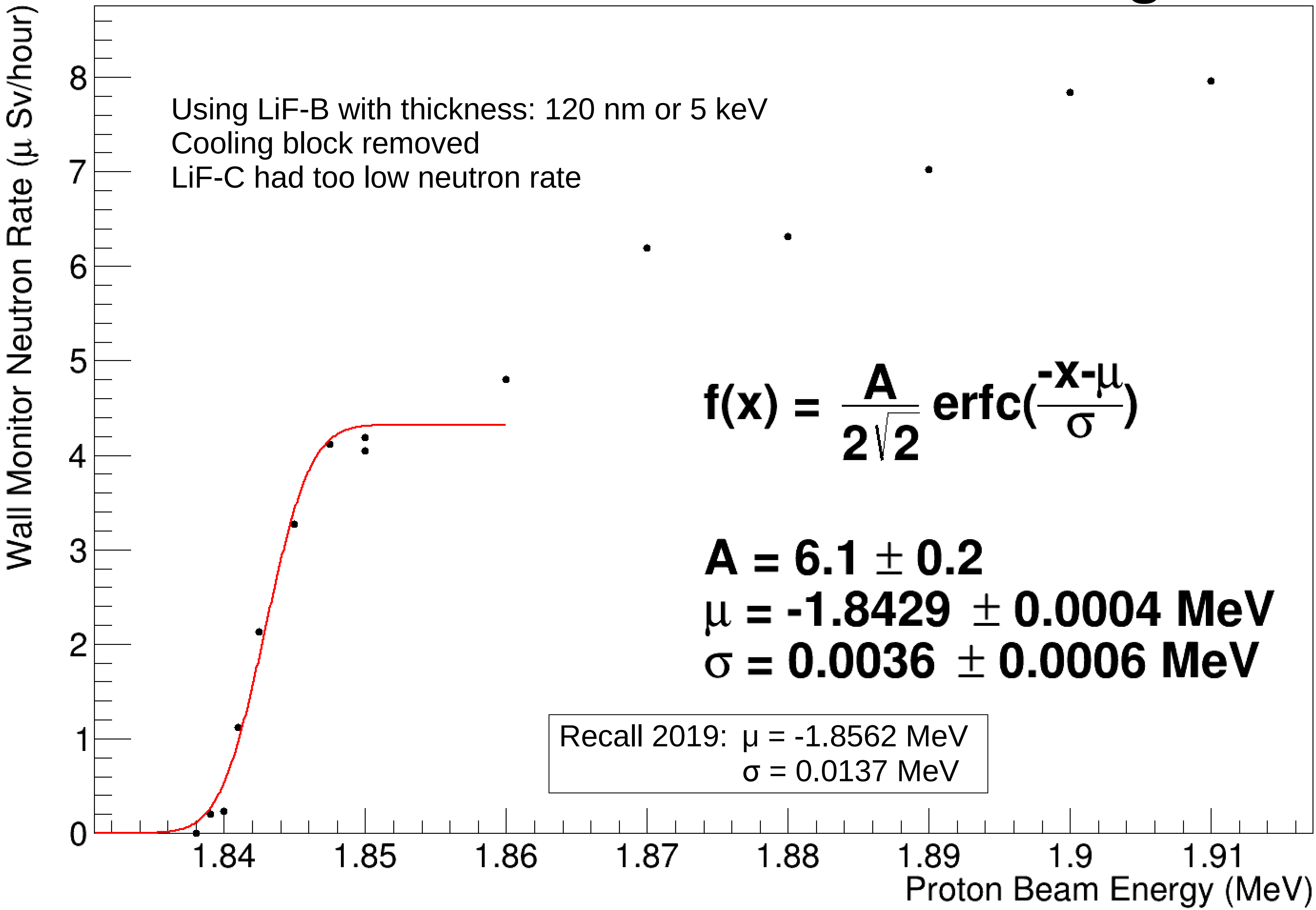
Ta and flange are electrically isolated from vacuum chamber by ceramic spacer and by using ceramic bolts.

Thermal compound is applied on both sides of ceramic spacer.

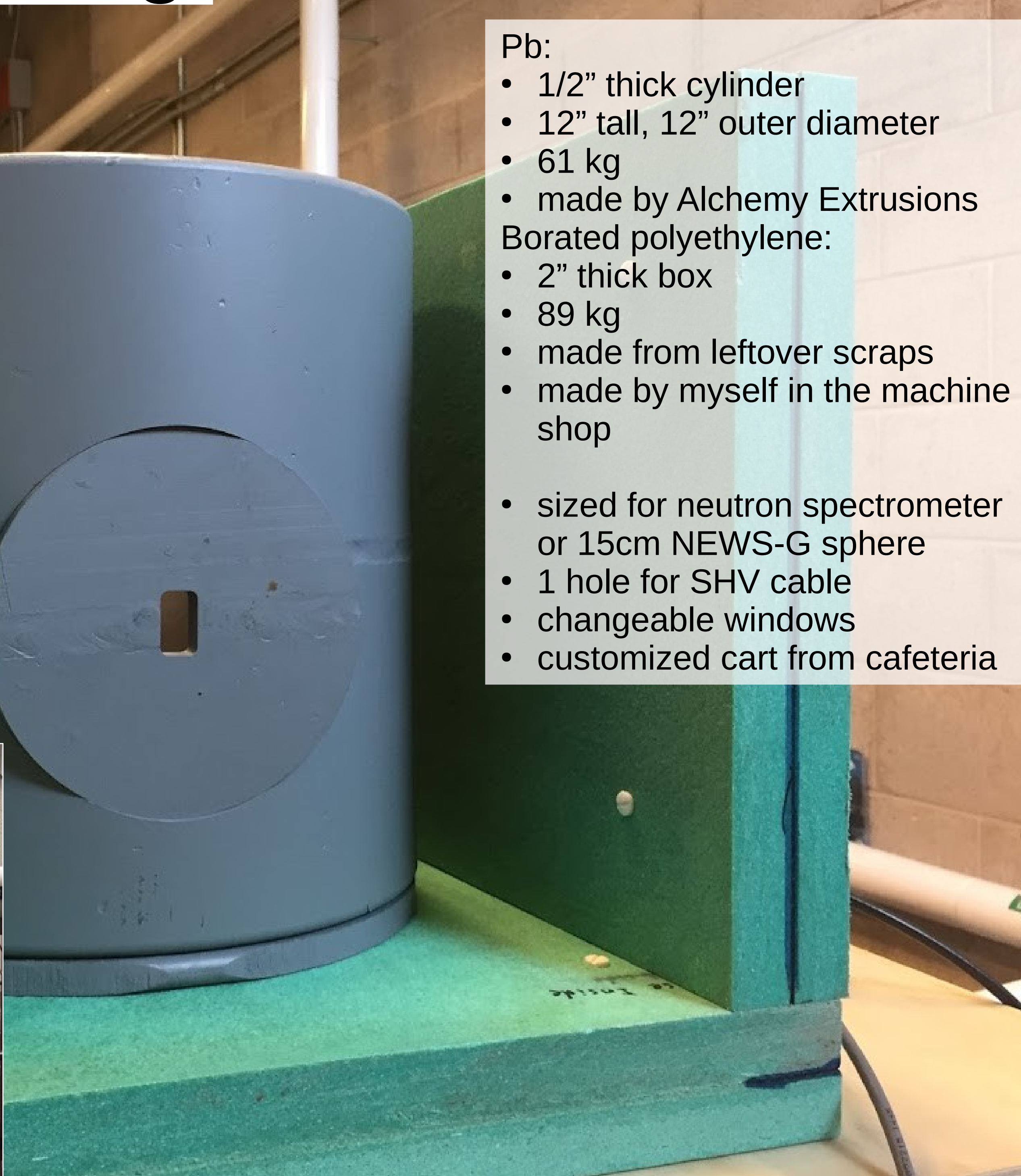
Target Temperature

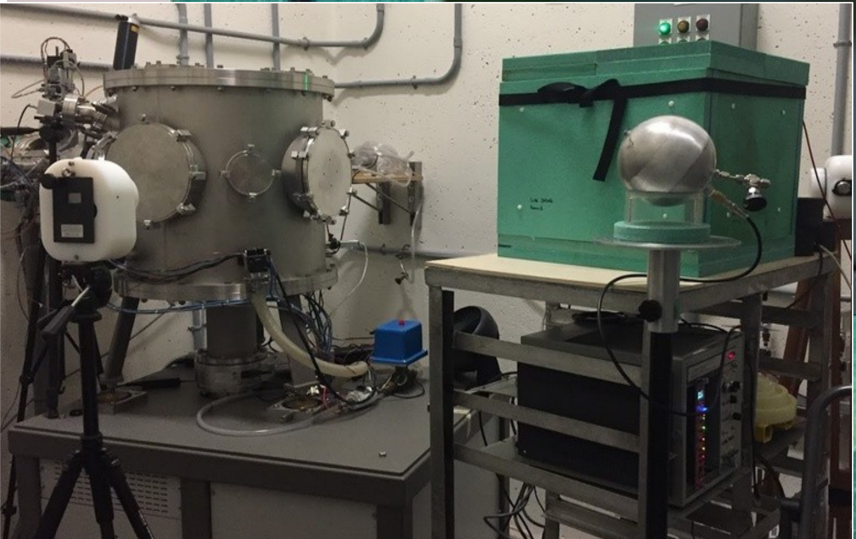


Neutron Production with New Targets



2020 New Shielding





Pb:

- 1/2” thick cylinder
- 12” tall, 12” outer diameter
- 61 kg
- made by Alchemy Extrusions

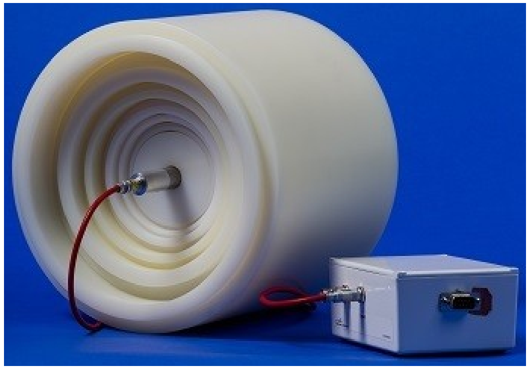
Borated polyethylene:

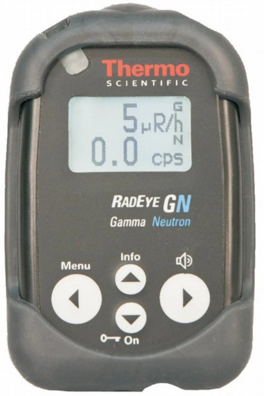
- 2” thick box
- 89 kg
- made from leftover scraps
- made by myself in the machine shop

- sized for neutron spectrometer or 15cm NEWS-G sphere
- 1 hole for SHV cable
- changeable windows
- customized cart from cafeteria

Things that didn’t work

- Neutron spectrometer at E_n ~30 keV
  - Output spectrum is parametrized by energy regions, and 30 keV is right at a boundary.
  - The effect of the shielding was inconclusive.
- Angular distribution measurements
  - Portable detectors found to be faulty, sent back for refurbishment.
- NEWS-G sphere data in beam
  - Data were taken, but inconclusive.
  - No calibration source at RMTL.*
  - Gas inside was likely contaminated.





Things that went well

- We can run with only passive cooling!
- LiF-B (120nm) produces a decent rate of neutron counts.
- Narrower threshold “turn-on” curve than 2019, but also different offset.
- Improved detector positioning & alignment.

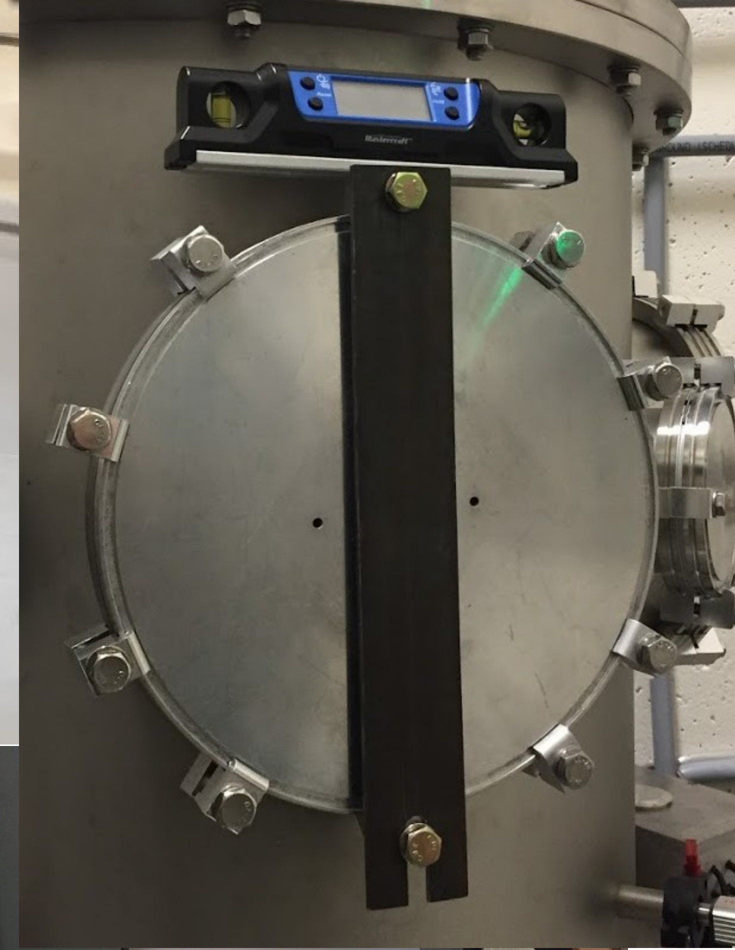
Next Steps

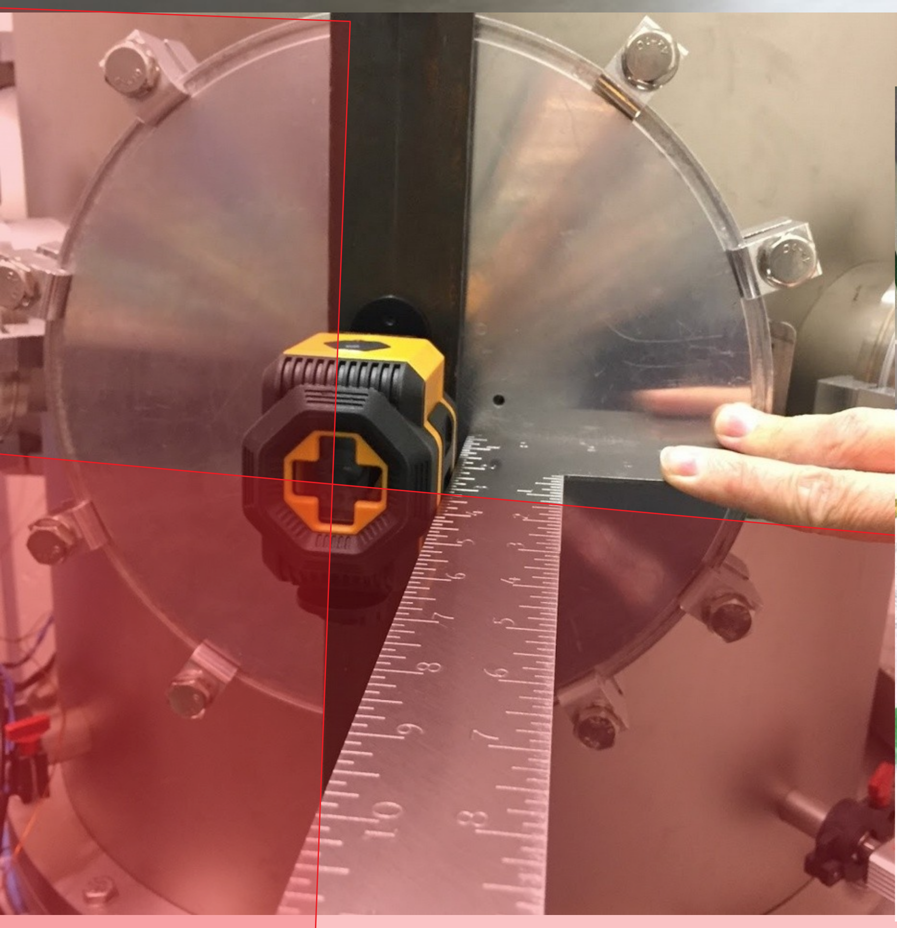
- Commission backing detector with faster DAQ.
- Produce 545 keV neutrons like at TUNL.
  - Neutron spectrometer parametrization should not pose a problem.
  - Angular measurement with portable detectors.
  - Get clean signals in NEWS-G sphere.
- Neutron scattering experiments!
- Reduce neutron energy towards 30 keV goal.

Maurice: I say too much, cut stuff & talk slower.
Pierre: don't say what I'll talk about later.

End

2020 New Alignment





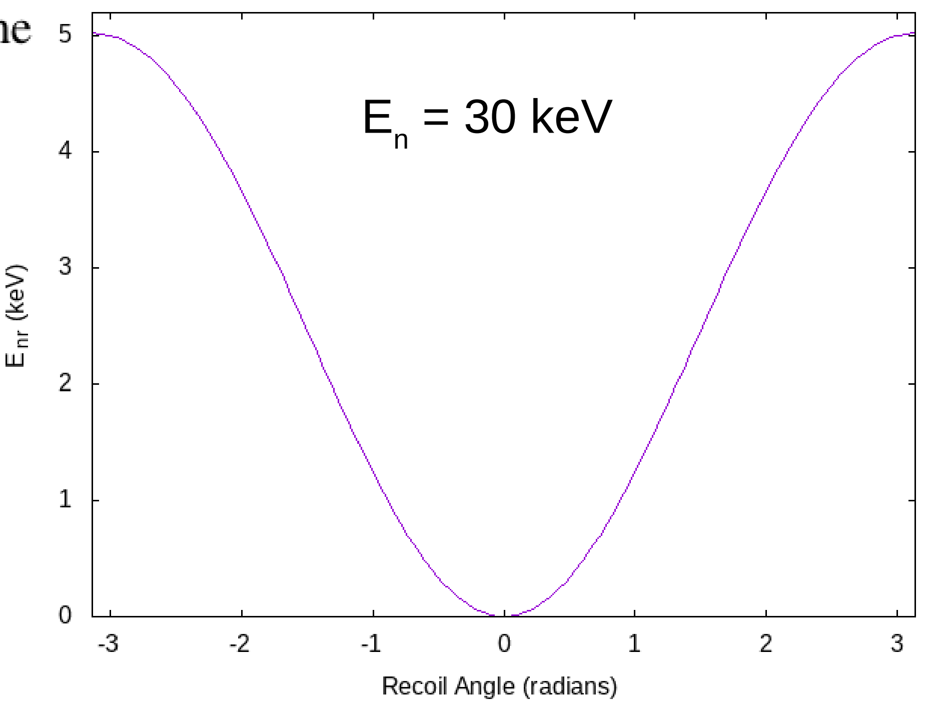
Improvement over previous ad-hoc positioning:
~1mm accuracy at 0°, ~1cm at 90°, 1.5m away.

Kinematics

Knowing the incident neutron energy and the scattering angle, the nuclear recoil energy deposited in the gas can be determined:

$$E_{nr}(\theta_s, E_n) = 2E_n \frac{M_n^2}{(M_n + M_T)^2} \times \left(\frac{M_T}{M_n} + \sin^2\theta_s - \cos\theta_s \sqrt{\left(\frac{M_T}{M_n}\right)^2 - \sin^2\theta_s} \right), \quad (2)$$

where θ_s is the scattering angle of the neutron with respect to its initial trajectory, E_n is the incident neutron energy, M_n is the neutron mass and M_T is the target mass of the nucleus (in our case neon nucleus).



Target Backing Plate