New Science and Applications at the SNS workshop, Oak Ridge National Lab, Jun 10-11, 2026

Possibilities for a Global-Flagship **Ultra-Cold** (and **Very-Cold**) **Neutron Source at the SNS**

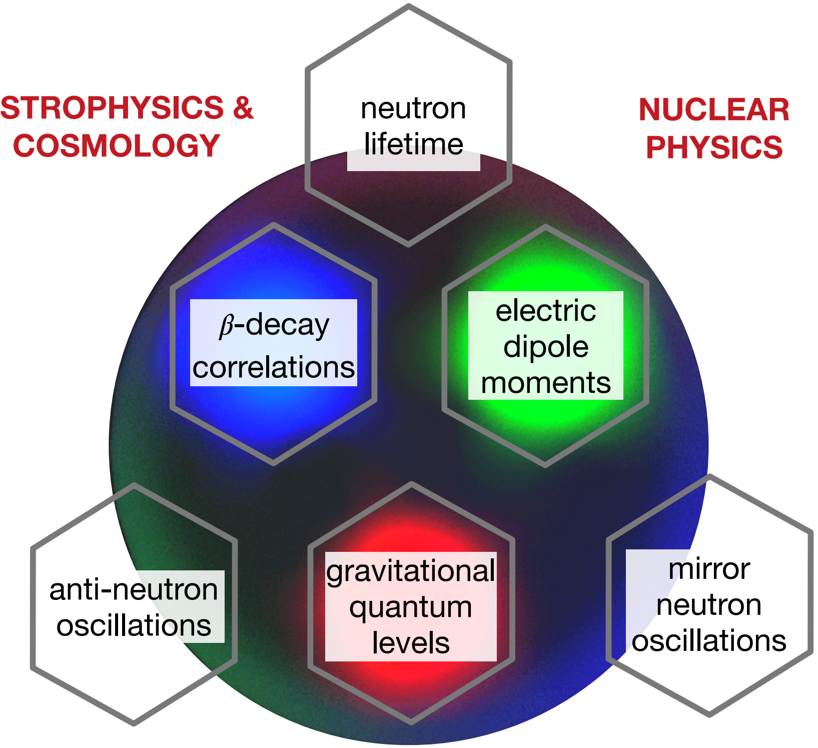
Kent Leung

Physics & Astronomy Department, Montclair State University, NJ (tri-state area)

Fundamental Neutron Physics

- Experimenter chooses between **all four fundamental forces** to study/control neutrons
- "Fundamental" **spin-1/2** baryon; **building block** of nuclei; **sizable magnetic moment**; unaffected by Lorentz force

Common experiments:



ASTROPHYSICS & COSMOLOGY

NUCLEAR PHYSICS

PARTICLE PHYSICS

neutron lifetime

β-decay correlations

electric dipole moments

anti-neutron oscillations

gravitational quantum levels

mirror neutron oscillations

+ condensed matter, surface physics, large molecules (not "fundamental" physics, per say)

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Common experiments:

Ultracold neutron (UCN) experments:

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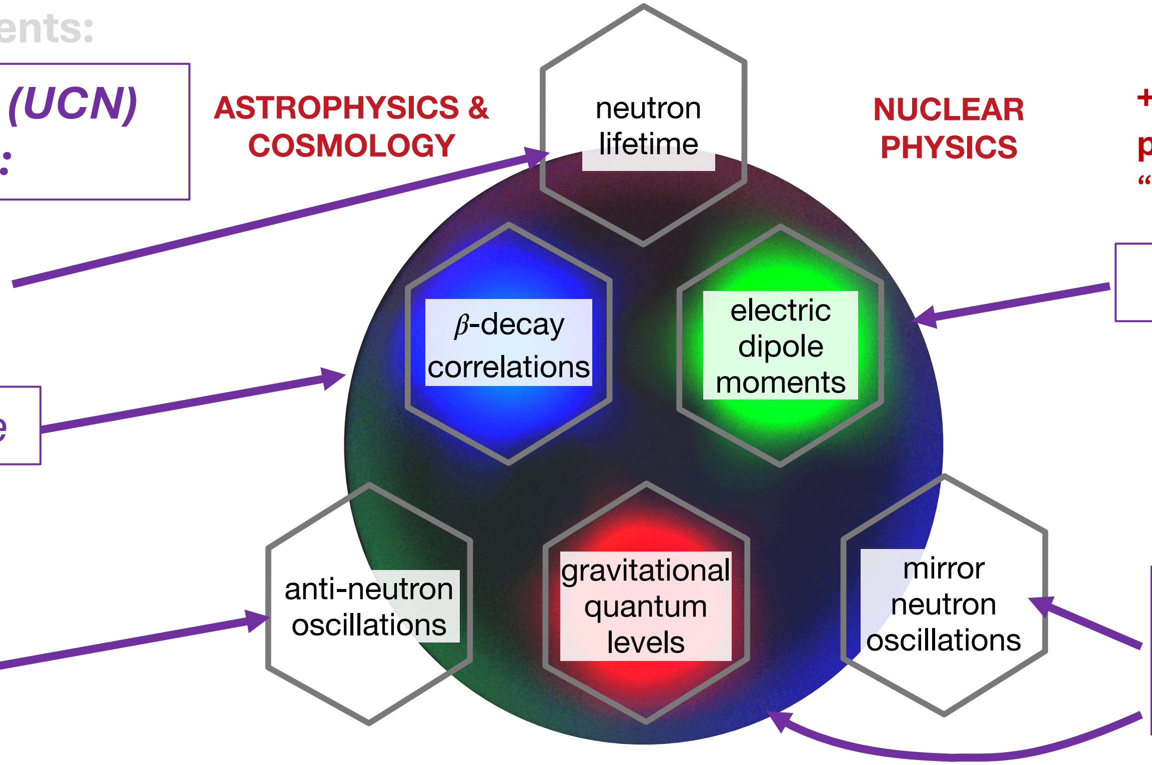

UCNs leads

UCN significantly leads

UCNs competitive

UCNs only

UCN possibilities

(Some experiments already + new theoretical suggestions)

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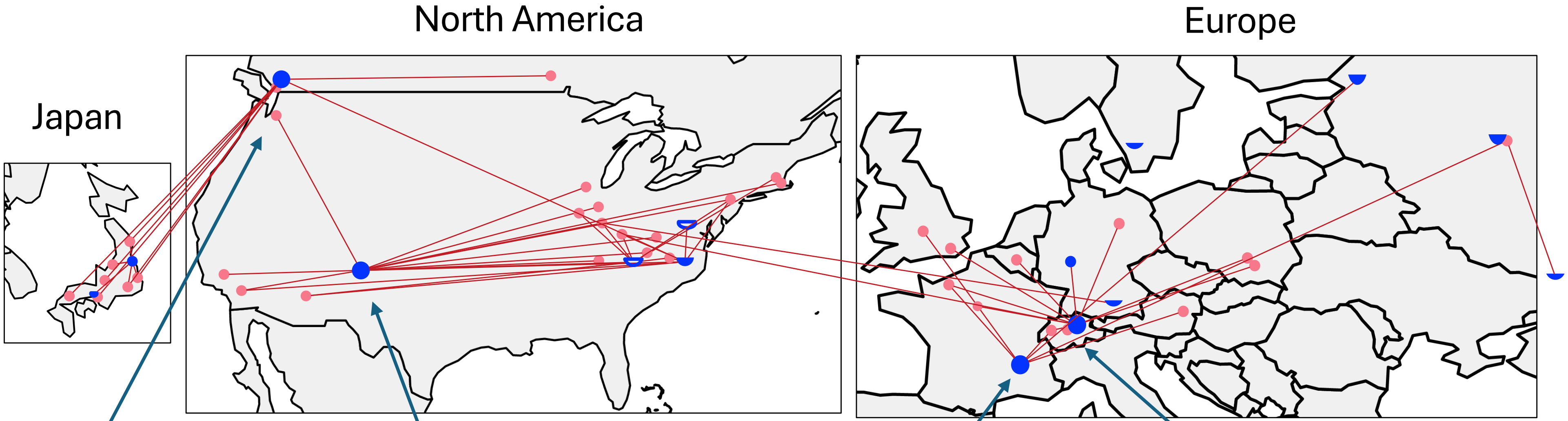
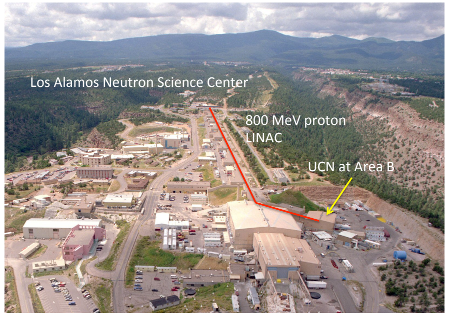
Ultracold Neutron Experimental Landscape

● = **major operating sources: LANL, TRIUMF, ILL and PSI** ● = **collaborators**

● = smaller operating sources: J-PARC, U. Mainz, ◡ = previous/proposed in-situ UCN experiments, ◡ = proposed/under construction

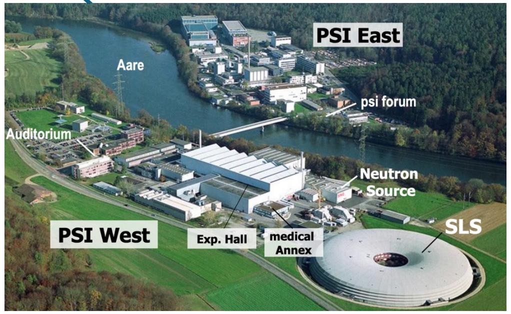


TRIUMF, Canada



LANSCE, LANL, NM

Institut Laue-Langevin, France.



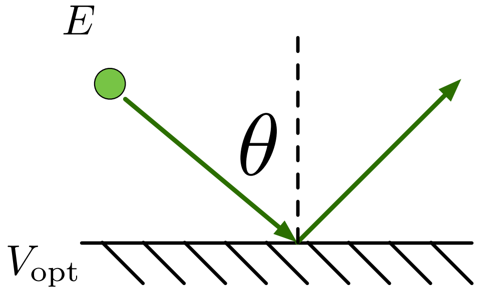
Paul Scherrer Institute, Switzerland

What are ultracold neutrons?

Neutron optical or
“Fermi” potential

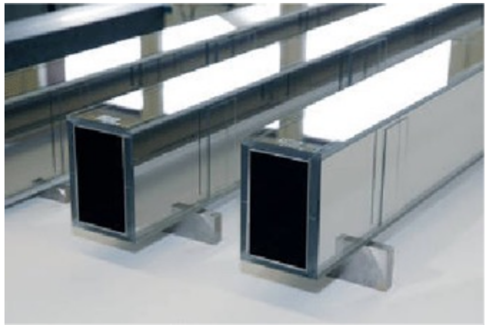
Material	V_{opt}
^{58}Ni	335 neV
Be	252 neV
Fluorocarbons	~100 neV
Al	54 neV
polyethylene	-9 neV
d8-polystyrene	160 neV

Reflection occurs if: $E_{\perp} = E\cos^2\theta \leq V_{\text{opt}}$



(Reflection can be non-specular/diffuse)

Neutron optics



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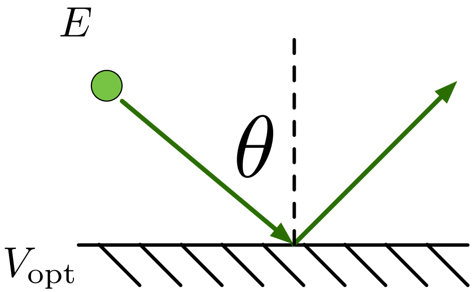

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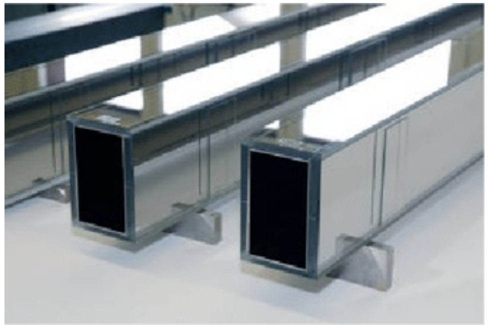
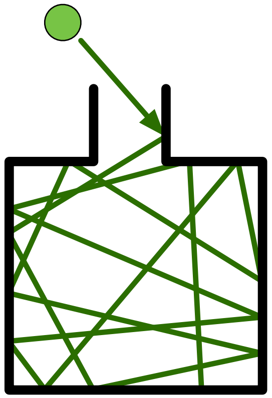


If **energy sufficiently low** (“ultracold”)
→ **optical reflections at all incident angles**
→ **ultracold neutrons** can be **stored in a box**

First idea: Fermi (1946); Published: Zeldovich (1959).

UCN energy, treatment and losses

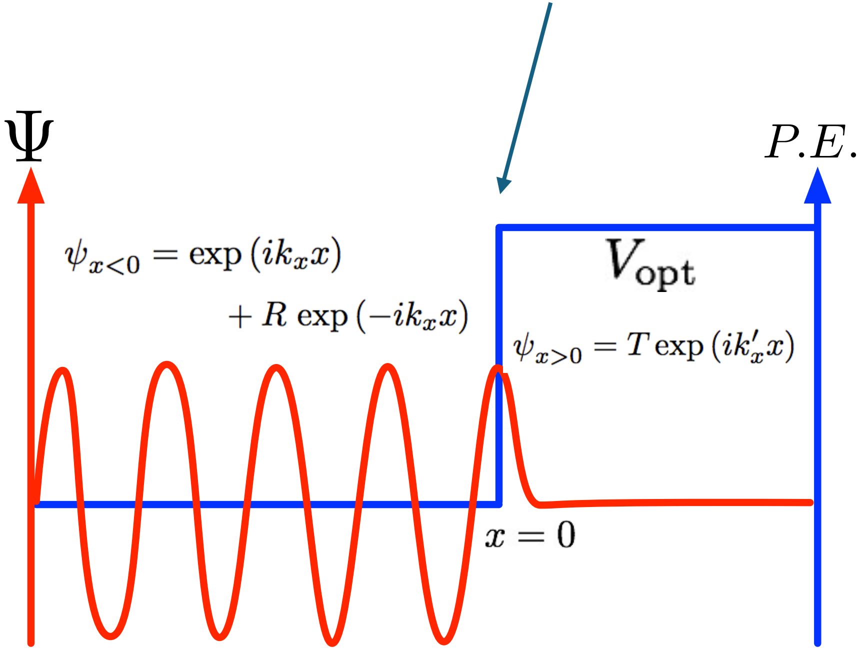


UCNs: E < 300 neV , λ > 60 nm, v < 7 m/s, "temperature" < 2 mK

- "ideal gas" of neutrons but not in thermal equilibrium with material (typically at 300 K)
- Treat UCN reflection as 1D particle incident on a potential barrier
- UCN wavefunction tunnels into barrier so some loss during reflections. Losses treated as imaginary part of optical potential:

$$U_{\mathrm{opt}} = V_{\mathrm{opt}} + iW$$

$$W = \frac{\hbar}{2}\sum_i n_i \sigma_{\mathrm{loss}}(v)v$$



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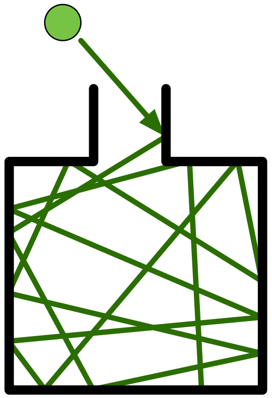

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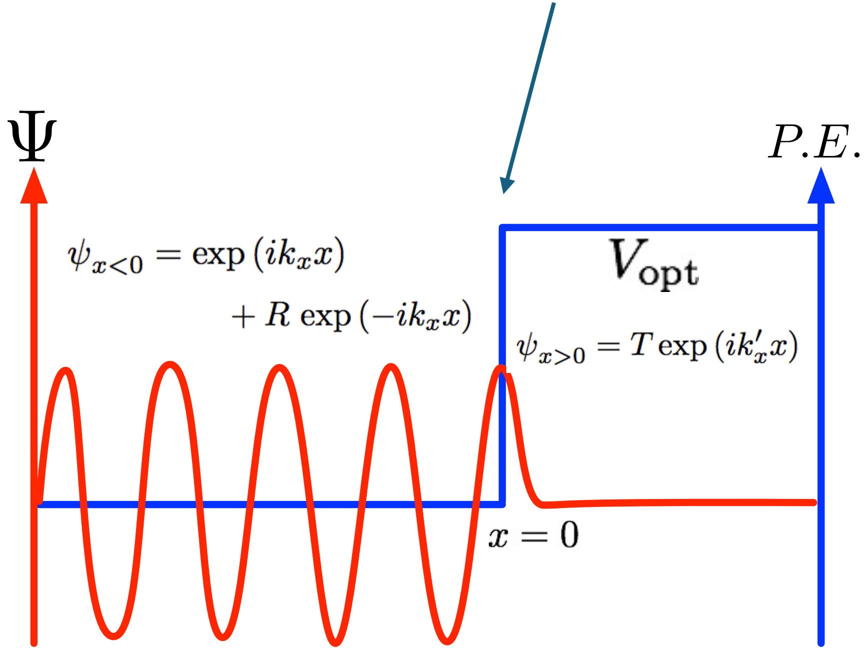
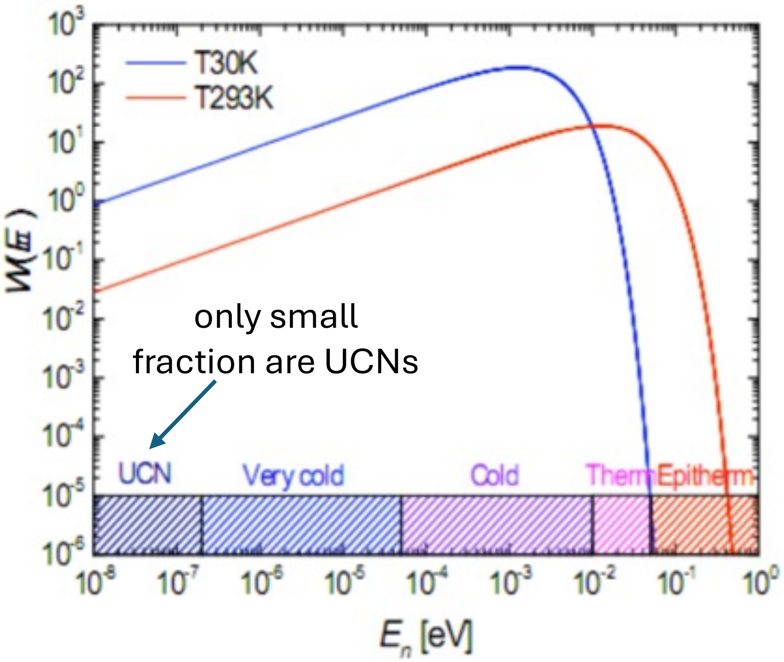


Loss mechanisms

- ○ nuclear capture
- ○ **up-scattering off excitations** (e.g. phonons) in material to above UCN energy
- ○ **Typically 10^{-4} loss probability per reflection** ⇒ store UCNs with time constant $\tau_{\text{tot}} \lesssim 600$ s depending on size of bottle
- ○ Can use loss rate to understand detailed properties of surfaces also (surface/condensed matter)

Producing UCNs: the limits of moderation

- **Fast neutrons (~MeV)** moderated in a material by scattering off protons and deuterons
- Neutrons come to **thermal equilibrium** in material & follow **Maxwell-Boltzmann distribution**:

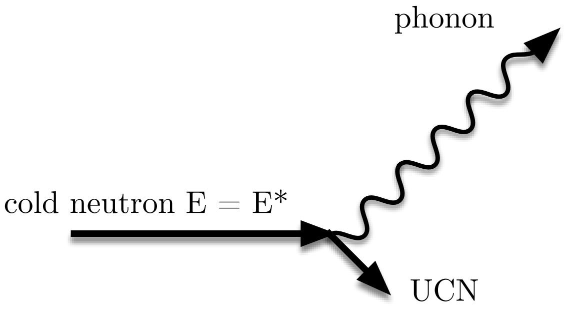


only small fraction are UCNs

- With moderation, UCN density ρ_{UCN} scales as ~ $T^{-3/2}$
- The estimated ρ_{UCN} inside LD_2 cold moderators at most powerful neutron sources ~ 1000 UCN/cm^3
- Can't increase density further with conservative potentials due to **Liouville's theorem on phase space density**. And then there are **UCN transport losses to an experiment.**
- ILL's PF2 extracts out of cold moderator to experiment achieves **~ 50 UCN/cm^3**

“Super-thermal” production of UCNs

- **Scattering off phonons** to **convert cold neutrons to UCN energy range**.
  Phonons pumped away by refrigerator. [Golub & Pendlebury, Physics Letters A (1977)]
- Two competing materials: **superfluid ^{4}He** (He-II) and **solid deuterium** (SD_2)



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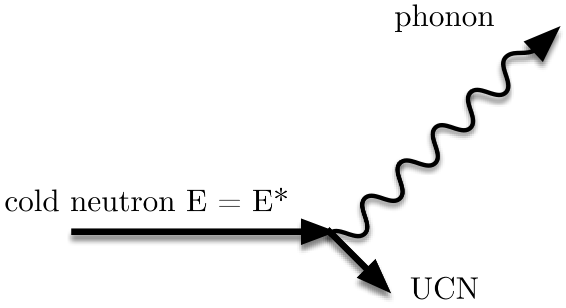

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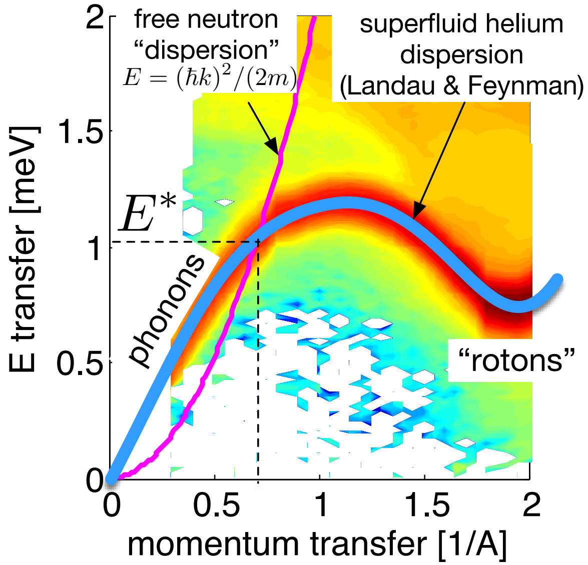
from [Andersen et al. J. Phys. Condens. Matter (1994)]



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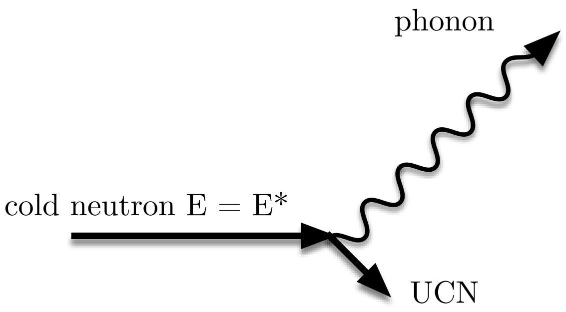

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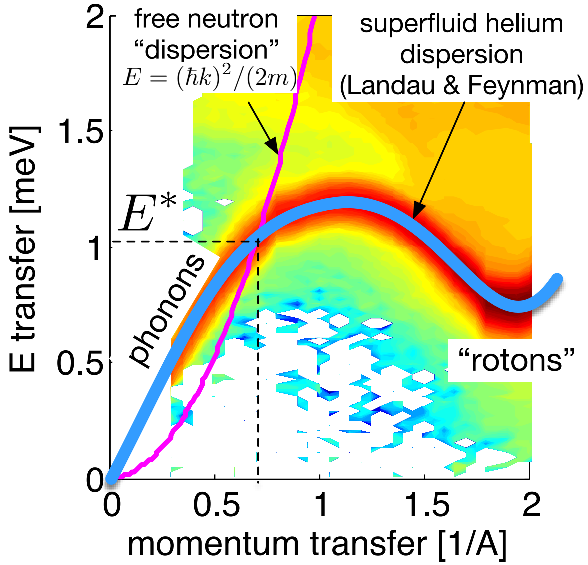
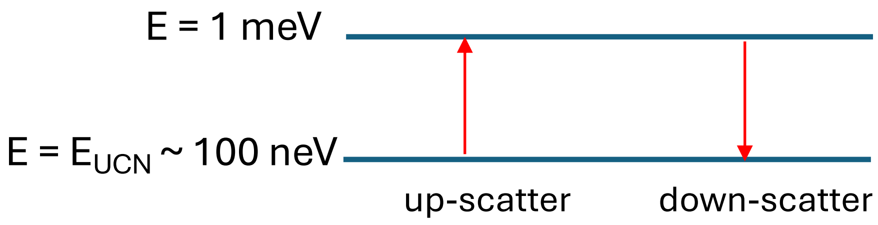


1 meV (9Å) CN & UCN state form a two level system:



In equilibrium the two processes linked by detailed balance:

$$\sigma(E_{UCN} \rightarrow E_{UCN} + E^*) = \frac{E_{UCN} + E^*}{E_{UCN}} e^{-E^*/k_B T} \sigma(E_{UCN} + E^* \rightarrow E_{UCN})$$

up-scattering

suppressed by Boltzmann factor (i.e. exponential)

down-scattering (~ constant)

- For **T = 0.5K, up-scattering time constant ≈ 2 hours**. Neutron absorption by ^{4}He is zero.
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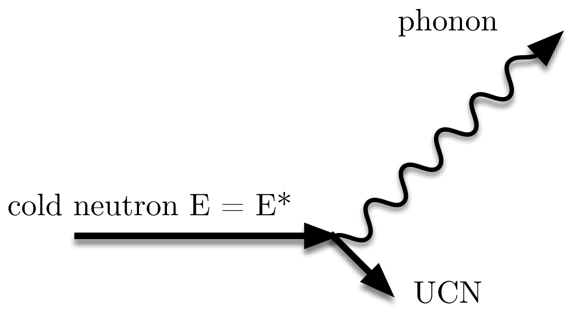
“Super-thermal” production of UCNs



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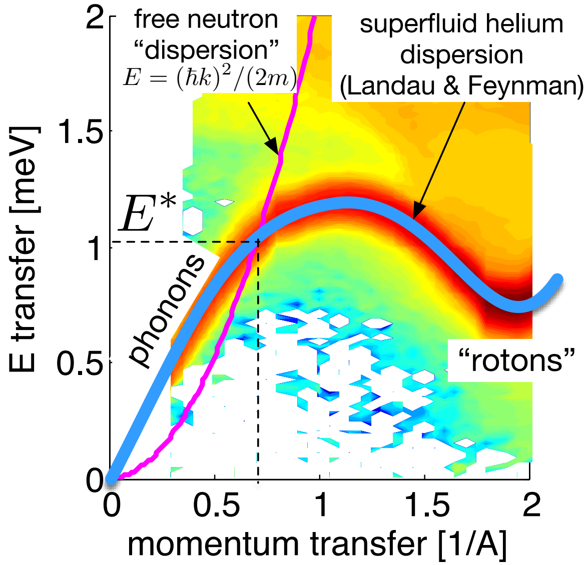

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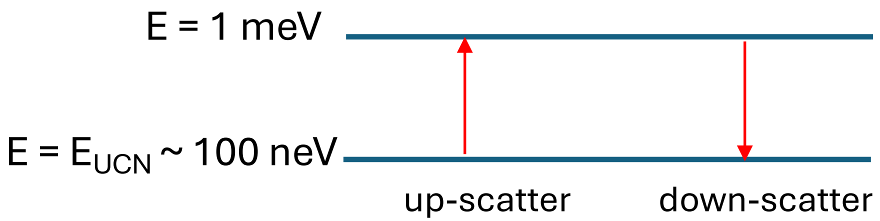

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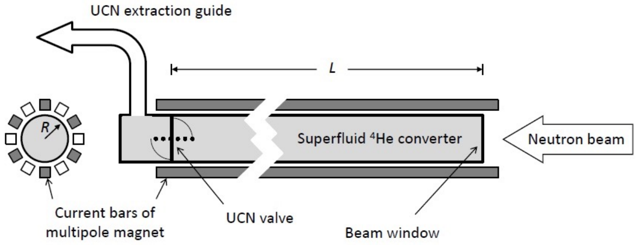
- For **T = 0.5K, up-scattering time constant ≈ 2 hours**. Neutron absorption by ^{4}He is zero.
- “Super-thermal” because UCNs are not in equilibrium with He-II converter
- **SD_2 has larger production cross-section (many phonon modes), only requires cooling to ~ 6 K, but up-scattering time ~50 ms**

UCN density or current source

Density [UCN/cm^3]

Current [UCN/s]
(or “integrated flux”)



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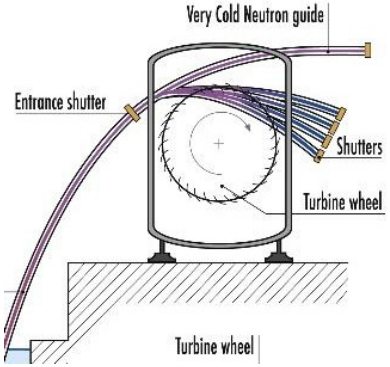
ILL’s PF2 Doppler turbine (~10 UCN/cm^3 @ experiment).



PF2 is also a great VCN source…

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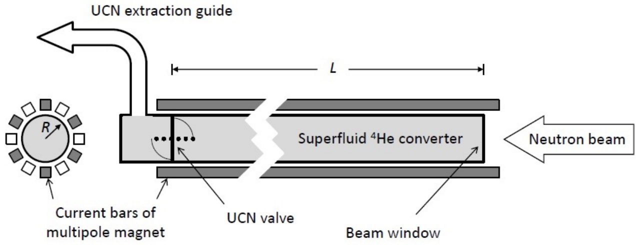

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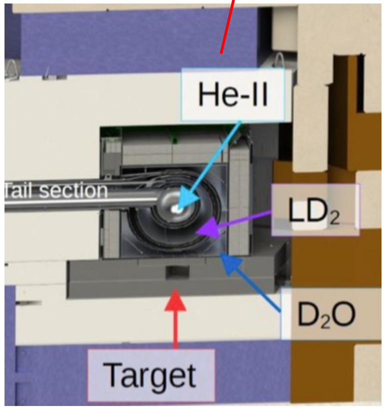
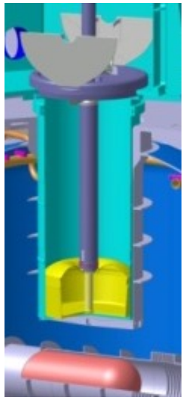


PNPI in-pile 4He (~1.3 K)

PSI sD2 (**demonstrated ~ 50 UCN/cm³** @ nEDM experiment)



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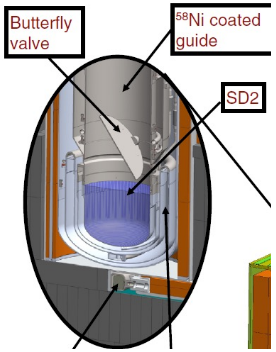

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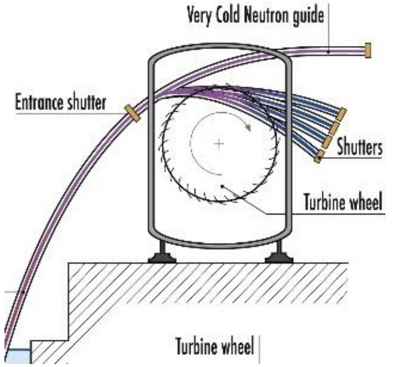

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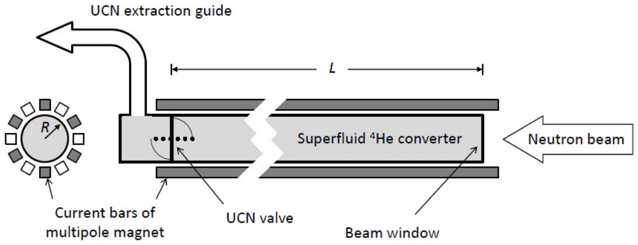

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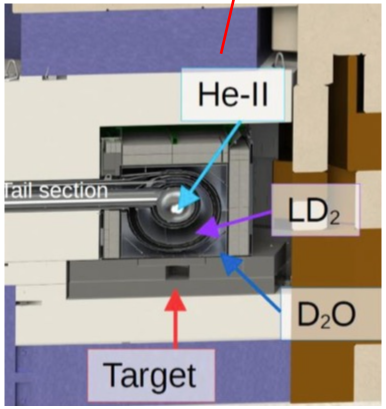

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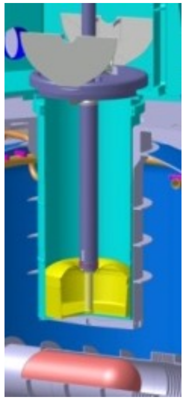

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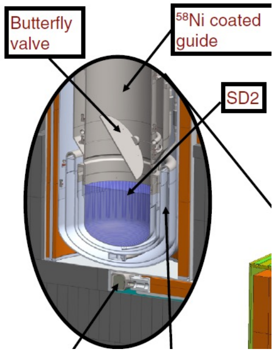

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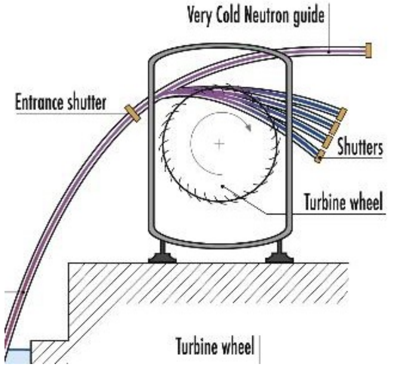


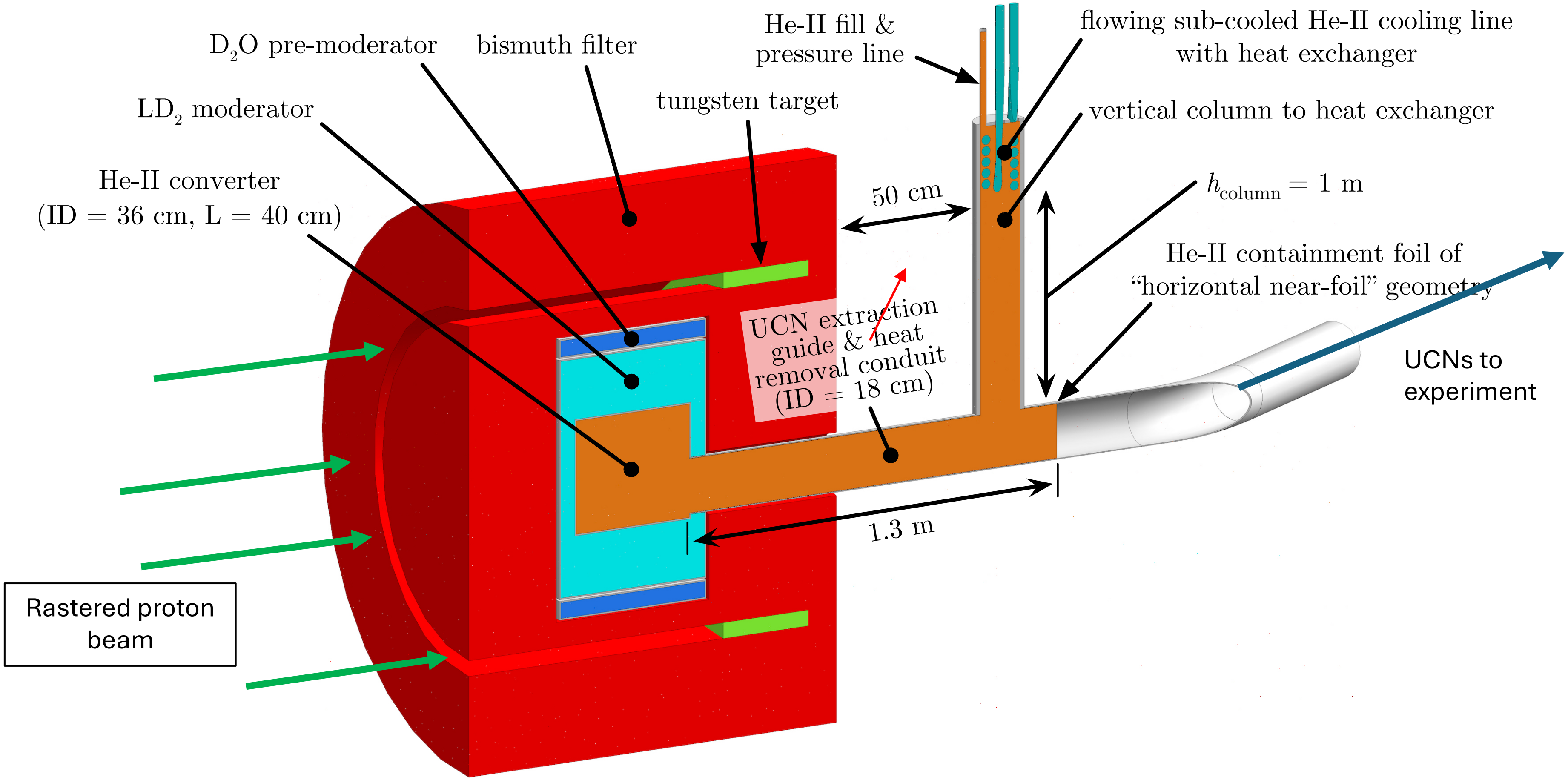
PF2 is also a great VCN source...

What about a **He-II current-optimized** UCN source?!

A next-generation inverse-geometry spallation-driven UCN source

J. Appl. Phys. **126**, 224901 (2019); https://doi.org/10.1063/1.5109879

K.K.H. Leung, C. Muhrer, T. Hügle, T.M. Ito, E.M. Lutz, M. Makela, C.L. Morris, R.W. Pattie, A. Saunders, & A.R. Young



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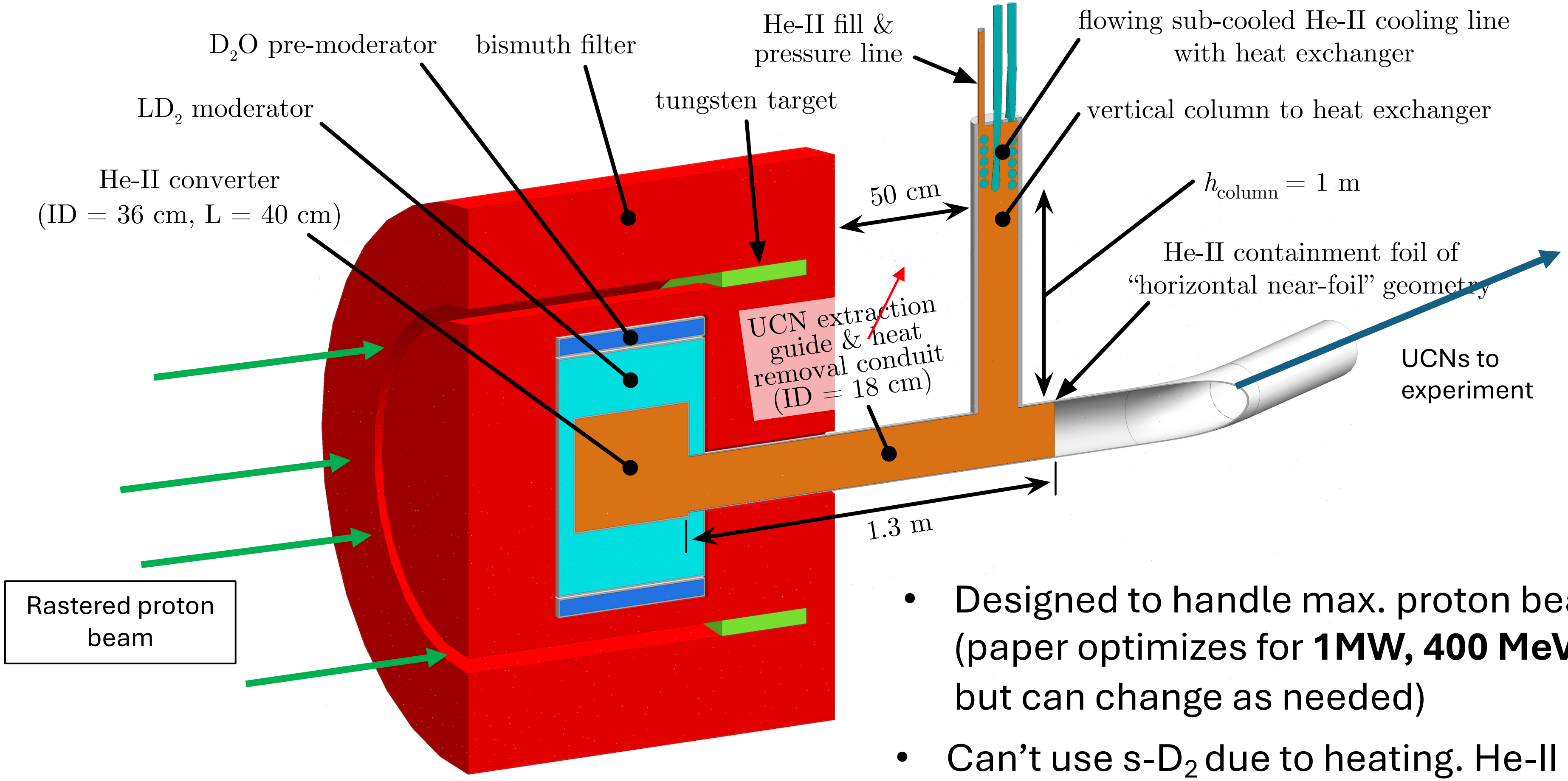
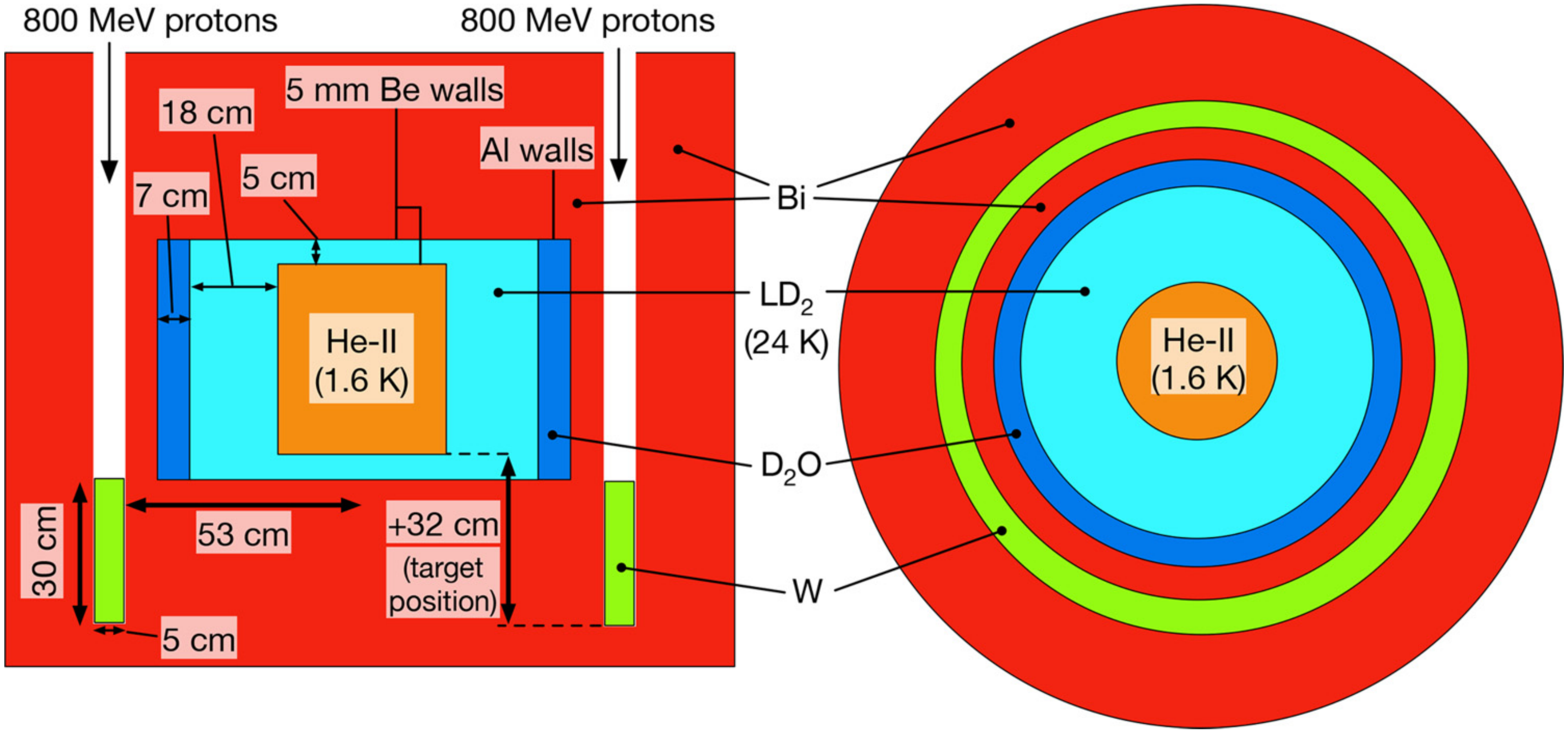


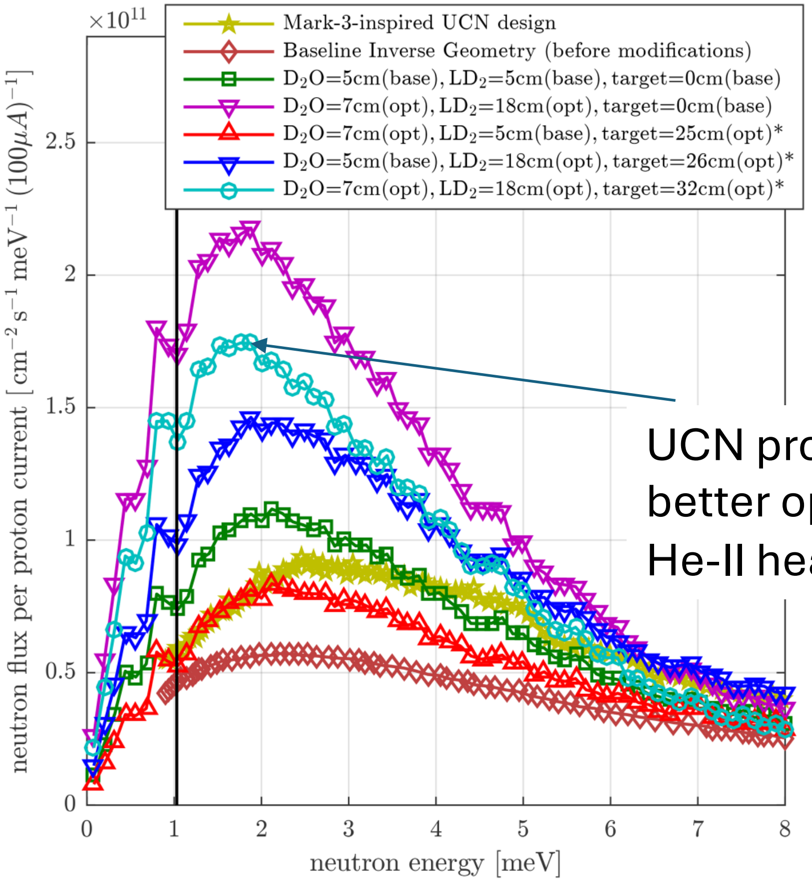
- Designed to handle max. proton beam powers (paper optimizes for **1MW, 400 MeV protons** but can change as needed)
- Can't use s-D_2 due to heating. He-II is a (near) perfect thermal conductor
- Leverage "recent" (~ 20 years) **"off-the-shelf" sub-cooled helium technology**

Maximizing flux of 8.9Å / 1 meV neutrons

- Raster proton beam with kicker magnets to distribute heat in tungsten target => water cooling
- MCNP calculations bench-marked with Los Alamos' Lujan Center Mark-3 target
- Place **40-L volume of superfluid ^{4}He** *inside* the target, pre-moderator, and moderator in "inverse geometry"
- Optimized D2O pre-moderator thickness, LD_2 moderator thickness, and "target location"

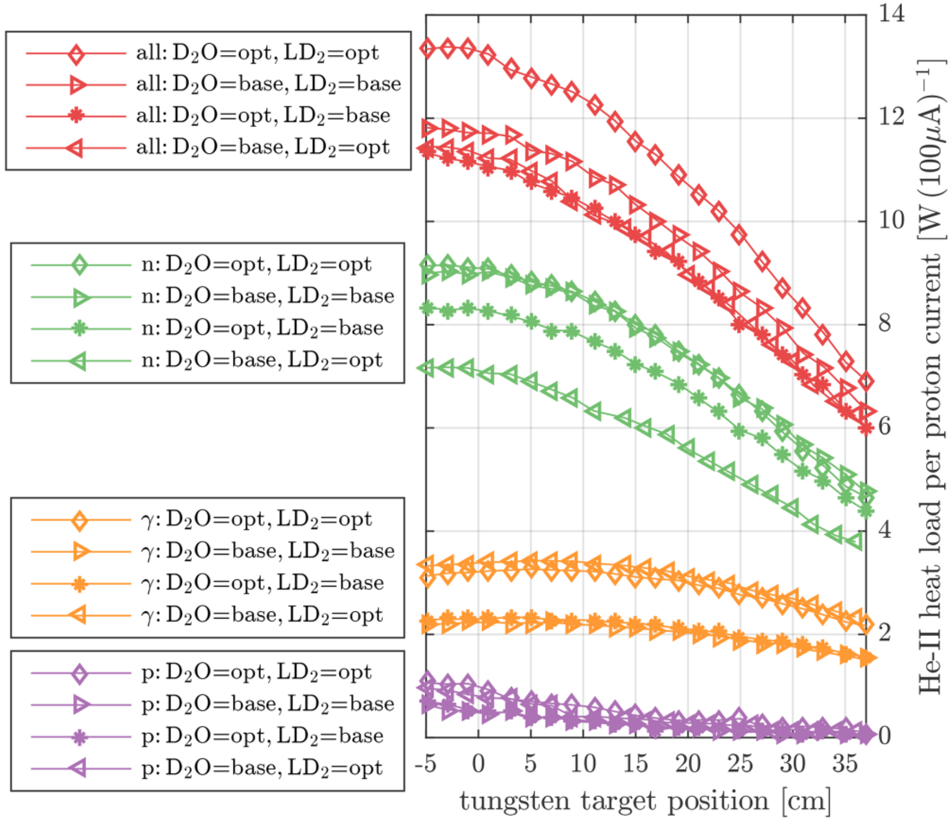


Cold neutron spectrum in He-II volume per 80 kW protons



UCN production better optimized per He-II heat load

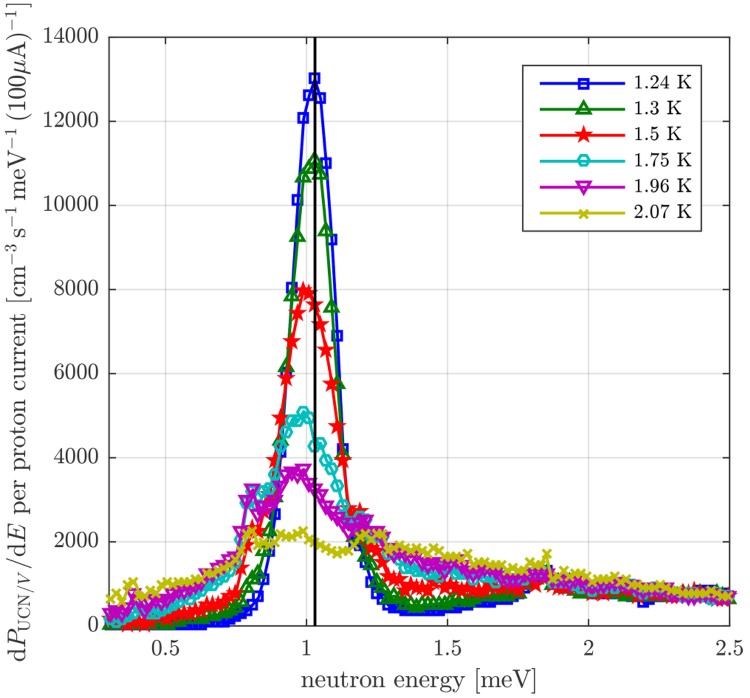
He-II heat load per 80 kW protons:



The neutron heating dominated by > 80 meV (epithermal to fast)

*legend are the D2O premoderator and LD2 moderator thicknesses at their ”base” and “optimized” values

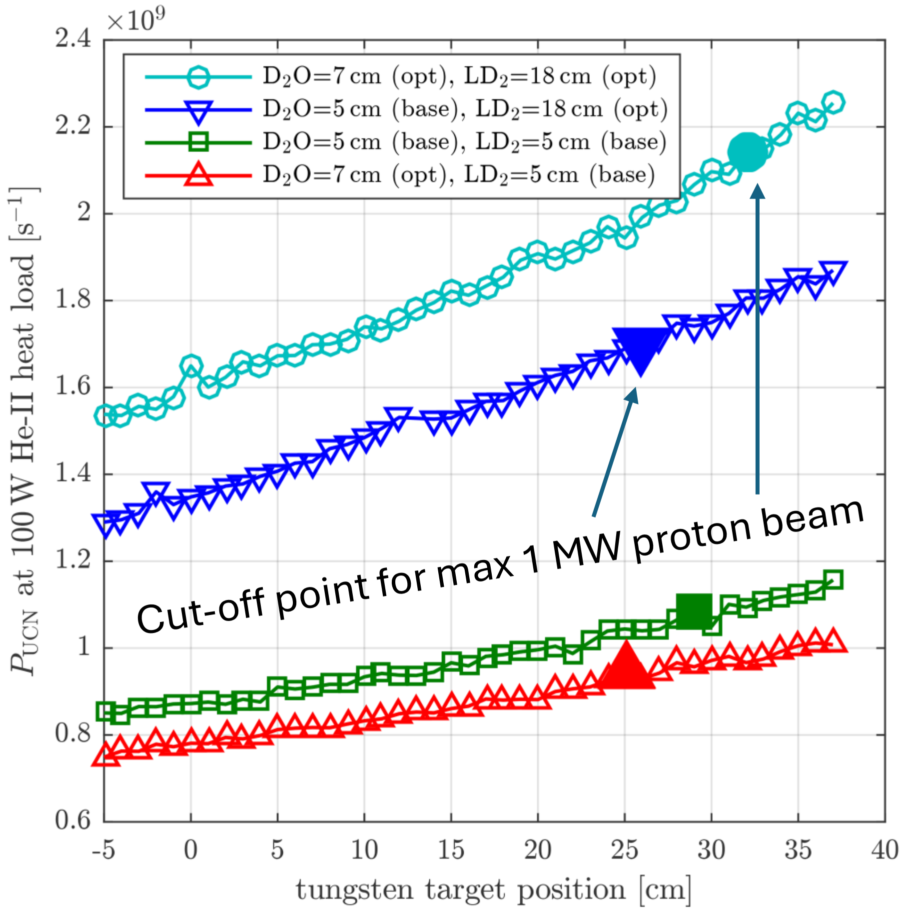
The CN-energy-differential UCN production rate (i.e. with multi-phonon UCN production)



^{58}Ni (335 neV) minus SF4He (18.5 neV) E_{ucn} cut-off energy

Thanks to Ken Andersen's data from 1994.

The total UCN production rate



Cut-off point for max 1 MW proton beam

- The total **UCN production rate** for **100 W of heat in the SF-4He** above is 2.1E9 UCN/s.
- Include some additional losses* of 15% and get **<u>1.8 x 10^9 UCN/s</u>**

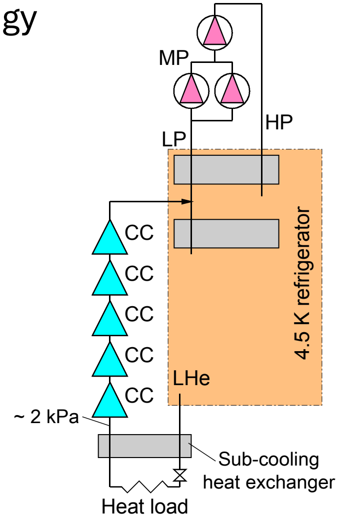
(*1 bar pressurized He-II to suppress bubble formation + lack of He-II kernel in MCNP)

Sub-cooled ^{4}He technology

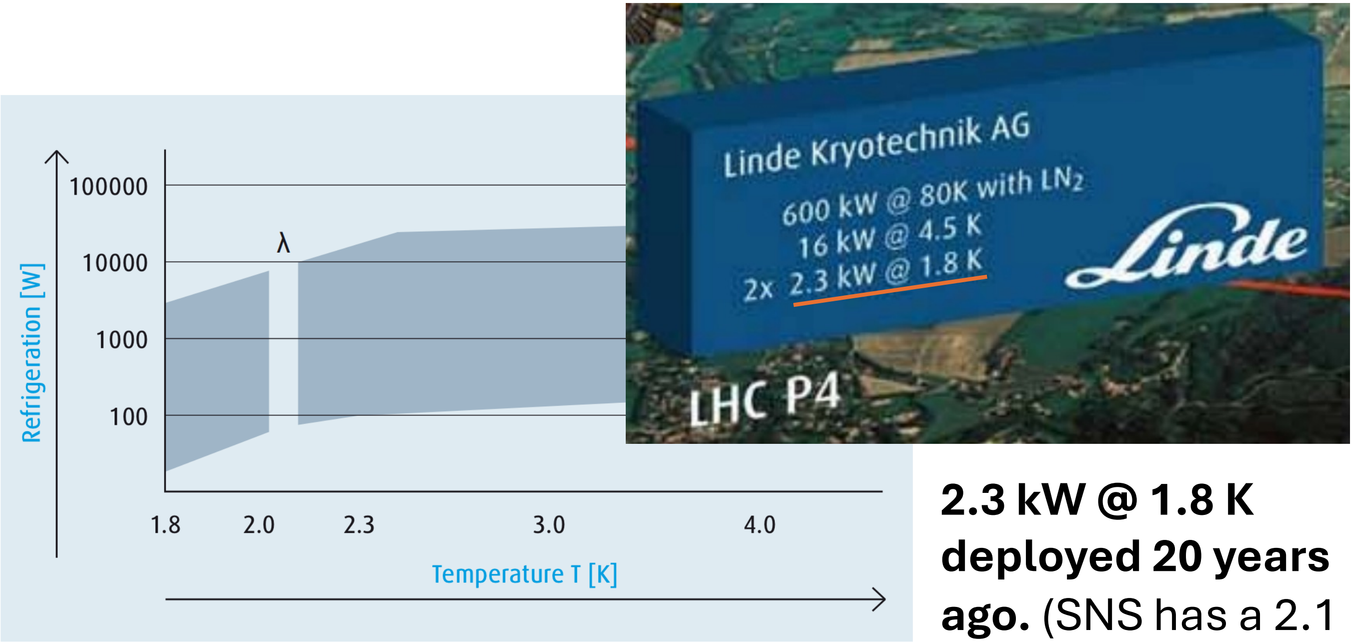
Superfluid helium refrigeration system

Used at Jefferson Lab, CERN, Fermilab, ESS, etc. for cryogenic superconducting cavities & magnets

Key enabling technology are cold compressors



“Cold” Compression

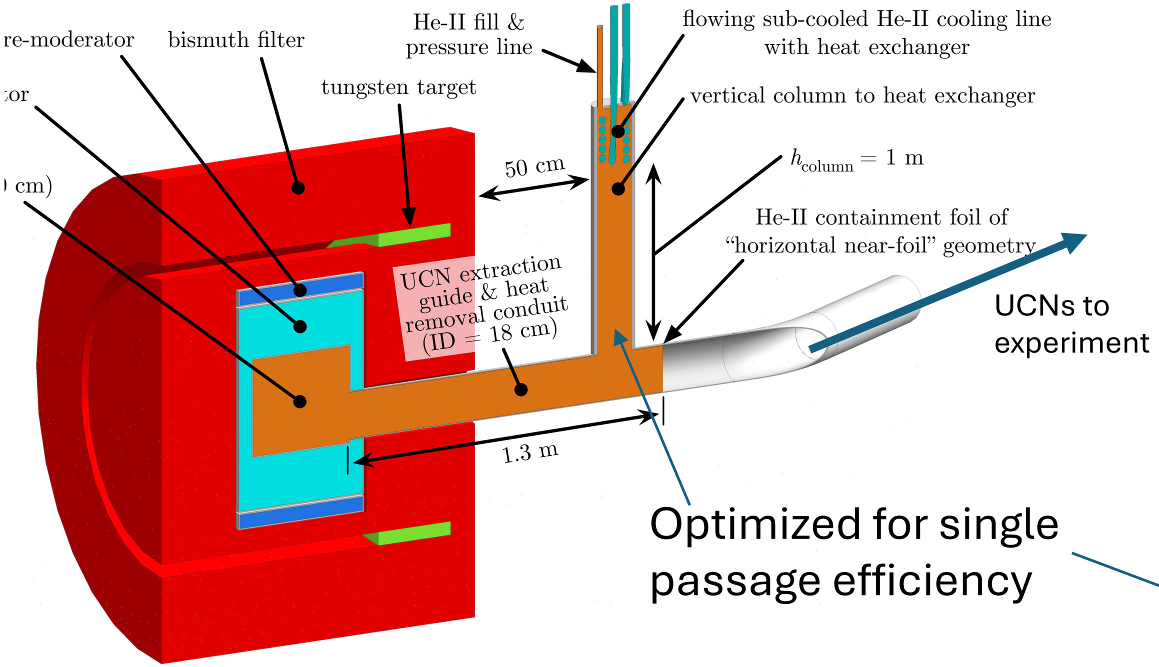


2.3 kW @ 1.8 K deployed 20 years ago. (SNS has a 2.1 K system)

- Generally, ~ 1.8 K lowest temp. Requires 4 cold compressors in series. Up to 3 kW of cooling!
- To reach to 1.6K need to go from 4 to 5 cold compression stages, which requires some R&D, which can be off-loaded to external company.
- Note: CERN’s Future Circular Collide also requires 1.6 K with kW cooling (we require only 100 W!).

Single-passage UCN extraction efficiency

- 18 cm Ø UCN extraction guide allows 100 W heat extraction to produce ΔT < 50 mK. (Our heat flux falls in the Gorter-Mellink regime, mutual friction between normal and superfluid components)
- Tee to heat exchanger. UCNs that reach heat exchanger assumed to be 100% loss (pessimistic)
- Add non-specular reflections in some places to extract UCNs faster
- He-II contained with polypropylene foil supported by a grid (transmission through foil ~ 68%).
- f-factor = W/U of UCN guides assumed to be 5E-4. 3% Lambertian diffuse. The up-scattering in He-II loss is ~55% of total.



Optimized for single passage efficiency

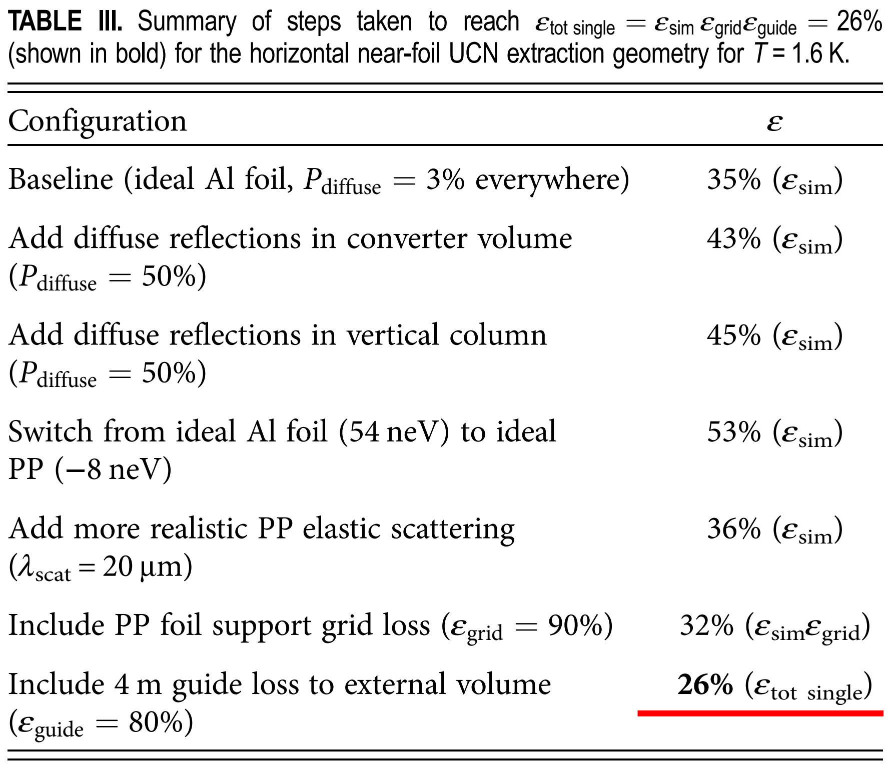


TABLE III. Summary of steps taken to reach $\varepsilon_{\text{tot single}} = \varepsilon_{\text{sim}}\,\varepsilon_{\text{grid}}\varepsilon_{\text{guide}} = 26\%$ (shown in bold) for the horizontal near-foil UCN extraction geometry for $T = 1.6$ K.

Configuration	ε
Baseline (ideal Al foil, $P_{\text{diffuse}} = 3\%$ everywhere)	35% (ε_{sim})
Add diffuse reflections in converter volume ($P_{\text{diffuse}} = 50\%$)	43% (ε_{sim})
Add diffuse reflections in vertical column ($P_{\text{diffuse}} = 50\%$)	45% (ε_{sim})
Switch from ideal Al foil (54 neV) to ideal PP (−8 neV)	53% (ε_{sim})
Add more realistic PP elastic scattering ($\lambda_{\text{scat}} = 20\ \mu$m)	36% (ε_{sim})
Include PP foil support grid loss ($\varepsilon_{\text{grid}} = 90\%$)	32% ($\varepsilon_{\text{sim}}\varepsilon_{\text{grid}}$)
Include 4 m guide loss to external volume ($\varepsilon_{\text{guide}} = 80\%$)	**26%** ($\varepsilon_{\text{tot single}}$)

UCN current out of source

- For our **1.8 x 10^9 UCN/s total production rate**. At the end of an 18 cm diameter guide 4 m away from the source (e.g. outside biological shielding) the UCN current becomes **5 x 10^8 UCN/s.**

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- If the 5 x 10^8 UCN/s current is used to fill an external "bottle" **assuming the (pessimistic) no return approximation:**

V_{bottle} (l)	5	50	500	5×10^3	5×10^4
ρ_{bottle} ($\times 10^4$ UCN cm^{-3})	1.12	1.11	1.05	0.80	0.31
τ_{bottle} (s)	0.11	1.1	10	80	315

UCN density loaded into external experimental volume

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UCN density loaded into external experimental volume

- Our high-current UCN source is ideal for filling experiments with **large volumes or experiments that require a high flow-through rate of UCNs**
- High-current UCN sources are also ideal for producing a high current of **Very Cold Neutrons** (VCNs). (Need more simulations, rough estimate ~ 10^2 higher than current strongest VCN beam)

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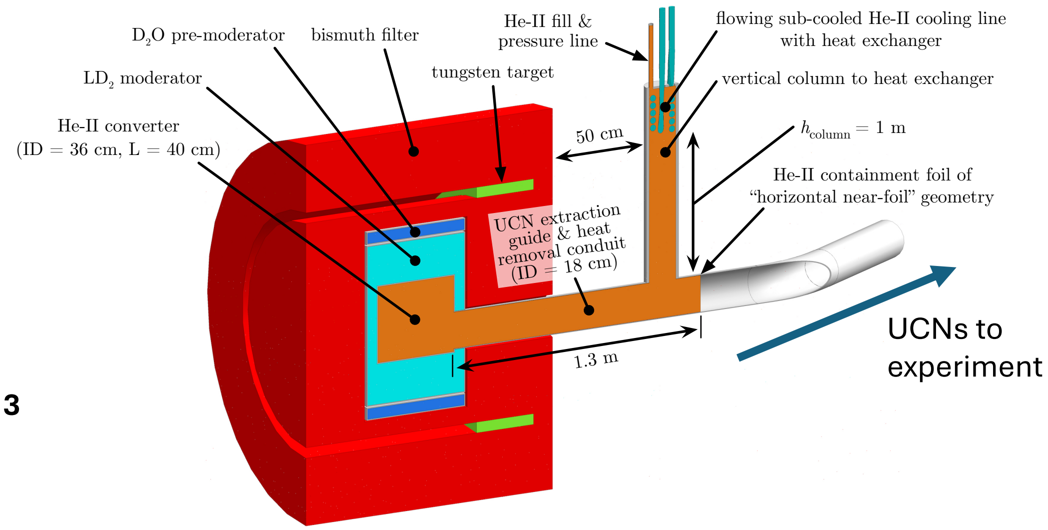
- Single-passage optimized sources (and assuming no return during filling) are less sensitivity to variations in UCN guide losses, especially difficult for cryogenic guides. Depending on the geometry, when using a density-optimized source to fill an external volume UCNs have to make several passages from source to volume. The transport extraction efficiency becomes $\sim (\epsilon_{\text{single passage}})^{\text{average no. of passages}}$

Summary

- 40 L vessel He-II @ 1.6 K with 100 W cooling
- Can handle 1 MW proton beam power
- 1.8 x 10^9 UCN/s production rate
- Optimize for single-passage extraction to get **5 x 10^8 UCN/s current 4 m away**
- Can deliver to experiments **~ 10,000 UCN/cm^3** (or 3,000 UCN/cm^3 for 160 neV max UCN energy)



- Big advantage: **filling large volumes or many experiments simultaneously** (or a flow-through UCN experiments)

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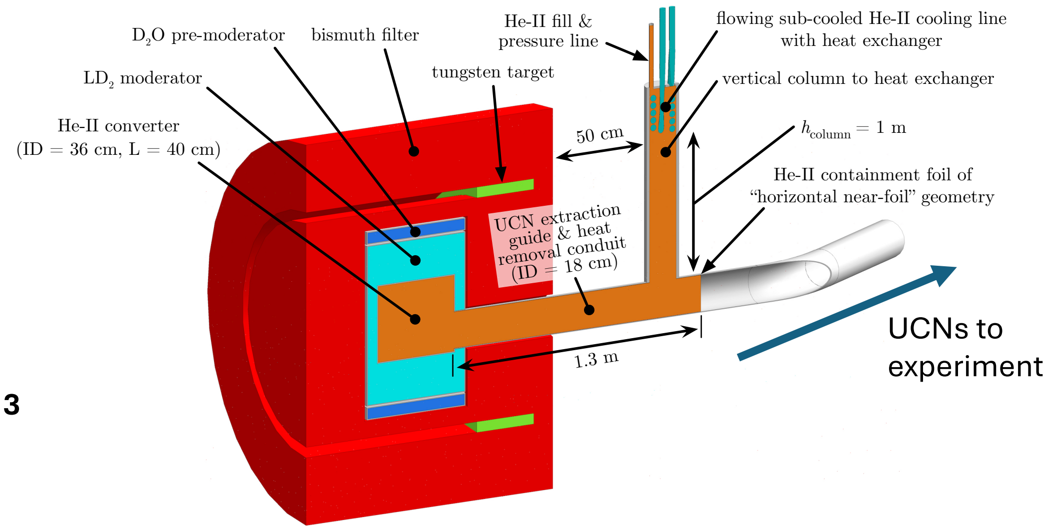

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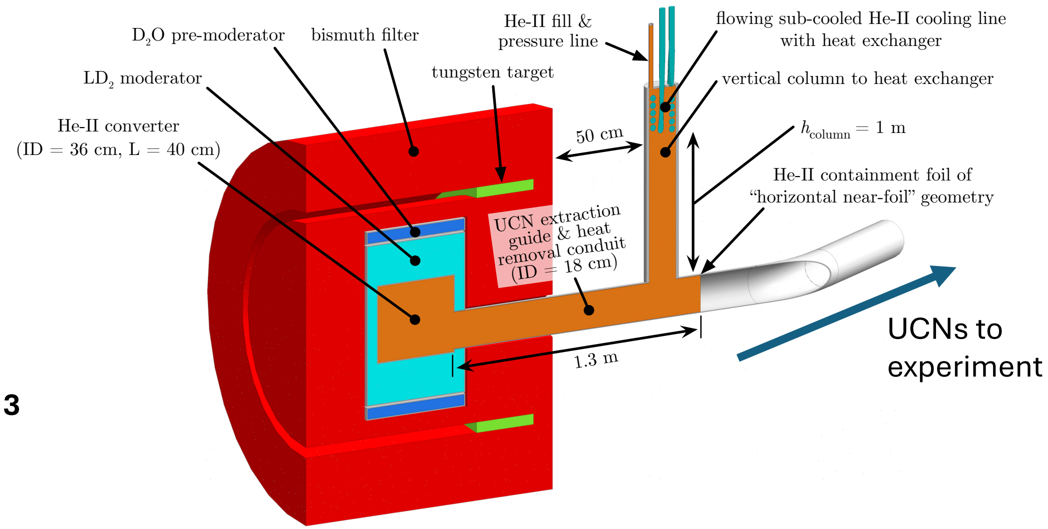
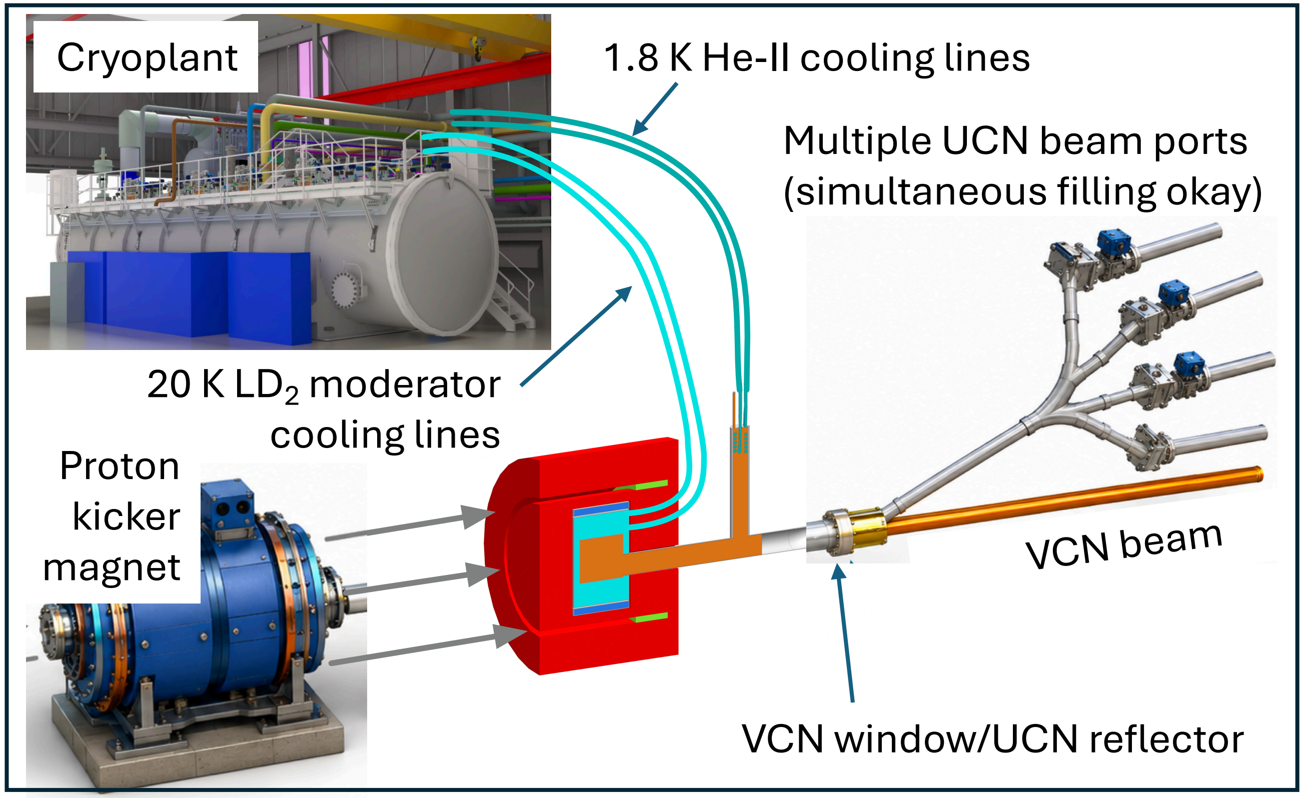


- Big advantage: **filling large volumes or many experiments simultaneously** (or a flow-through UCN experiments)
- This source would **transform the UCN and VCN physics landscape and establish the SNS as the field's global flagship facility.**
- nEDM, neutron lifetime, β-decay, quantum levels experiments would all reach a new level. Many of these are "shovel-ready" and can be brought here and run immediately. New previously not-possible experiments could then emerge.

UCN source facility and proton beam use



UCN source facility and proton beam use

Proton beam use time structure

~ 30 - 60 s | ~ 600-1500 s | ~ 30 - 60 s | ~ 600-1500 s

Beam ON @ max. power

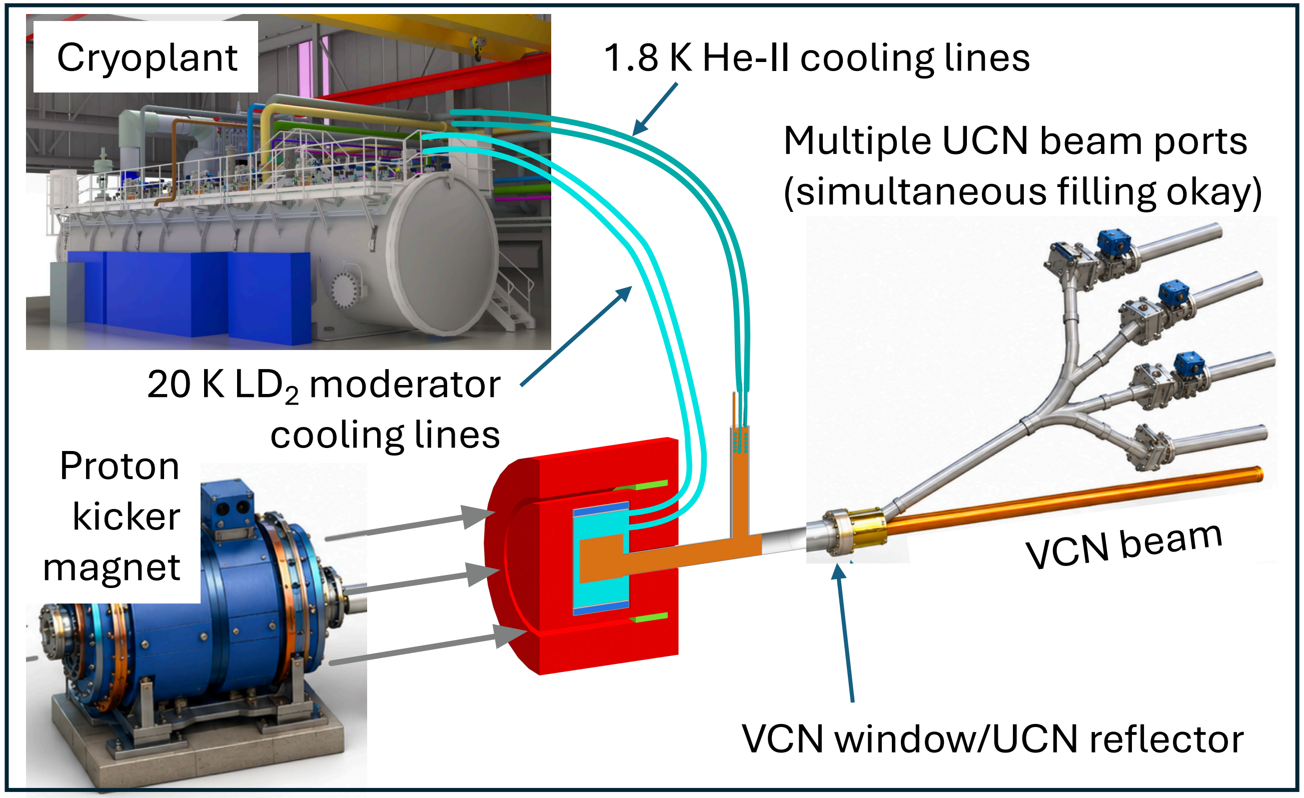
Beam off. UCNs being manipulated and studied

Beam ON @ max. power

Beam off. UCNs being manipulated and studied

…

Time



- This “fill and empty/study” time structure **used in most UCN experiments**
- Density source requires very **short fill times**

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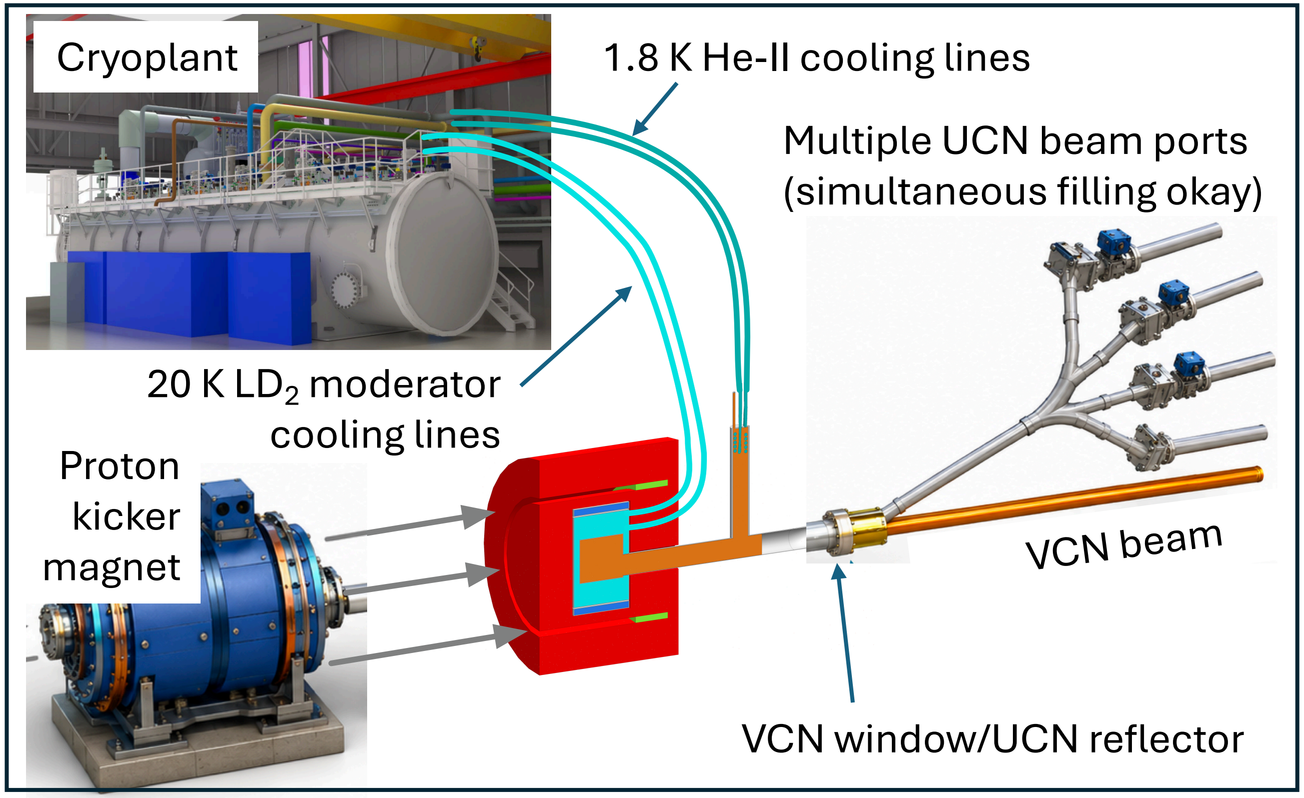
Proton beam use time structure

~ 30 - 60 s	~ 600-1500 s	~ 30 - 60 s	~ 600-1500 s	
Beam ON @ max. power	Beam off. UCNs being manipulated and studied	Beam ON @ max. power	Beam off. UCNs being manipulated and studied	…

Time



- This "fill and empty/study" time structure **used in most UCN experiments**
- Density source requires very **short fill times**
- This UCN facility would only use **2-10% time-averaged power.**
- **Great for sharing with other facilities!**

Thank you!

ChatGPT thinks this UCN source facility would look something like this at the SNS....

Extra slides

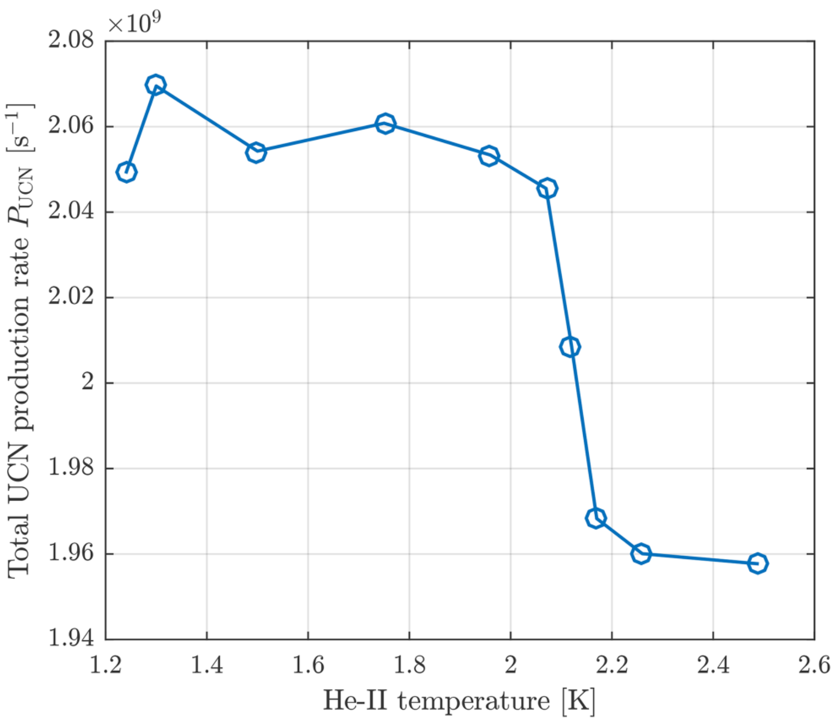
What if we use warmer SF-^{4}He in a UCN source?

PHYSICAL REVIEW C **93**, 025501 (2016)

Ultracold-neutron production and up-scattering in superfluid helium between 1.1 K and 2.4 K

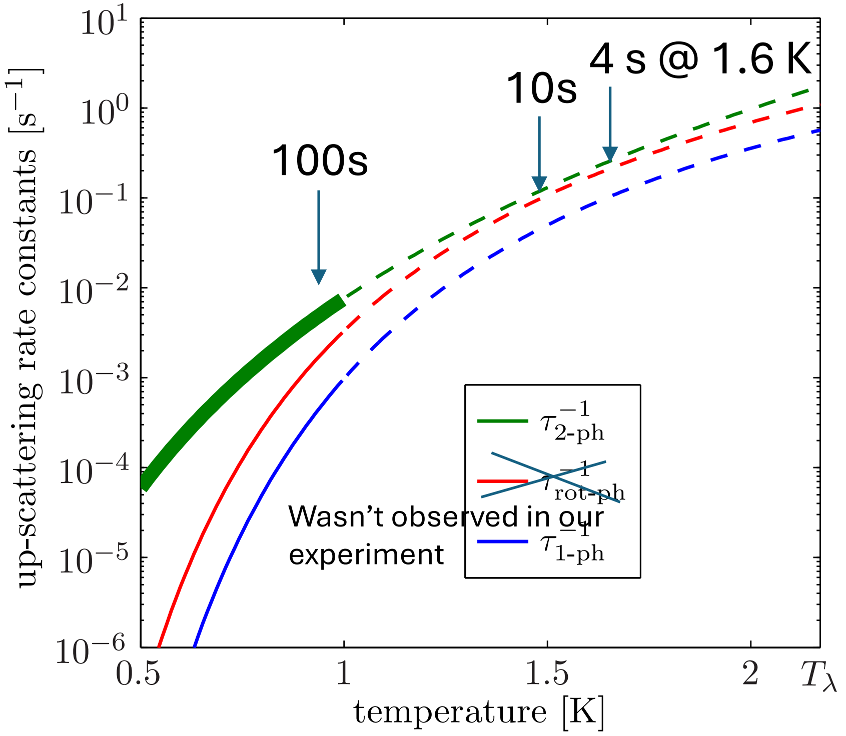
K. K. H. Leung,[1,2] S. Ivanov,[1] F. M. Piegsa,[1,3] M. Simson,[1] and O. Zimmer[1]

Little impact on UCN production rate



(This is for our CN spectrum)

UCN “up-scattering loss” increases



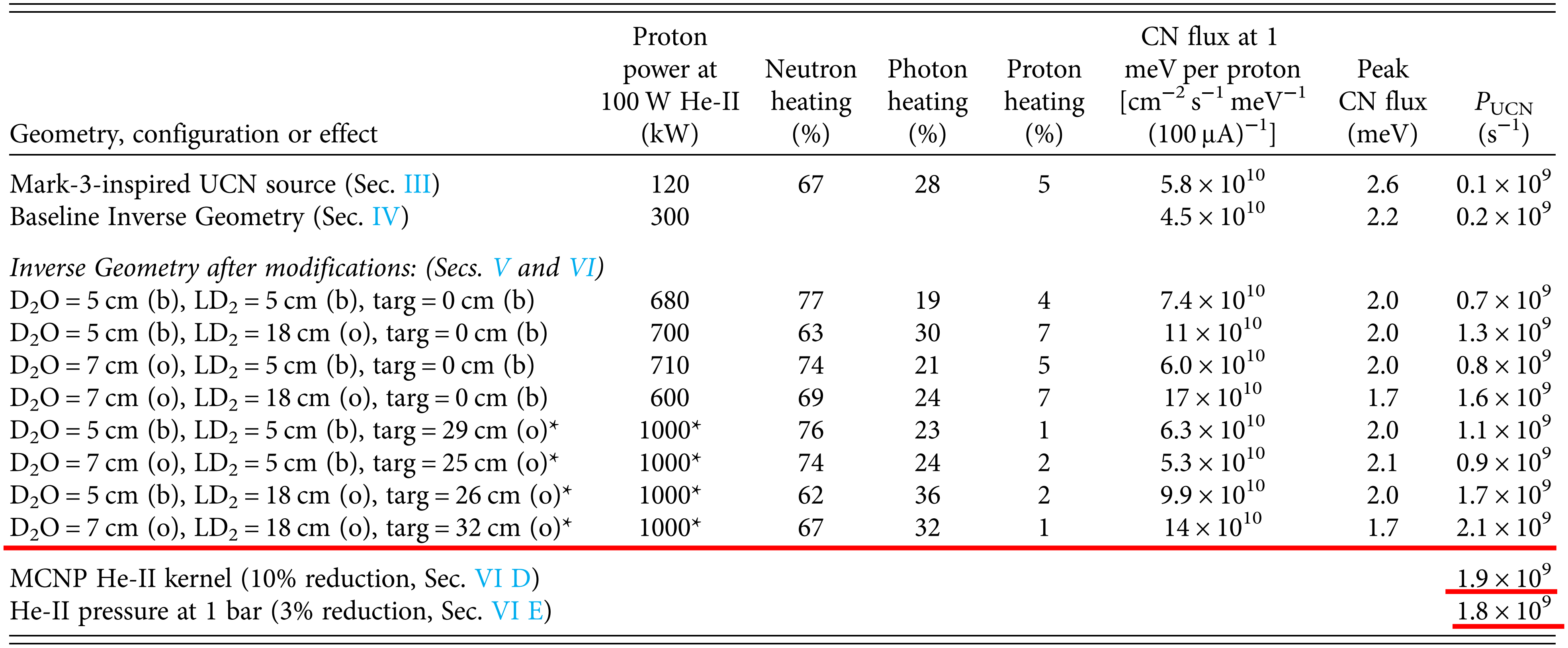
4 s @ 1.6 K

10s

100s

Wasn’t observed in our experiment

Summary and additional effects on total UCN production rate



Geometry, configuration or effect	Proton power at 100 W He-II (kW)	Neutron heating (%)	Photon heating (%)	Proton heating (%)	CN flux at 1 meV per proton [cm^{-2} s^{-1} meV^{-1} $(100\ \mu A)^{-1}$]	Peak CN flux (meV)	P_{UCN} (s^{-1})
Mark-3-inspired UCN source (Sec. III)	120	67	28	5	5.8×10^{10}	2.6	0.1×10^9
Baseline Inverse Geometry (Sec. IV)	300				4.5×10^{10}	2.2	0.2×10^9
Inverse Geometry after modifications: (Secs. V and VI)							
$D_2O = 5$ cm (b), $LD_2 = 5$ cm (b), targ = 0 cm (b)	680	77	19	4	7.4×10^{10}	2.0	0.7×10^9
$D_2O = 5$ cm (b), $LD_2 = 18$ cm (o), targ = 0 cm (b)	700	63	30	7	11×10^{10}	2.0	1.3×10^9
$D_2O = 7$ cm (o), $LD_2 = 5$ cm (b), targ = 0 cm (b)	710	74	21	5	6.0×10^{10}	2.0	0.8×10^9
$D_2O = 7$ cm (o), $LD_2 = 18$ cm (o), targ = 0 cm (b)	600	69	24	7	17×10^{10}	1.7	1.6×10^9
$D_2O = 5$ cm (b), $LD_2 = 5$ cm (b), targ = 29 cm (o)*	1000*	76	23	1	6.3×10^{10}	2.0	1.1×10^9
$D_2O = 7$ cm (o), $LD_2 = 5$ cm (b), targ = 25 cm (o)*	1000*	74	24	2	5.3×10^{10}	2.1	0.9×10^9
$D_2O = 5$ cm (b), $LD_2 = 18$ cm (o), targ = 26 cm (o)*	1000*	62	36	2	9.9×10^{10}	2.0	1.7×10^9
$D_2O = 7$ cm (o), $LD_2 = 18$ cm (o), targ = 32 cm (o)*	1000*	67	32	1	14×10^{10}	1.7	2.1×10^9
MCNP He-II kernel (10% reduction, Sec. VI D)							1.9×10^9
He-II pressure at 1 bar (3% reduction, Sec. VI E)							1.8×10^9

- MCNP did not have a superfluid 4He scattering kernel. Since our paper, we have developed this kernel with Chris Lavelle & Takeyasu Ito
- We want to pressurize SF4He to a modest 1 bar to reduce bubble formation that can scatter UCNs