TRIUMF

A spallation target at TRIUMF for fundamental neutron physics

TUCAN

Sean Vanbergen for the TUCAN Collaboration

INTDS2022 – 2022-09-25-2022-09-30 – PSI, Switzerland

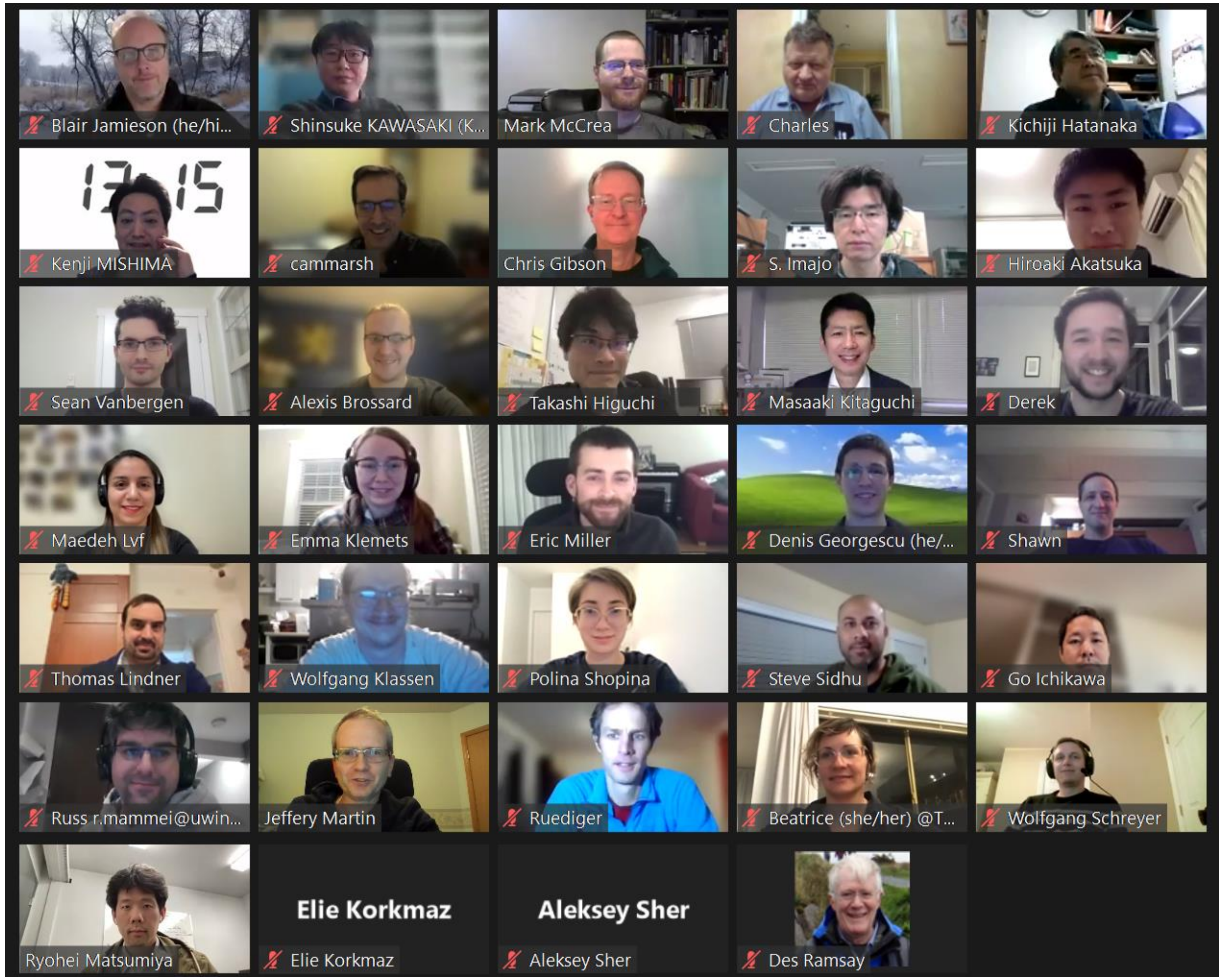
Outline

- TUCAN collaboration
- Physics justification
- TUCAN source
- Target design
    - Composition
    - Cooling system
    - Remote handling
- Target characterization
    - Gold foil activation
    - UCN production

TUCAN Collaboration

Collaboration Goals

1. Create the world's strongest ultracold neutron source.
2. Search for a neutron electric dipole moment with a sensitivity of 10^{-27} ecm (1σ) in 400 beam days.
3. Establish an international user facility for fundamental research using ultracold neutrons.

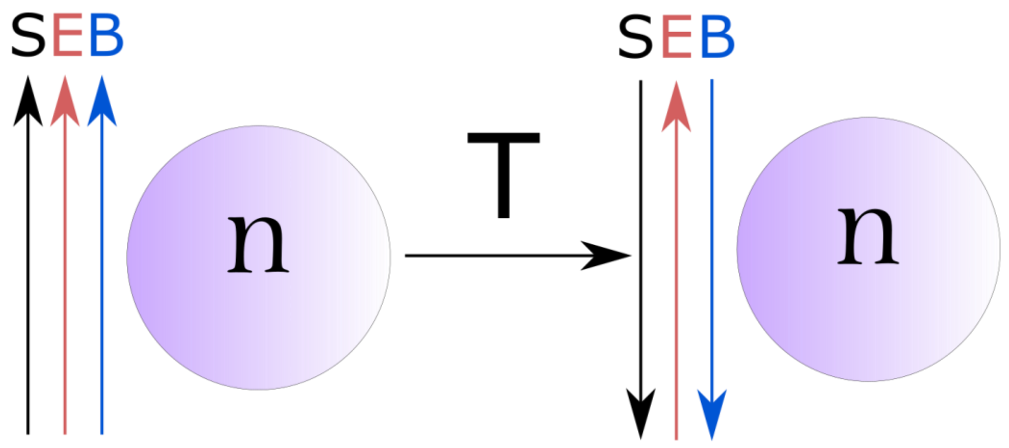


2022 Collaboration Meeting

KEK, RCNP, University of Manitoba, The University of British Columbia, Nagoya University, UNBC University of Northern British Columbia, The University of Winnipeg, SFU Simon Fraser University Engaging the World

The Neutron Electric Dipole Moment

- Neutron can have a permanent electric dipole moment due to its internal charge structure
- Permanent EDMs are symmetry-violating



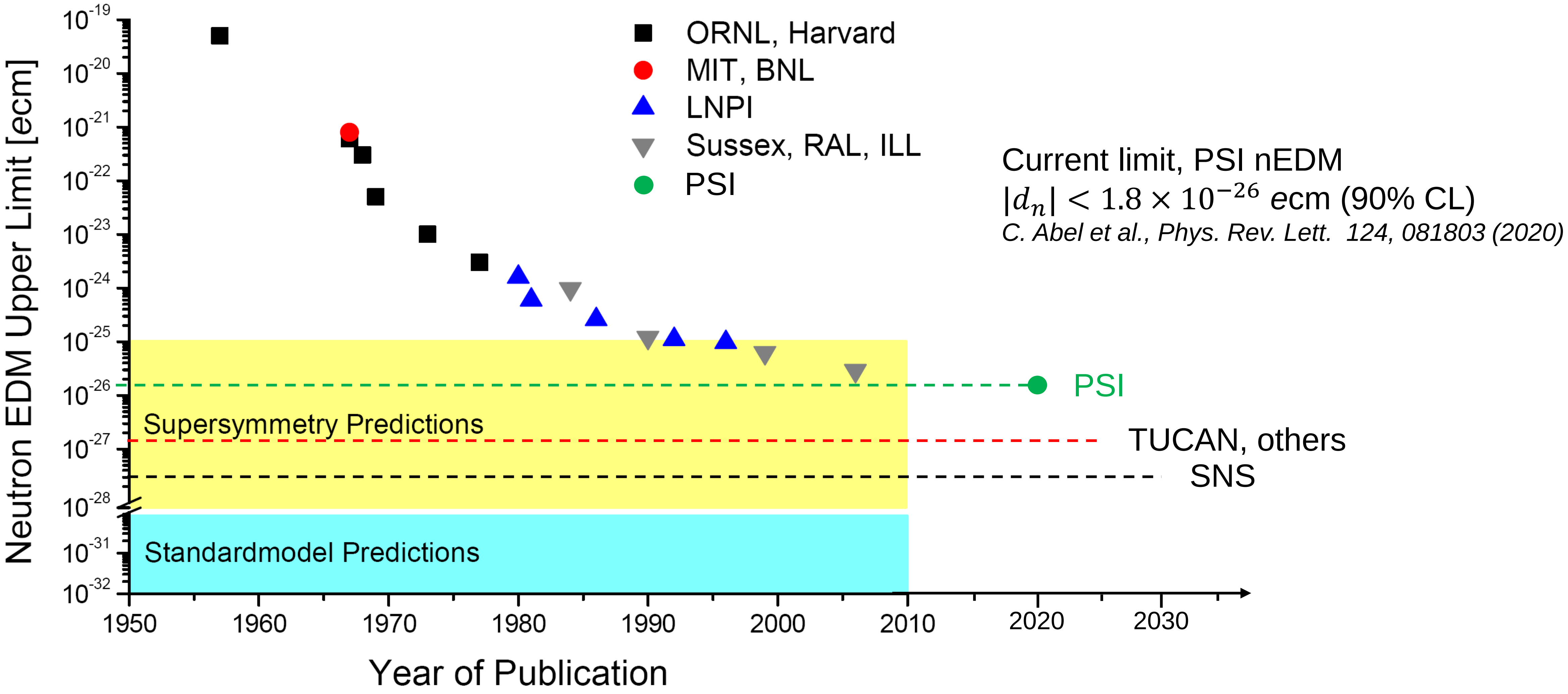
$$H = -\mu_n \boldsymbol{B} \cdot \frac{\boldsymbol{S}}{S} - d_n \boldsymbol{E} \cdot \frac{\boldsymbol{S}}{S} \rightarrow H = -\mu_n \boldsymbol{B} \cdot \frac{\boldsymbol{S}}{S} + d_n \boldsymbol{E} \cdot \frac{\boldsymbol{S}}{S}$$

Assuming CPT symmetry, T-violation → CP-violation

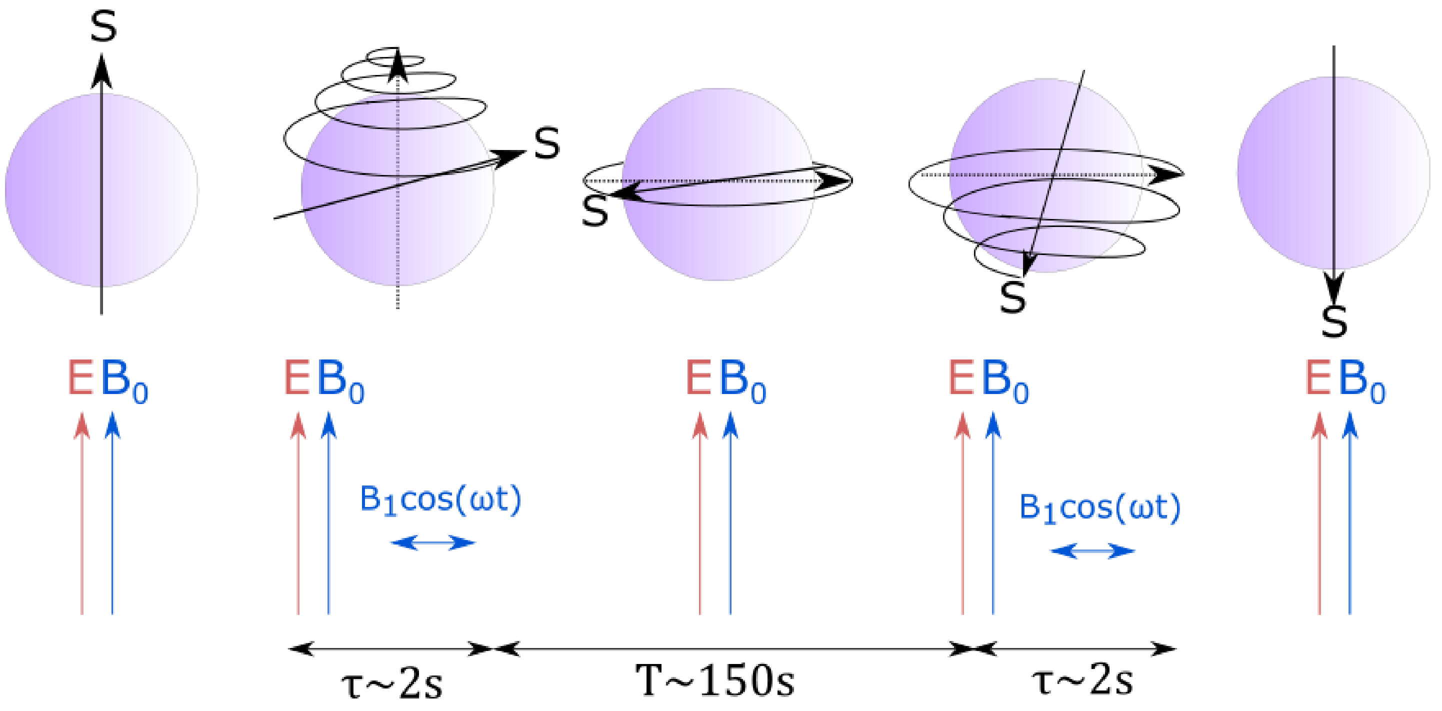
Baryogenesis

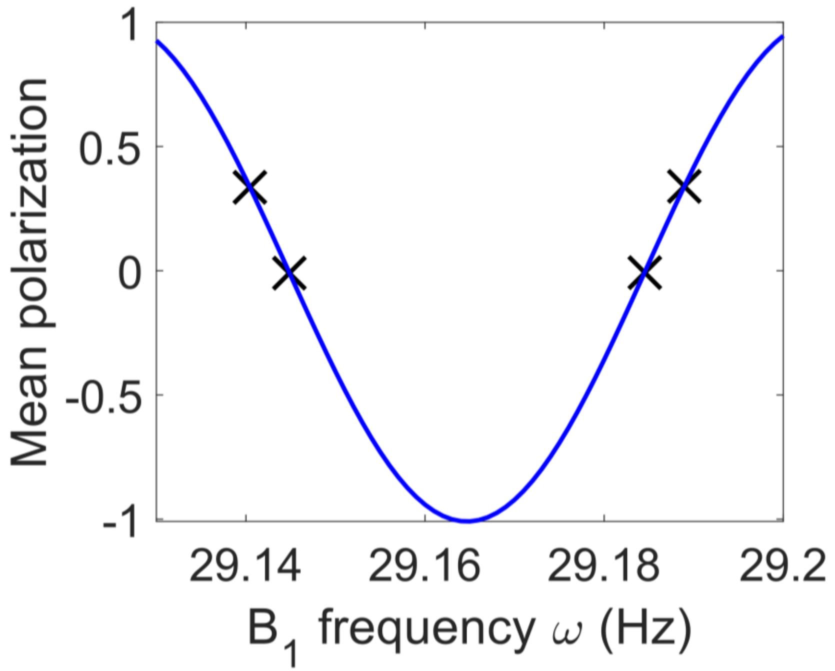
- Universe has an imbalance of matter over antimatter
- To generate such an imbalance, Sakharov conditions require:
  1. Baryon number violation
  2. C and CP violation
  3. Non-thermal-equilibrium
- However… there is not enough symmetry-violation in the standard model
- EDM searches provide insight into symmetry-violating physics beyond the standard model

Progress in Measuring the nEDM



Ramsey Interferometry and Statistical Limitations





$$\hbar\omega_{L,\pm} = 2\mu_n|B_0| \pm 2d_n|E| \rightarrow d_n = \frac{\hbar(\omega_{L,+} - \omega_{L,-})}{4|E|}$$

Statistical sensitivity:

$$\sigma \sim \frac{1}{ET\sqrt{N}}$$

Ultracold Neutrons (UCN)

- Kinetic energy < 350 neV
- De Broglie wavelength > 50 nm
- Typical interatomic spacing < 0.5 nm
- UCN can “see” many nuclei at once, such that they interact with a constant potential

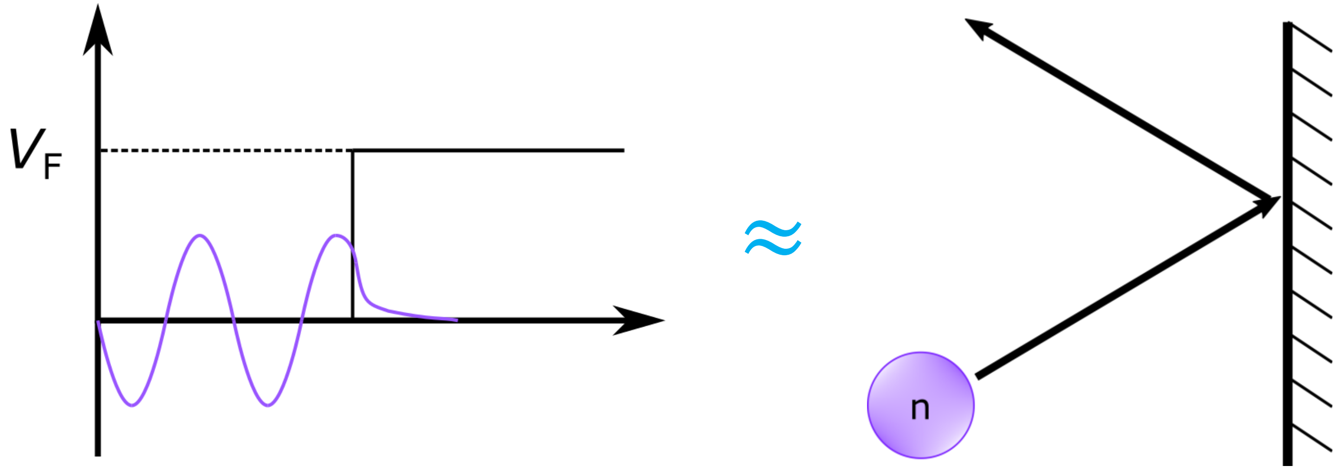
$$V_F = \frac{2\pi\hbar^2}{m_n}\sum n_i\, a_i$$

Number density of species *i*

Neutron scattering length of species *i*

- If kinetic energy < V_F, then neutrons can be contained in specially prepared vessels

Material	V_F (neV)
NiP	213
DLC	243
dPS	170



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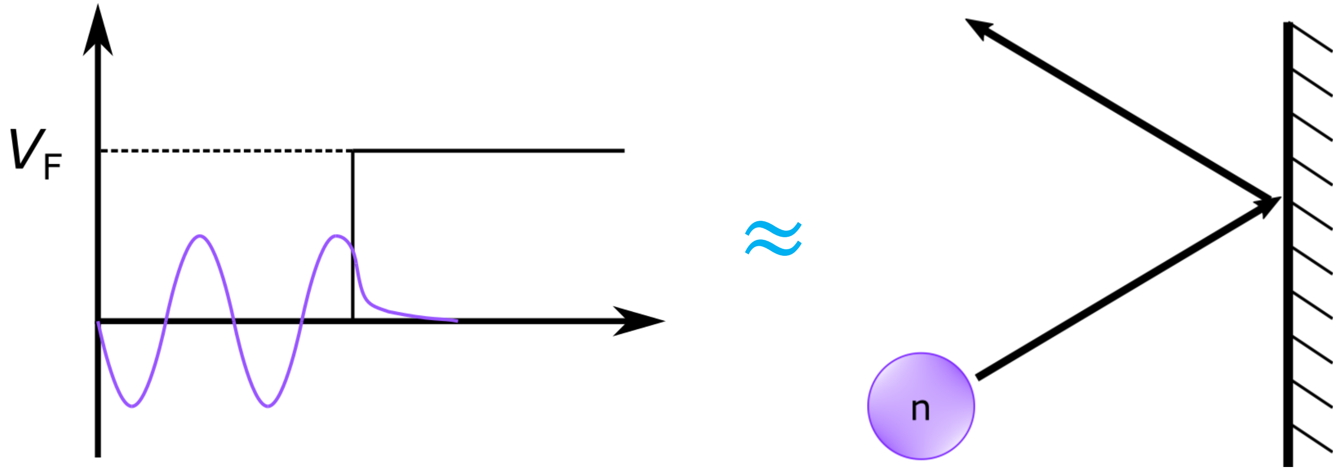
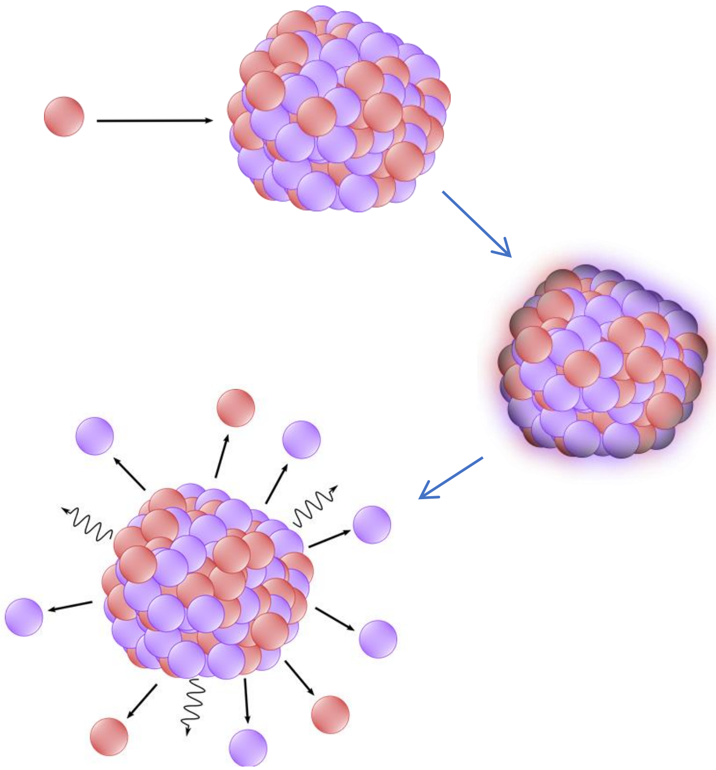


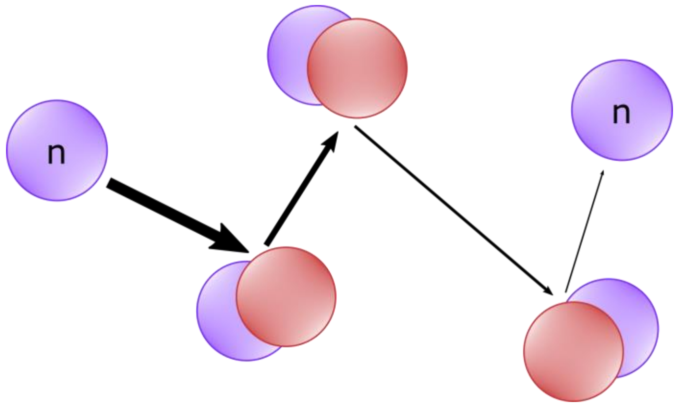
Long measurement time T (100-200 s) is possible!

Making Ultracold Neutrons

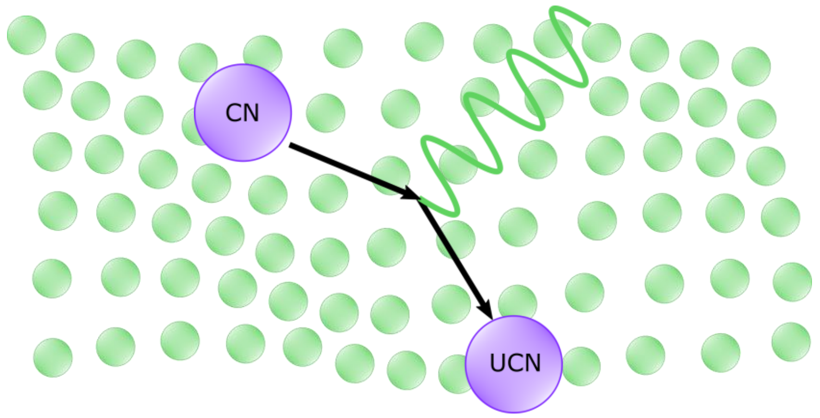
1. Make a large number of high energy neutrons using a spallation target



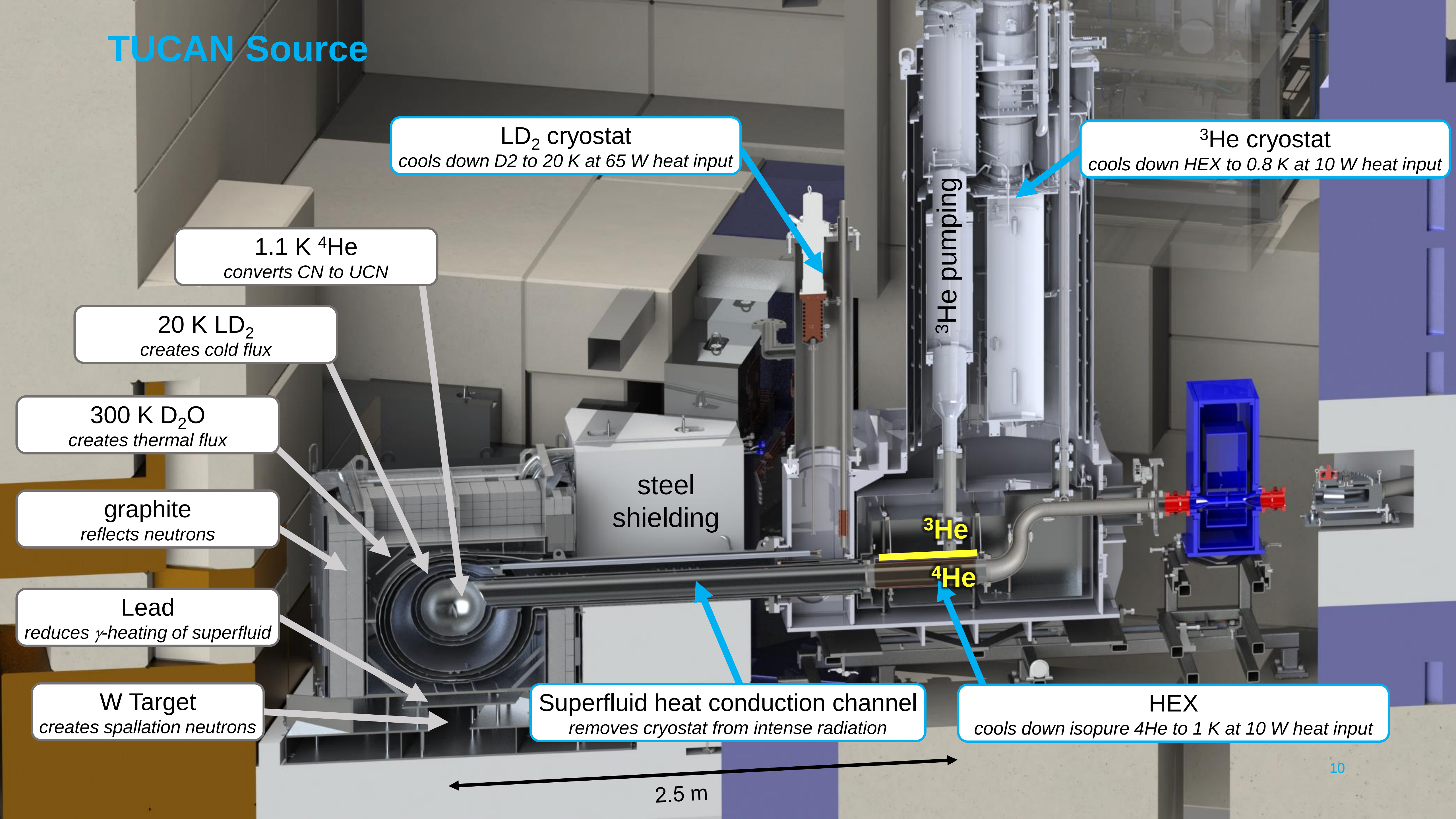
2. Moderate fast neutrons to thermal/cold energies in successive moderators



3. Convert cold neutrons to UCN through the process of phonon/roton emission in superfluid helium



TUCAN Source



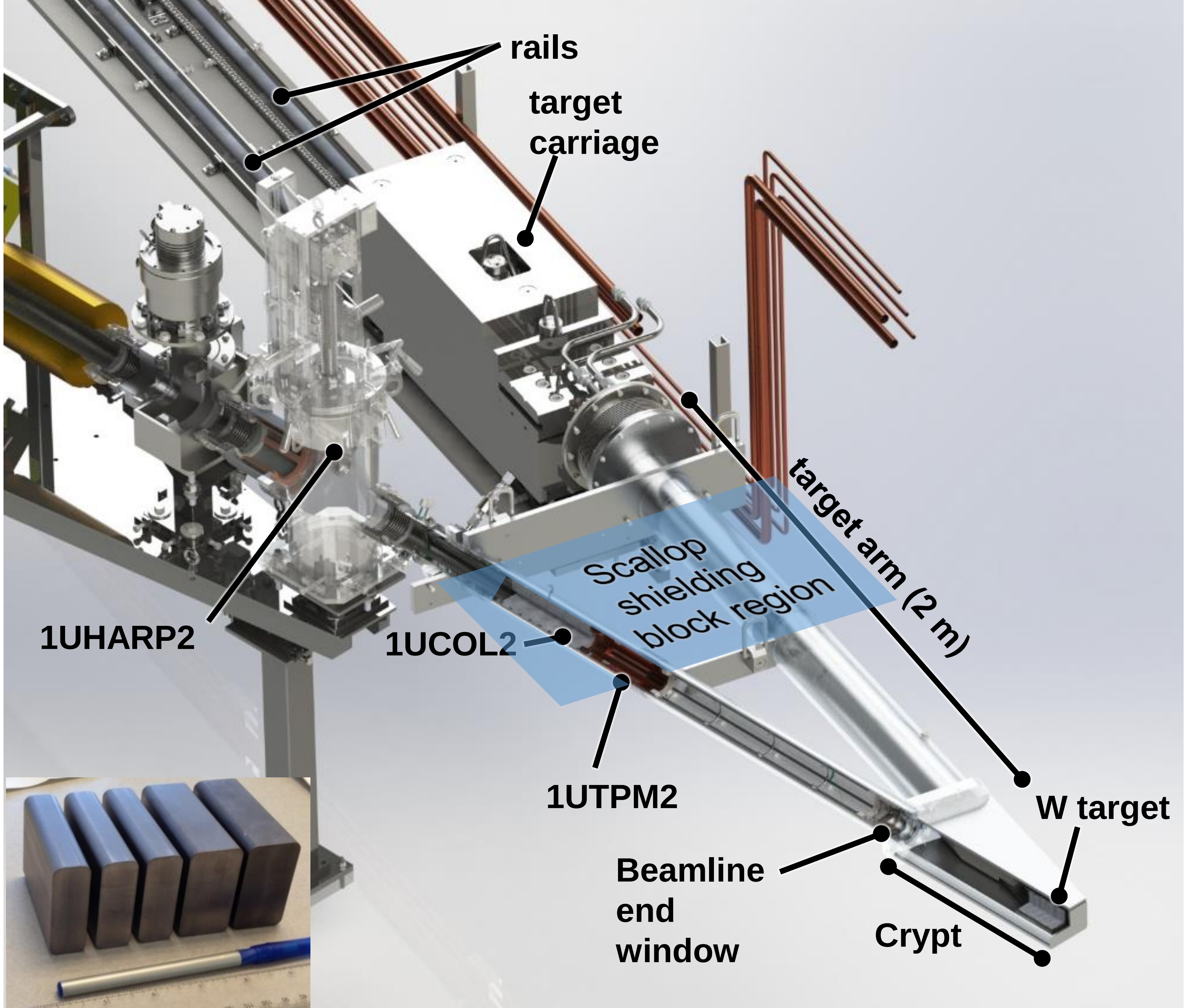
TUCAN Source Expected Performance

	Published		Future		
EDM Experiment	ILL	PSI nEDM	PSI n2EDM*	LANL EDM**	**TUCAN*** **
UCN detected per cycle	14 000	15 000	121 000	78 000	**1 600 000**
Storage cell size	20 l	20 l	116 l	40 l	**63 l**
Density detected	0.7	0.75	1	2	**26**

* expected, based on PSI nEDM.
** expected, based on storage experiments.
*** expected, extensive MC simulations using experimentally-determined parameters.

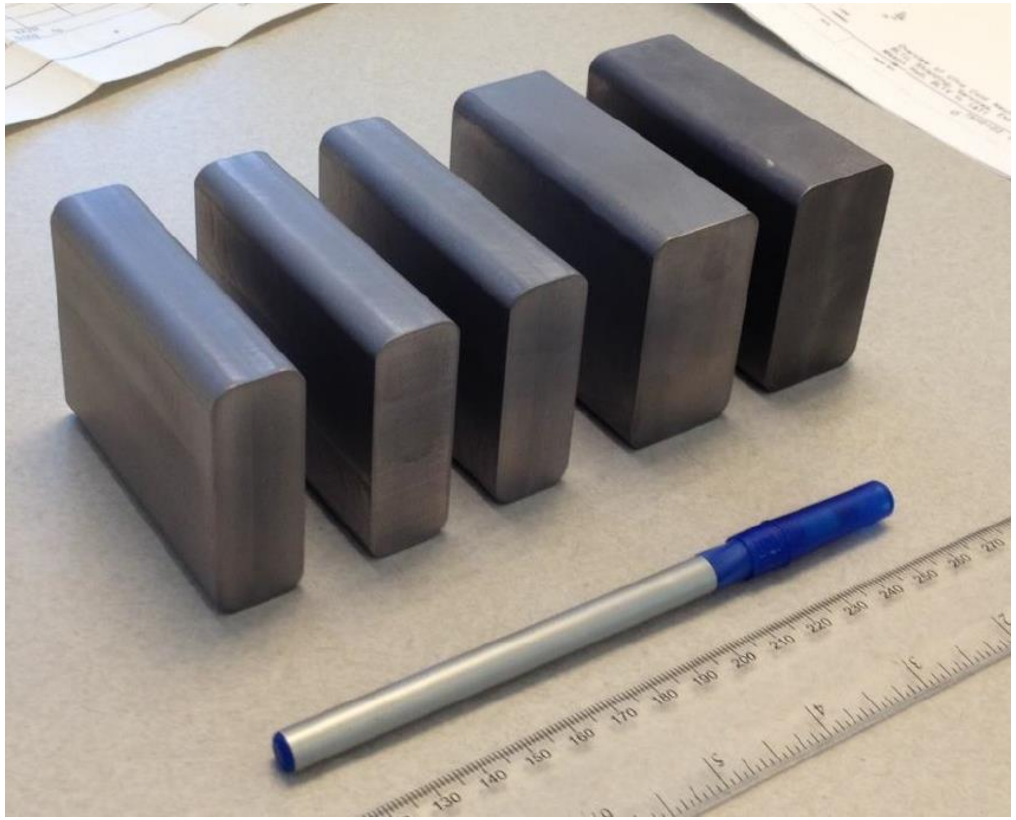
Spallation Target

- Tungsten target contained in a helium-filled crypt at the end of a proton beamline
- Driven by TRIUMF 520 MeV cyclotron
- Current is shared with muon beamlines via kicker magnet
- Maximum current onto target is 40 μA
- Total power ~20 kW



Target Design

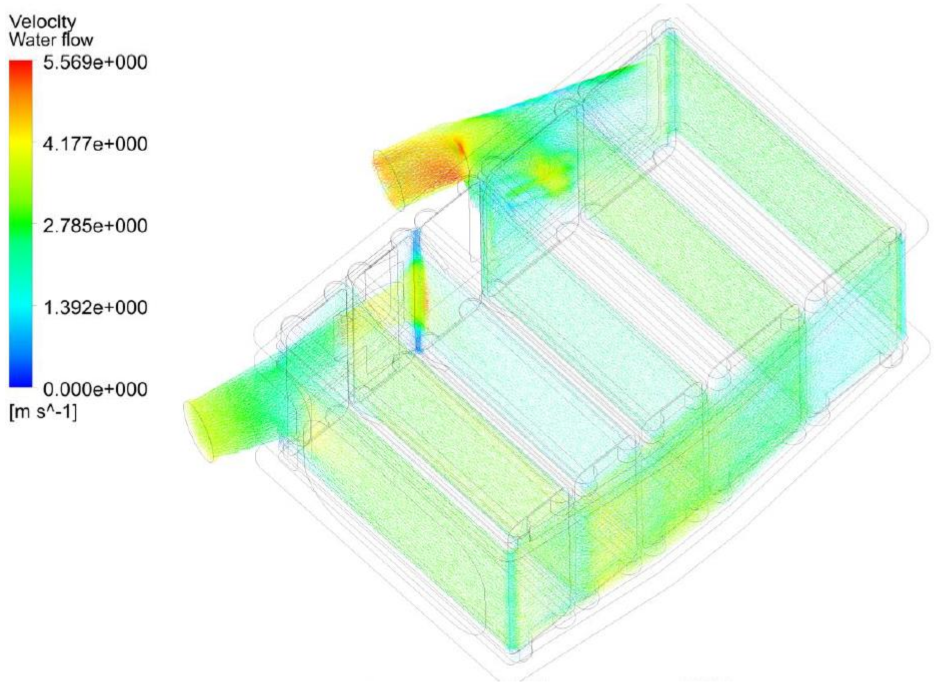
- Based on KENS target design
  (M. Kawai, et al., J. Nucl. Mater., 296 (2001)
- Set of 5 tantalum-clad, water-cooled tungsten blocks
- 12 cm target depth doubles as beam stop

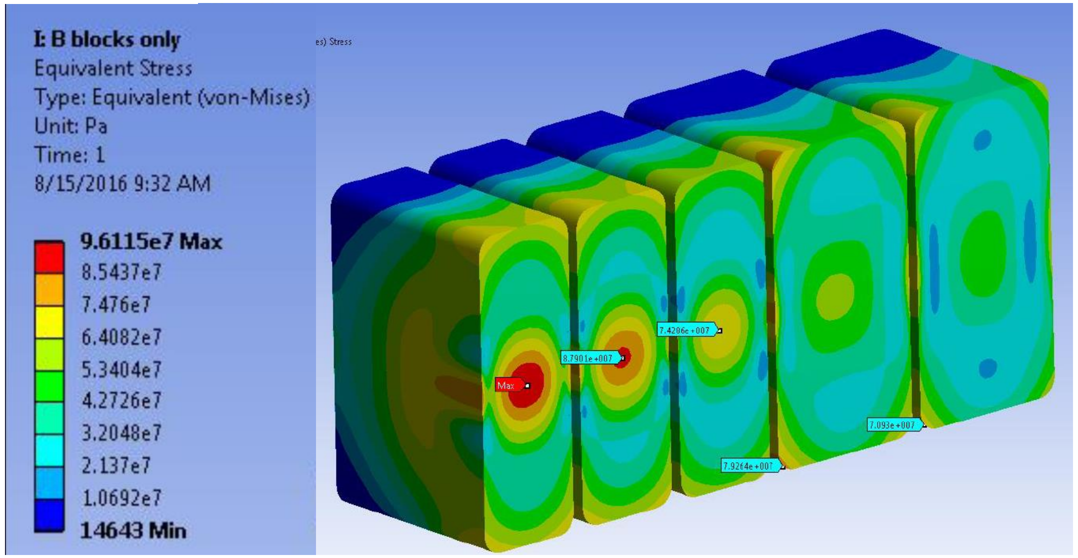


- 0.86 mm tantalum cladding prevents corrosion of tungsten in cooling water
- Achieved by hot isostatic pressing (HIP)
  - Performed by Allied Material Inc.
  - 1500ºC, 200 MPa under 5N Ar

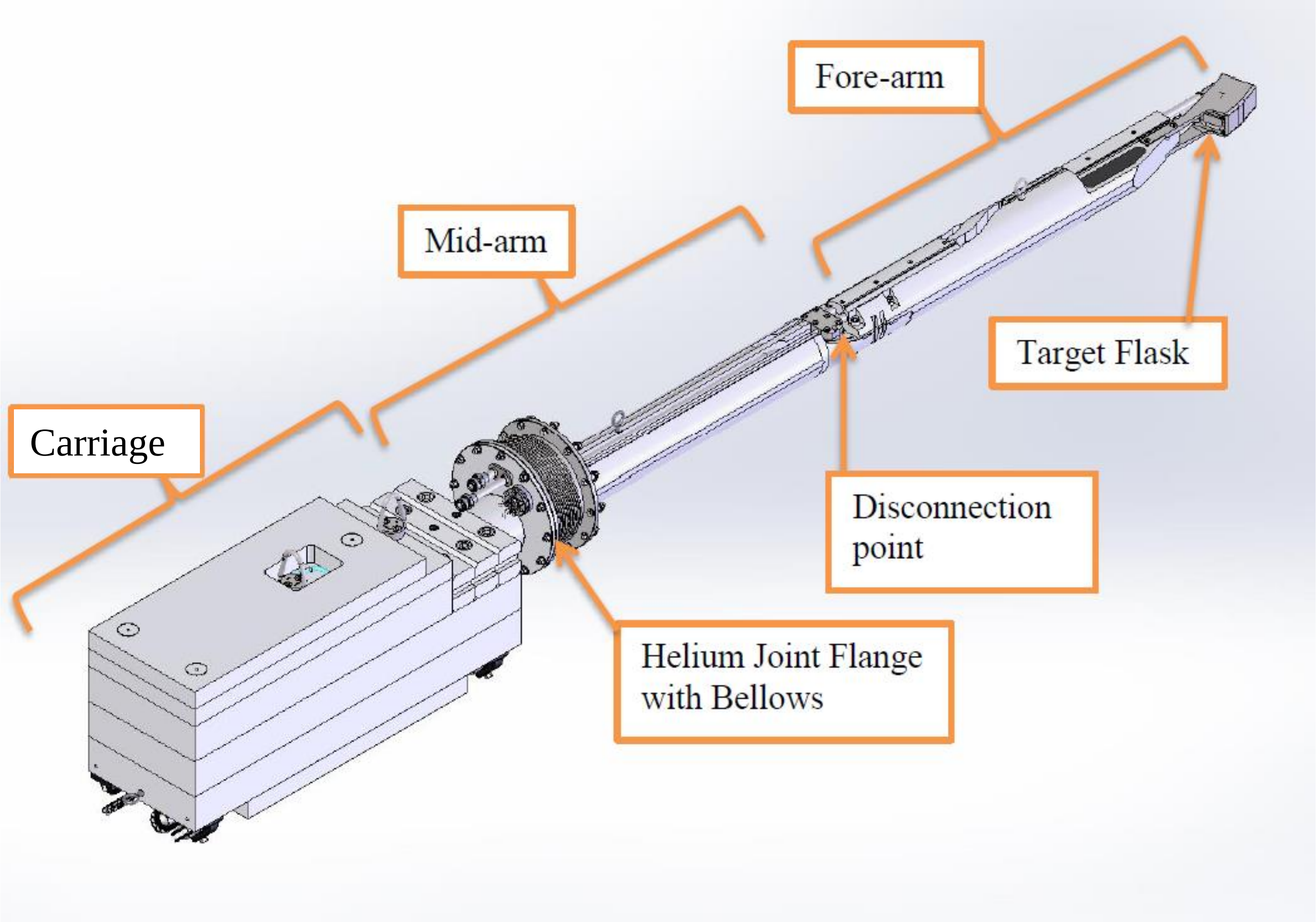
Target Cooling Design

- Target is contained within a stainless steel flask
- Pressurized water (0.483 MPa gauge) circulates inside the flask
- Optimized to minimize stress in target blocks
- Water cooling removes 15 kW of heat with 5 ºC average temperature increase
- Limit target stress to 96 MPa at 158ºC max temperature





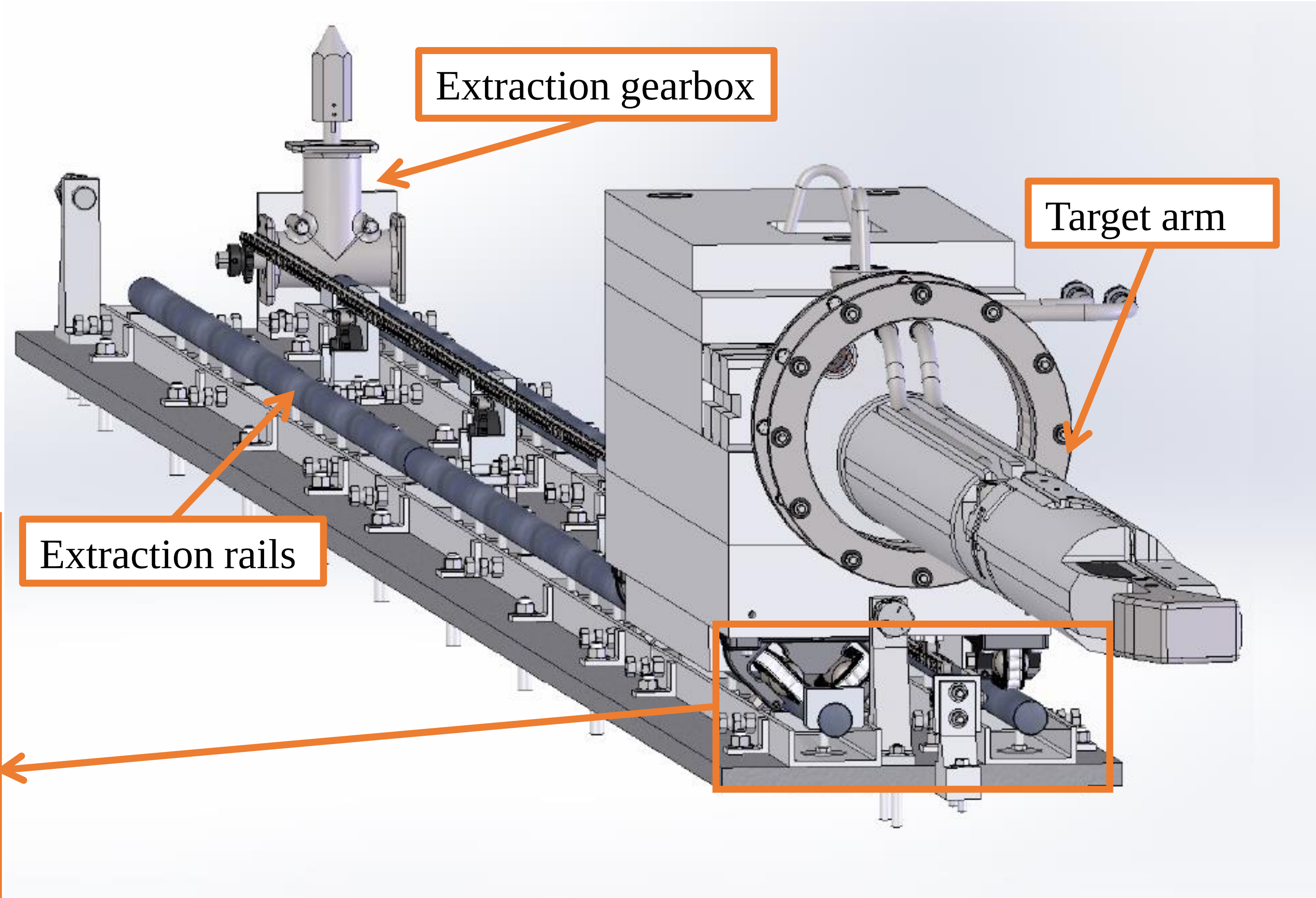
Target Handling: Target Arm

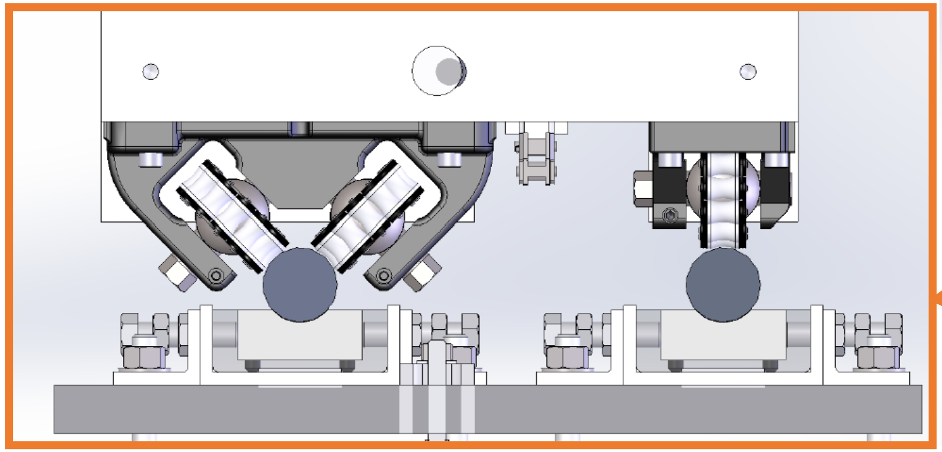


- Necessary to access the target in case of failure or end of life (design life of 10 years)
- Flask is connected to a long cantilevered arm
- Fore-arm can be disconnected for disposal of target
- Carriage provides counterweight and shielding

Target Handling: Extraction System

- Target arm carriage rests on rails
- Chain connects arm to gearbox
- A long rod can be used to drive the gearbox from range, moving the target arm out of the beamline





Target Handling: Storage

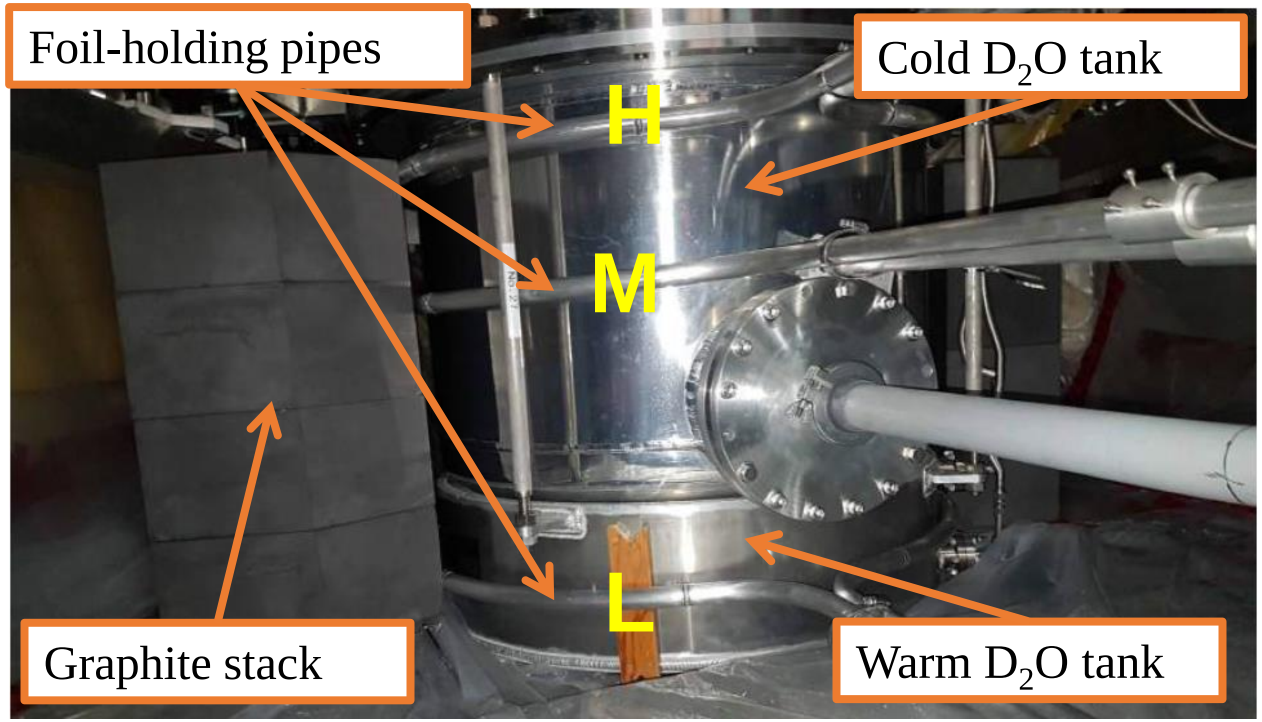
- Once target arm is extracted from beamline, the fore-arm can be inserted into a target cask and disconnected from the rest of the arm for storage

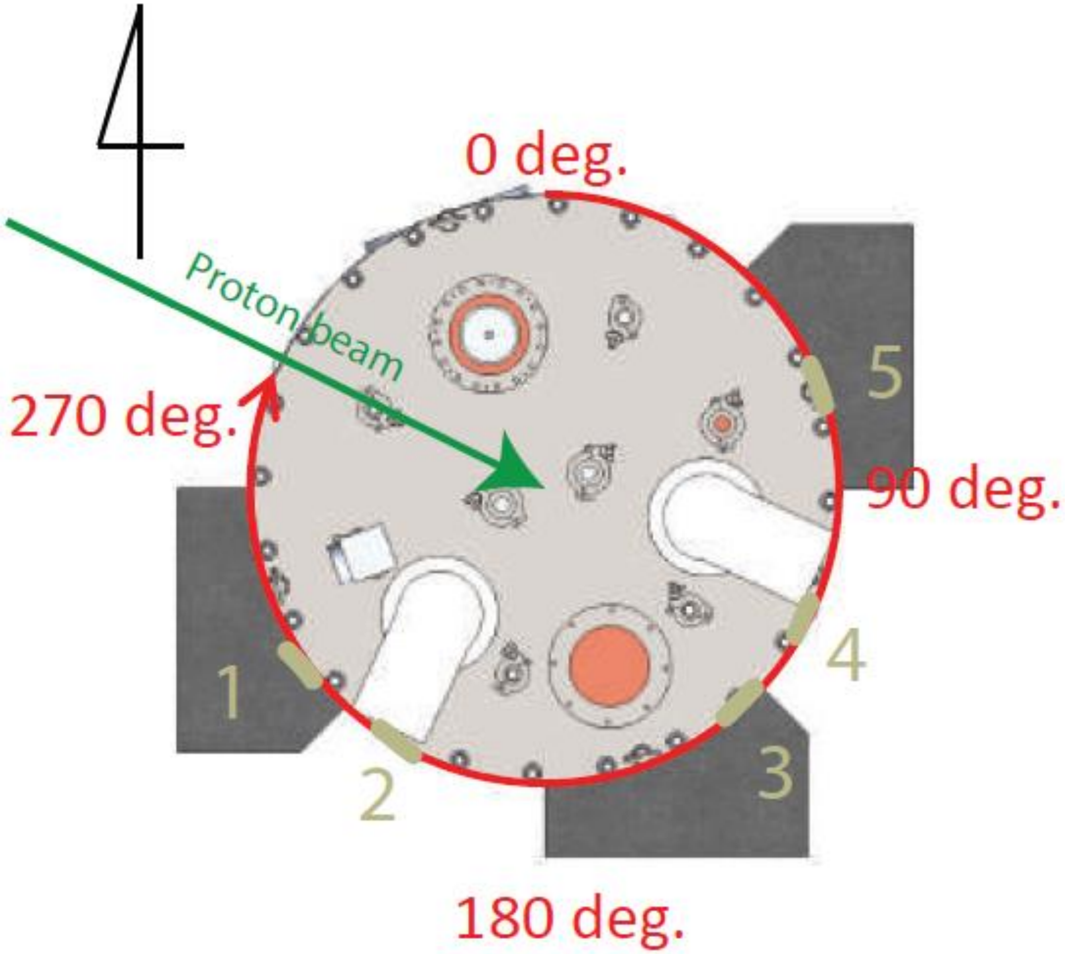
- Target cask provides 15 cm of lead shielding to reduce dose rate from 1 Sv/hr to 50 µSv/h, at a distance of 50 cm, after 10 days of cooling

- Cask was final part of the target system to be built – in 2020

Target Characterization – Gold Foil Activation

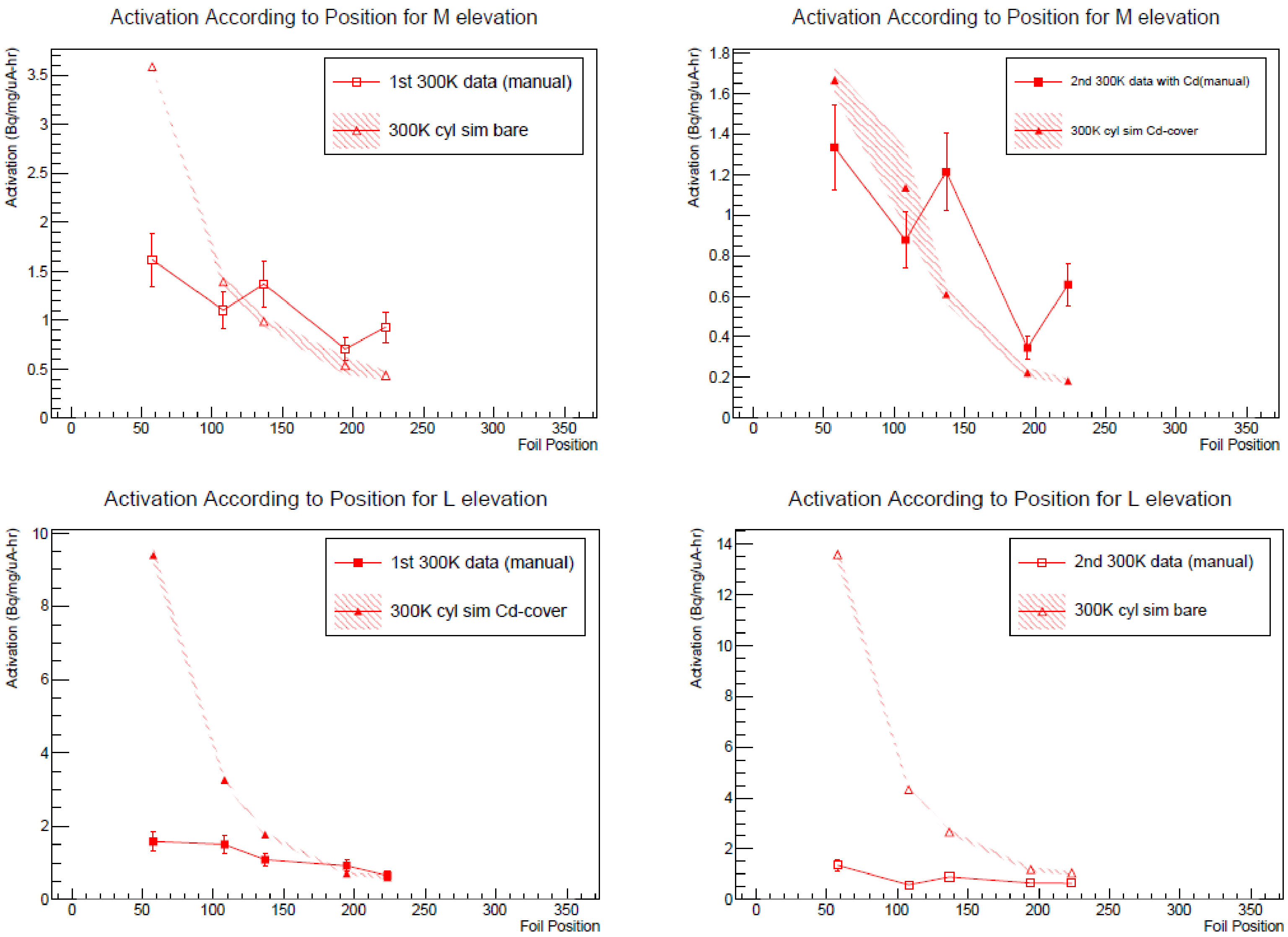
- Attempted measurement of thermal/cold neutron flux using Au foil activation in 2016
- Foils inserted around D_2O tank at 5 positions and 3 heights
- Irradiated and measured using HPGe detector



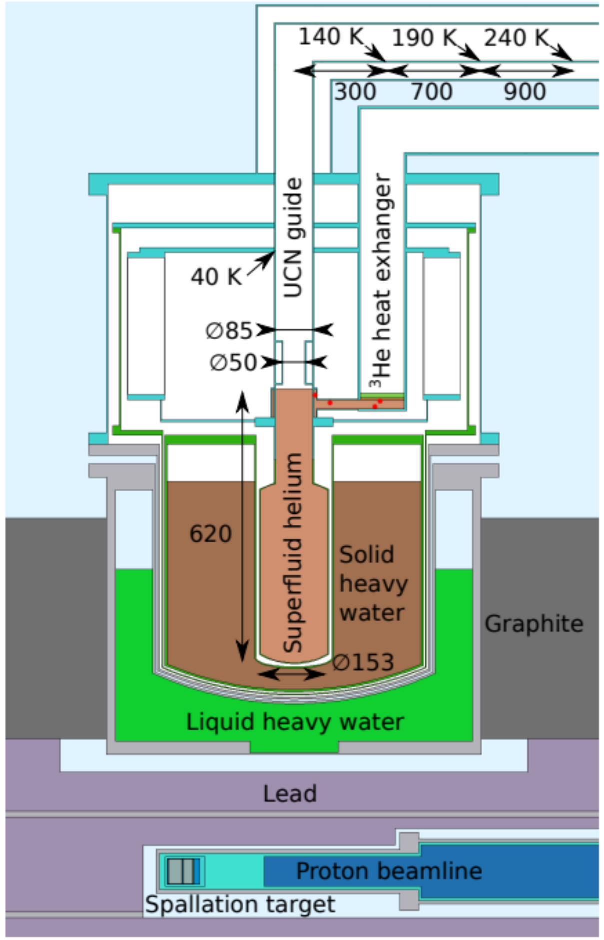


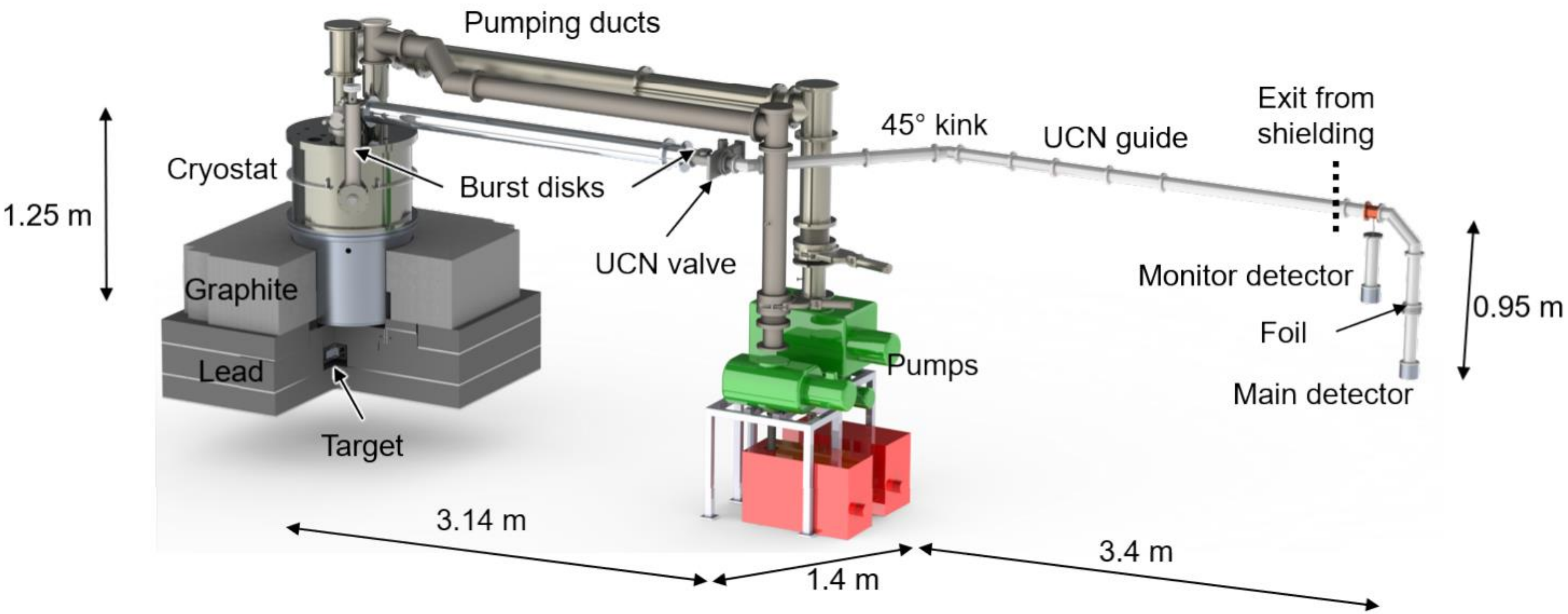
Target Characterization – Gold Foil Activation

- Experiment was compared to MCNPX simulations
- Results were inconsistent
- Suggested that this could be due to
  - Inconsistent tuning/steering of the beam, resulting in beam loss on upstream collimator
  - Poor modelling of the graphite
- We moved away from activation measurements to focus on UCN production



Target Characterization – UCN Production

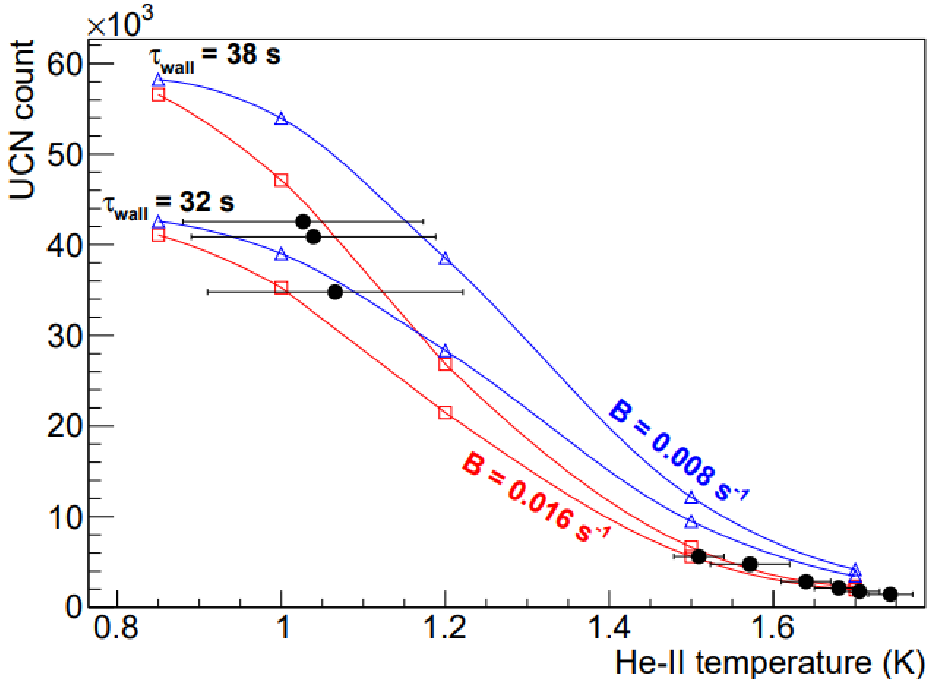


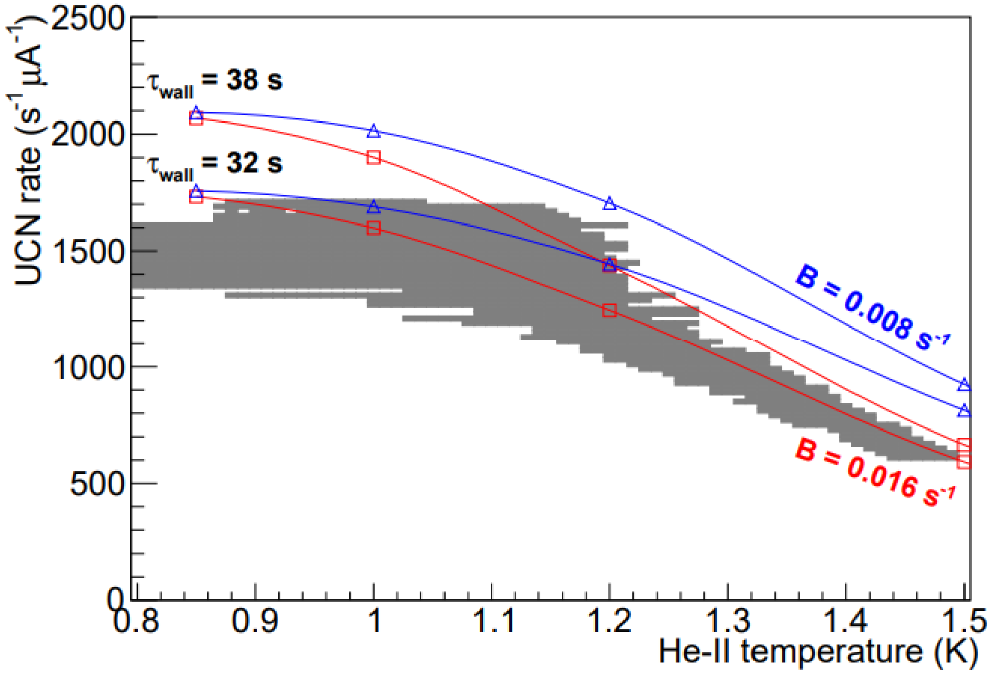


- From 2017-2019 we installed and operated a prototype UCN source
  - Different moderators, smaller He-II volume, different geometry
  - Limited to 1 μA for continuous operation
- Used this source to perform many development experiments with UCN, among which were production experiments to benchmark the source performance (*S. Ahmed, et al., Phys. Rev. C 99, 025503 (2019)*)

Target Characterization – UCN Production

- MCNP6.1 simulation of spallation/moderation + PENTrack simulation of UCN transport out of source to detectors
- Some significant temperature uncertainty was present, but overall we conclude that we have agreement between experiment and simulations
- Estimated production rate of 20600 ± 600 $s^{-1}\mu A^{-1}$
- Results of these experiments feed into our predictions of future source performance





Summary & Outlook

- A new spallation target at TRIUMF will be used for fundamental neutron physics using ultracold neutrons
- Design and installation of all targetry components is complete
- Characterizations of the prototype source indicate that the target works as expected
- Installation of the TUCAN source is underway, expected to be completed late 2023, with commissioning to full beam power to follow

Thank you!