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Full Solid Deuterium VCN source for ESS

Ben Folsom

9 May 2023

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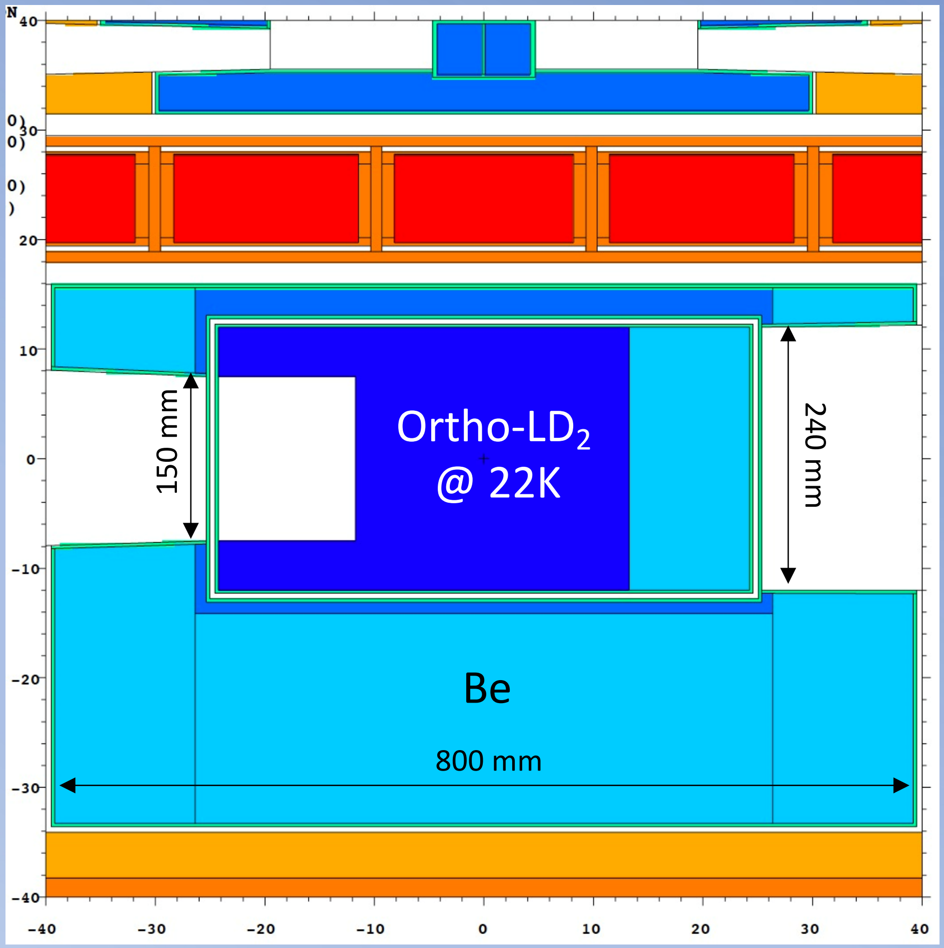
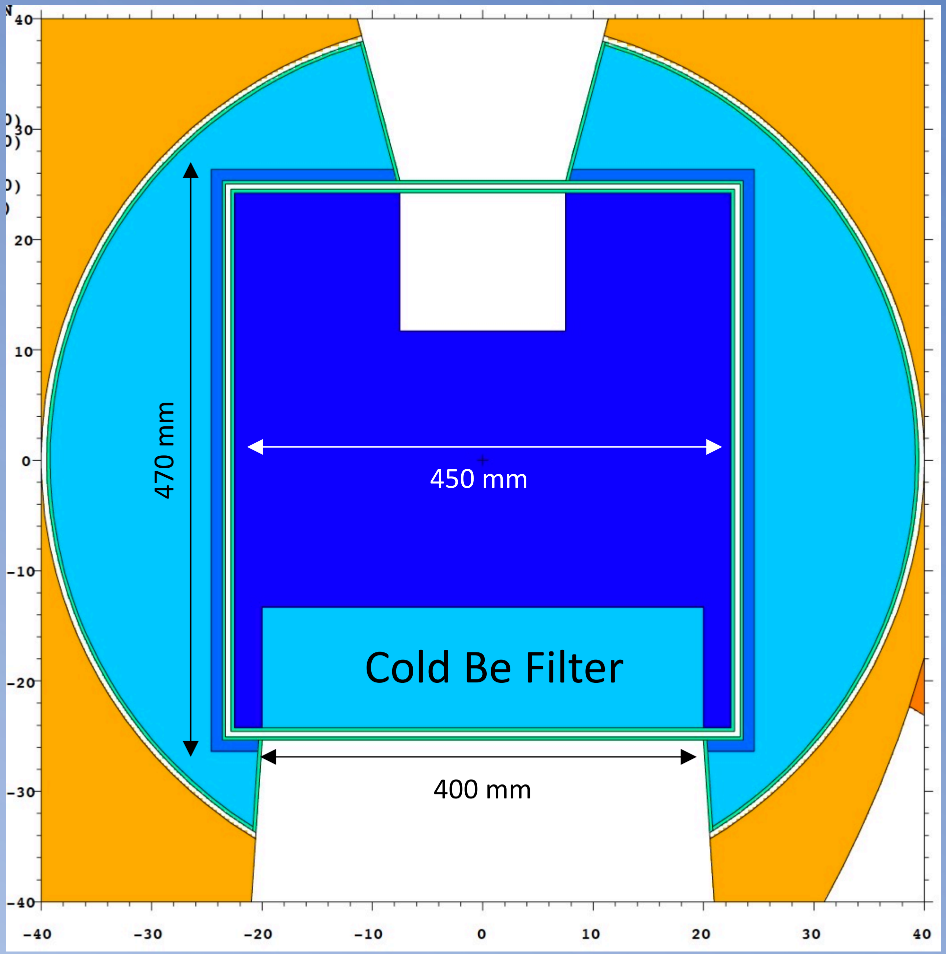
The baseline cold source





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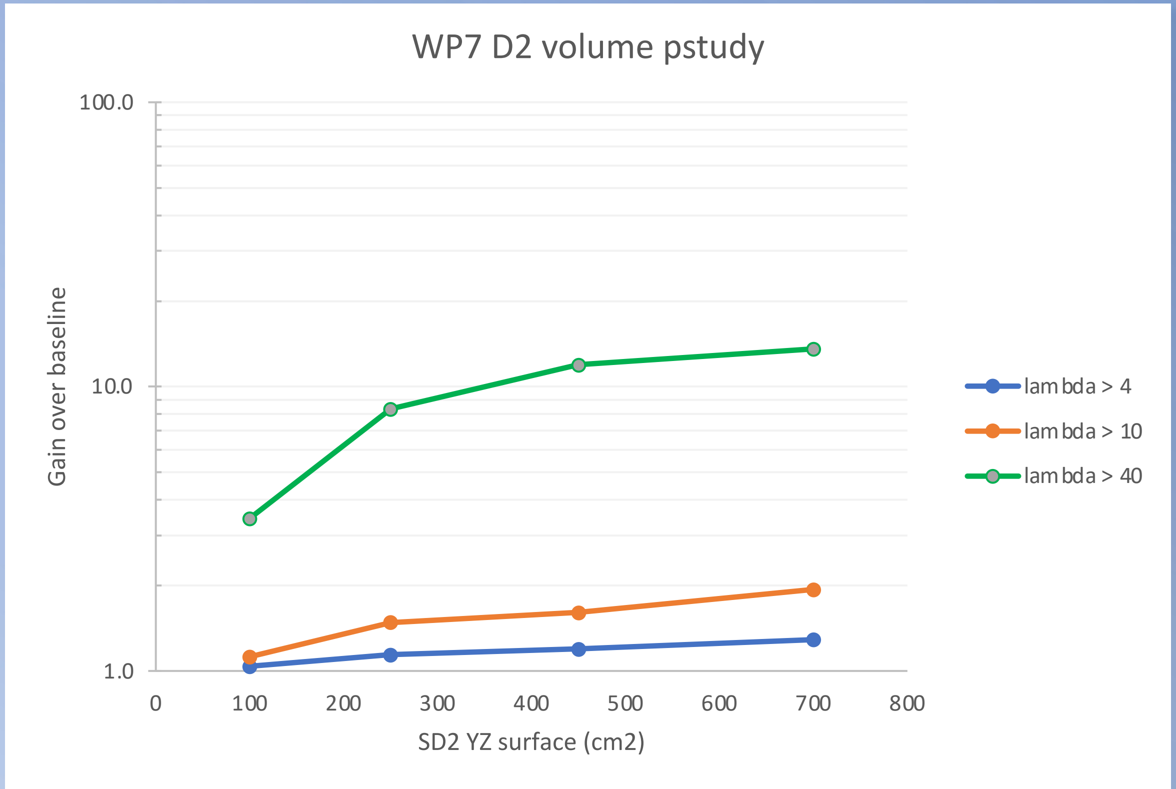
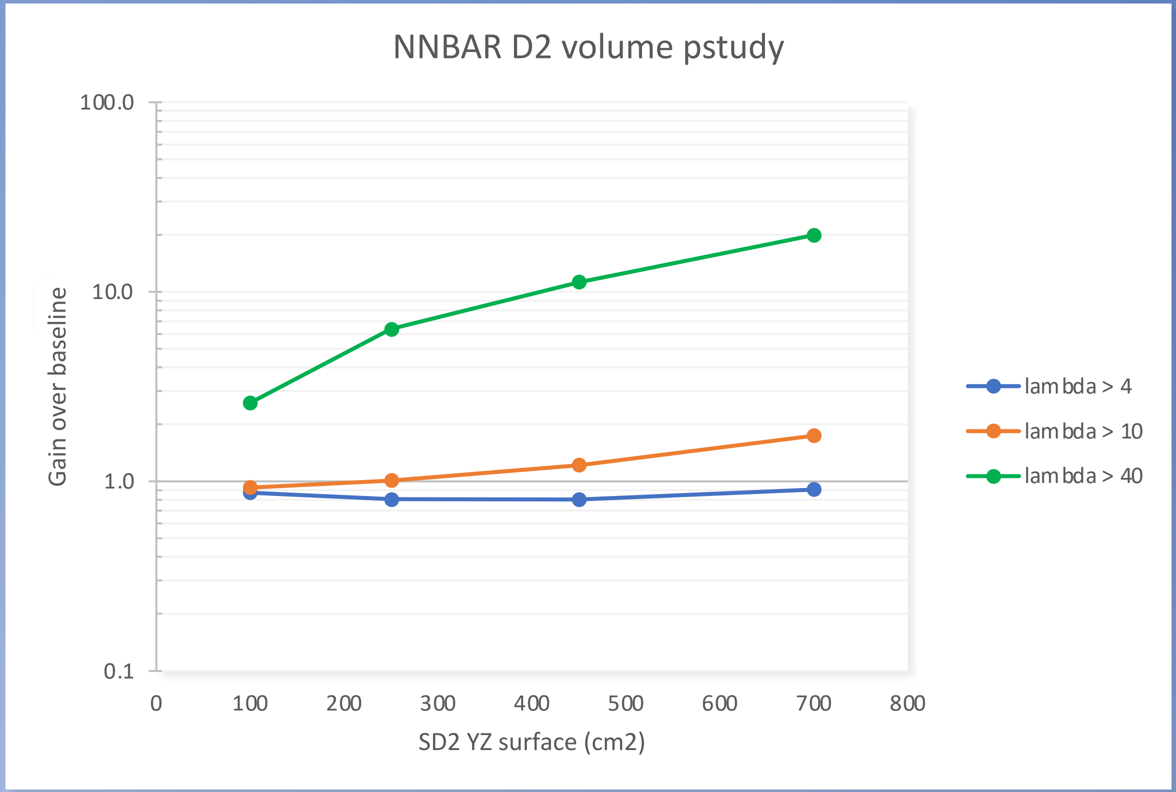
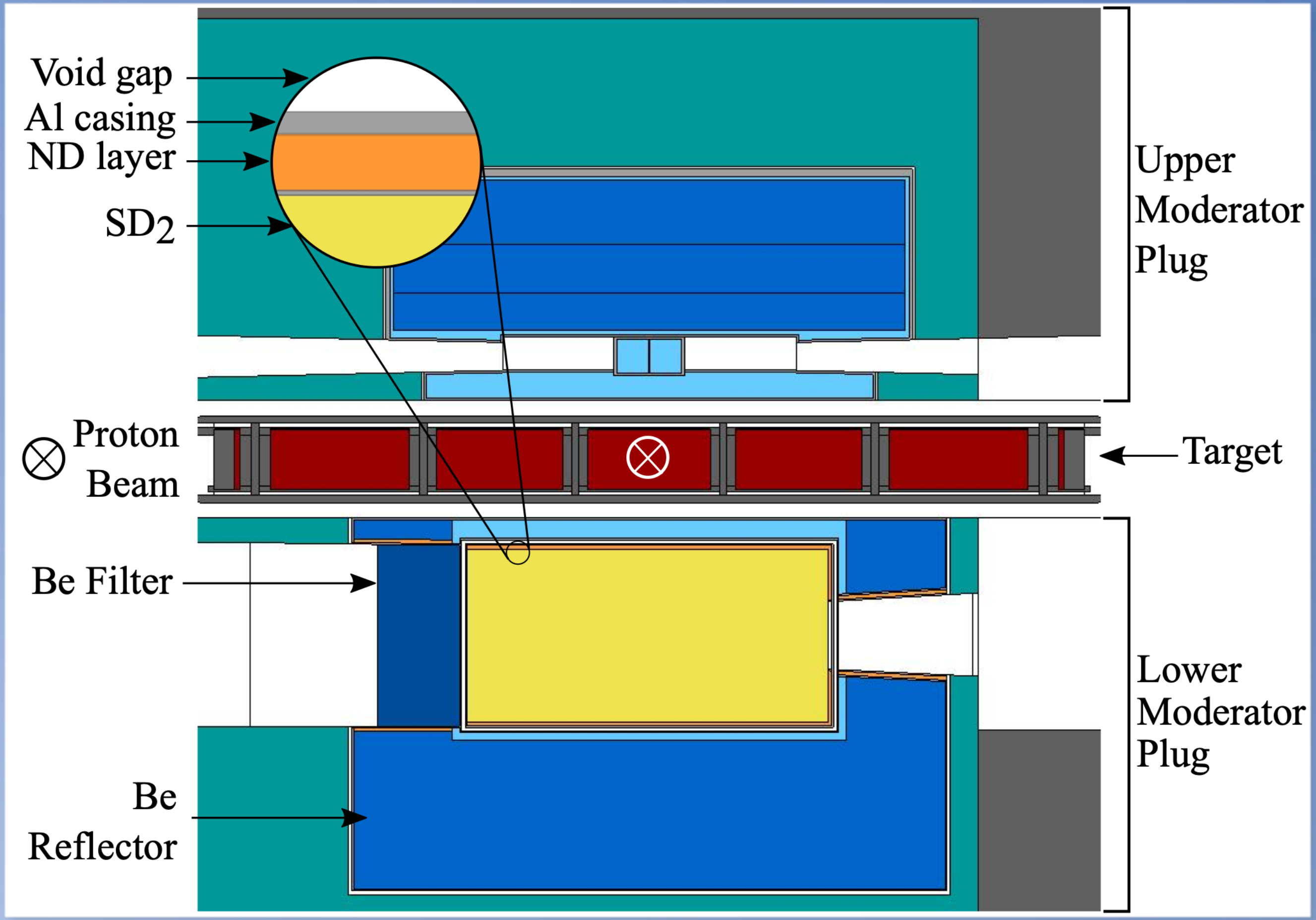
The more SD_2 the better





SD_2 VCN moderator

- 45 x 49 x 24 cm^3 box shape
- 50 L of solid-D_2 (SD2) at 5 K
- Reflector layer made of nanodiamond (ND) 5 mm thickness
- 10-cm Be filter at 20 K on the NNBAR side



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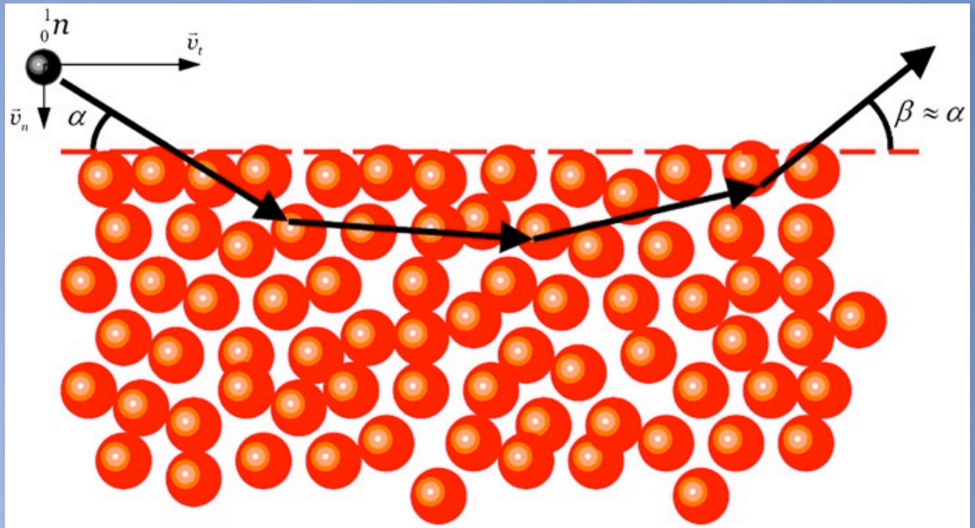
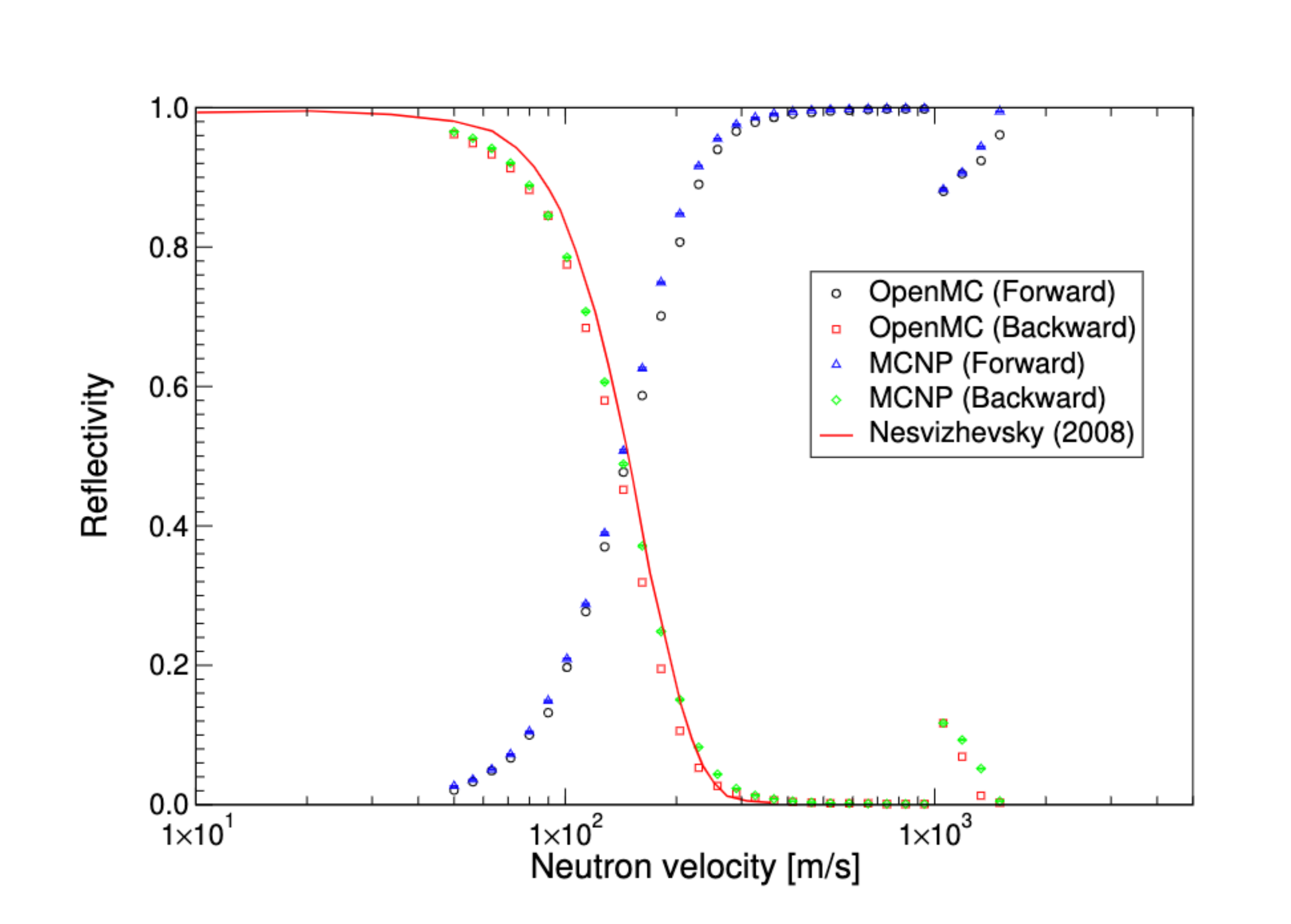
Why nanodiamonds?

- Nanodiamond Powder samples showed efficient reflector properties for very cold neutrons (VCN) up to 10^{-4} eV [1].
- Good quasi-specular reflectivity for cold neutrons [2]
- Nanoparticles provide a sufficiently large cross-section for elastic scattering on a spatial scale comparable to VCN wavelengths
- Carbon has a low absorption cross-section
- Relatively cheap to fabricate
- Fairly radiation tolerant



Ref [3]

Why nanodiamonds?



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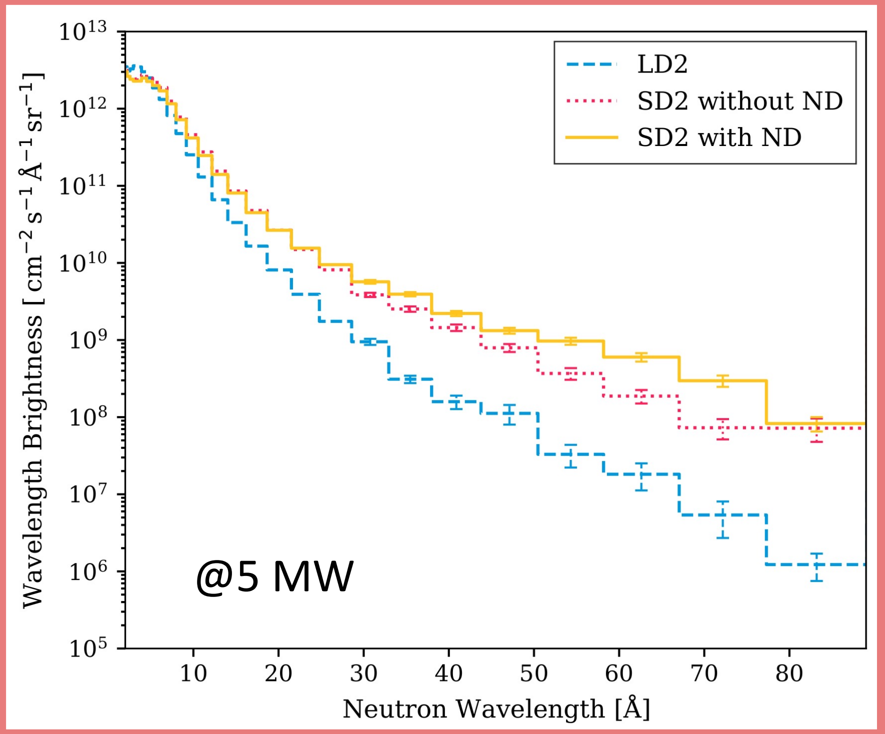
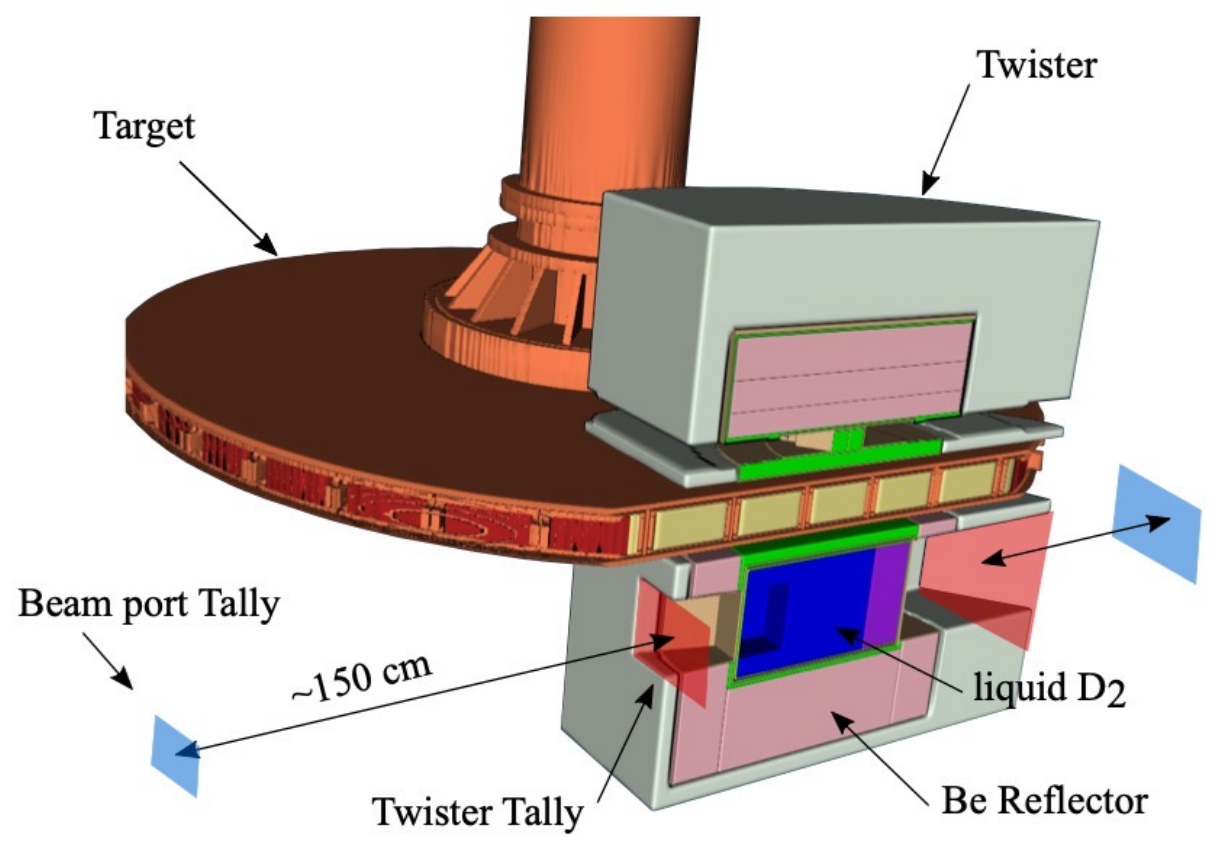
Performance





LD2: VCNs go as a Maxwellian tail with λ^{-5} dependence

SD2 w/ND: Approximately $\lambda^{-3.5}$ dependence

Gains for SD2 over LD2 Baseline

	> 40 Å	10 Å to 40 Å	4 Å to 10 Å	2.5 Å to 4 Å
N.S.	19.0	2.4	1.2	0.7
NNBAR	14.3	2.3	1.3	0.6

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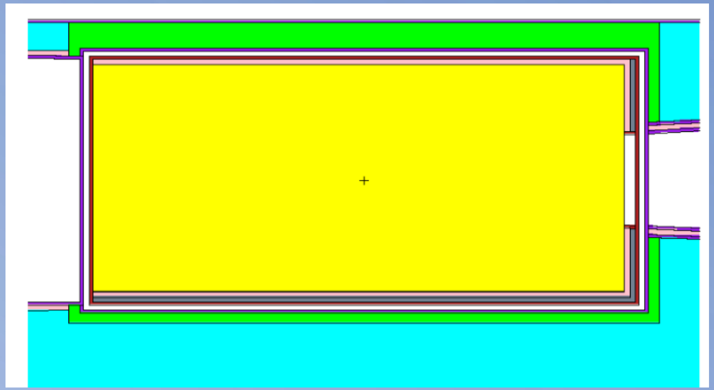
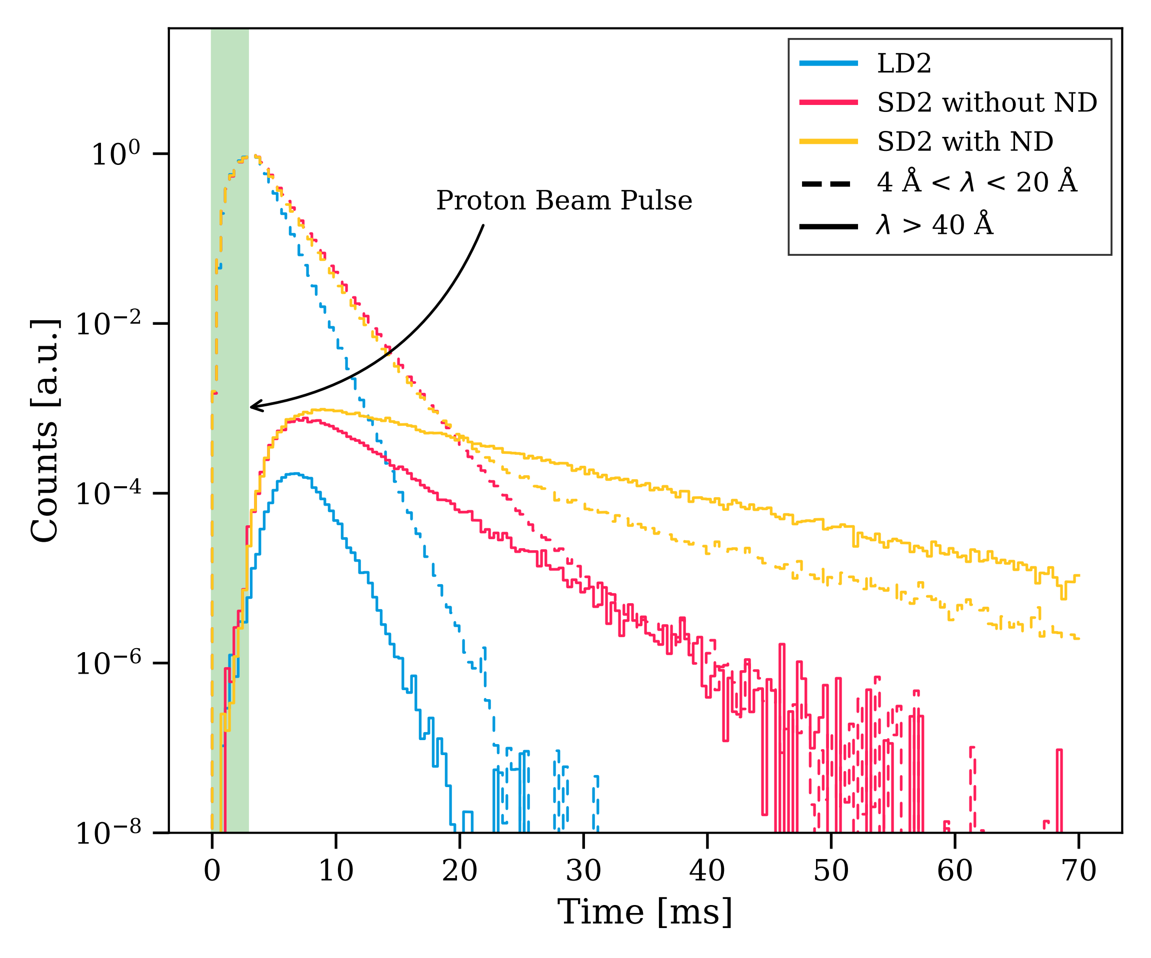
Spectra at 2 m, Be Filter Effects

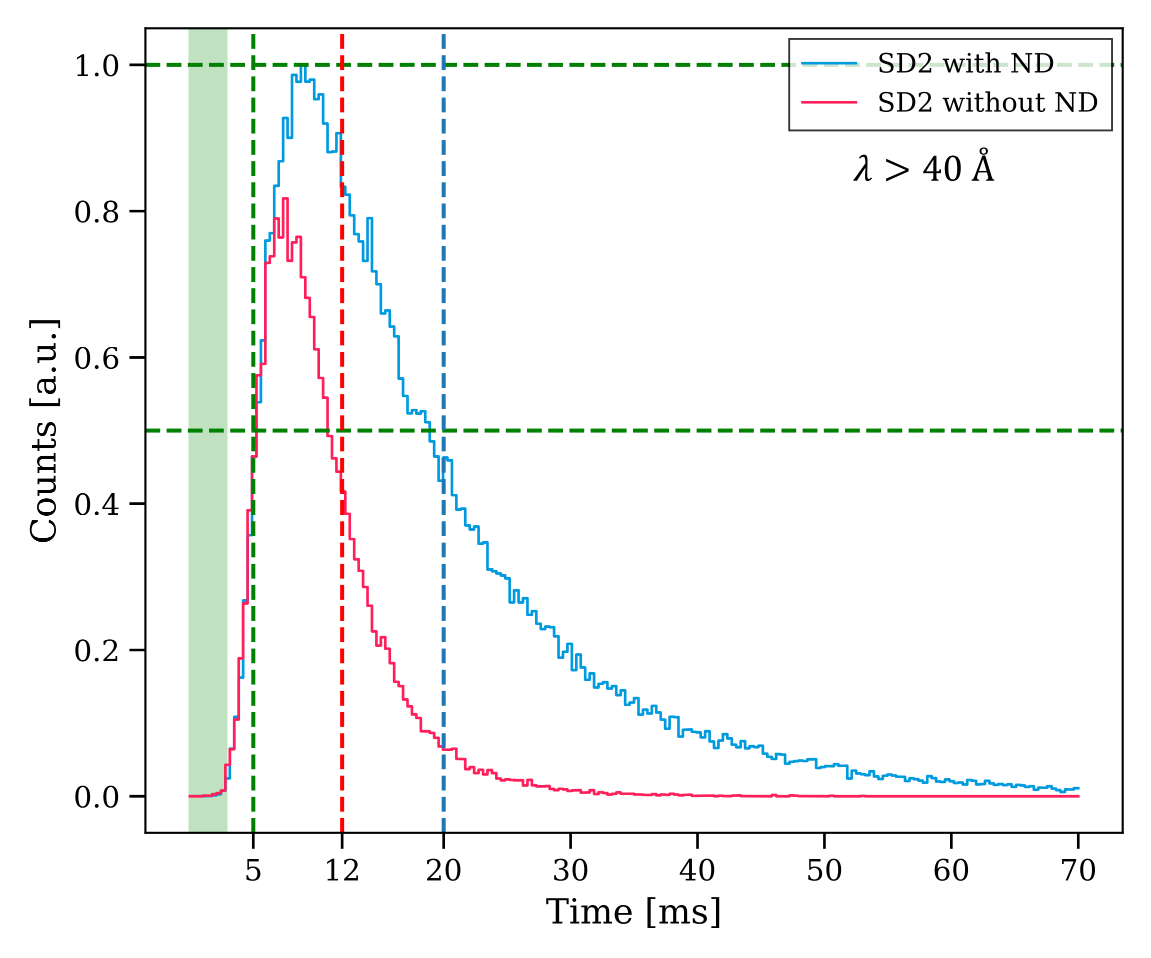


WP7 (Scattering Side) n/nps @ 2m	λ>40Å		10Å<λ<40Å		4Å<λ<10Å		2.5Å<λ<4Å	
	Value	Rel.err.	Value	Rel.err.	Value	Rel.err.	Value	Rel.err.
	7.56E-07	0.3835	2.11E-05	0.0349	1.32E-04	0.0272	6.06E-05	7.49E-02
Gain over LD2	34.3		2.4		1.1		0.7	
Gain over SD2 w/Be filter	1.4		1.0		0.9		1.0	
NNBAR Side n/nps @ 2m	λ>40Å		10Å<λ<40Å		4Å<λ<10Å		2.5Å<λ<4Å	
	Value	Rel.err.	Value	Rel.err.	Value	Rel.err.	Value	Rel.err.
	2.60E-05	0.0899	1.15E-03	0.0048	6.81E-03	0.0038	3.16E-03	0.0104
Gain over LD2 Baseline	16.6		2.0		0.9		1.9	
Gain over SD2 w/Be Filter	1.2		0.9		0.8		3.2	

- Without the beryllium filter, the 4–10Å range is reduced by at least 10%. This is a critical range for the NNBAR FOM.
- The filter also increases flux on the scattering side by 5% across the cold and very cold range.

Pulse characteristics





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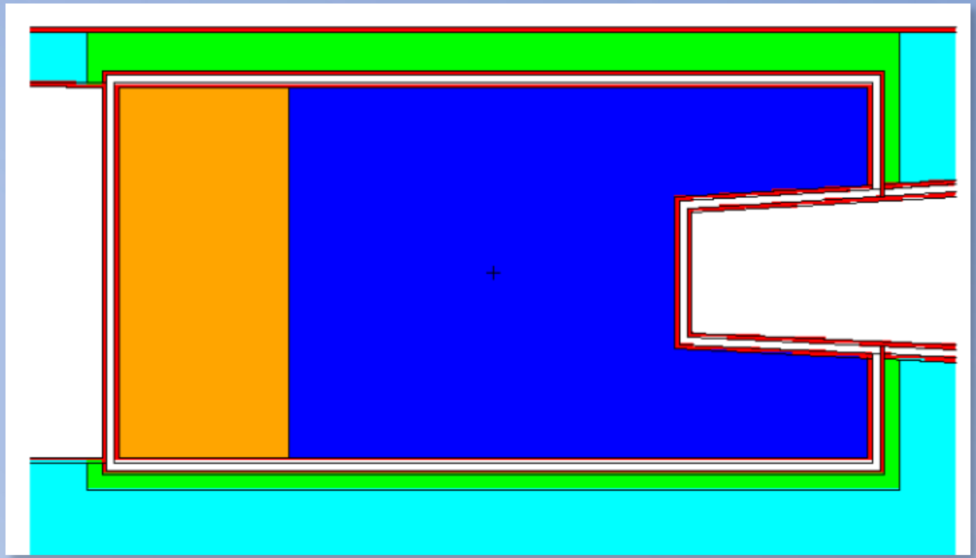
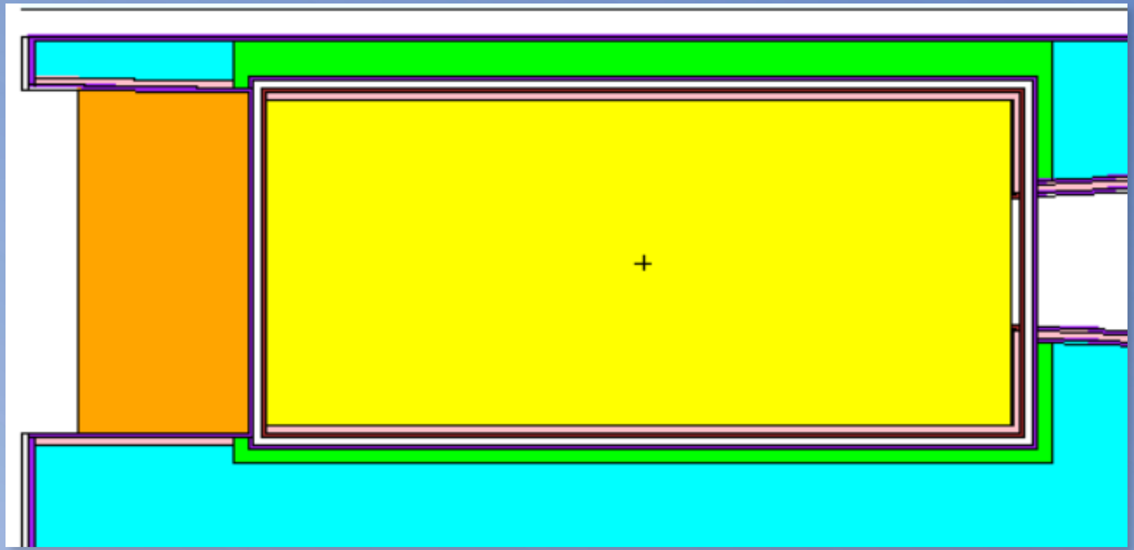
How do we plan to cool it?

For LD2, flow guides and beryllium-filter support pillars are required which add approximately 4% aluminum to the moderator volume.

For SD2, the required heat extraction to keep well below the ~17K melting point cannot be achieved with conventional techniques. A strong option is metallic-foam heatsinks (3–15% per volume).





For preliminary neutronics simulations, we treat both of these cases as simple mixtures (emulsions) with their relative moderator materials.

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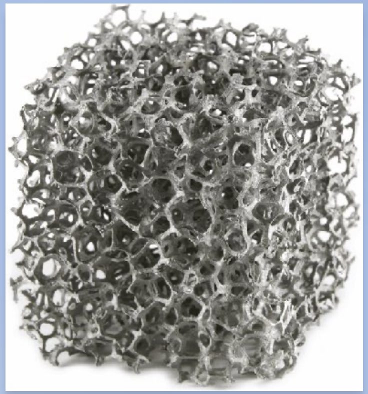
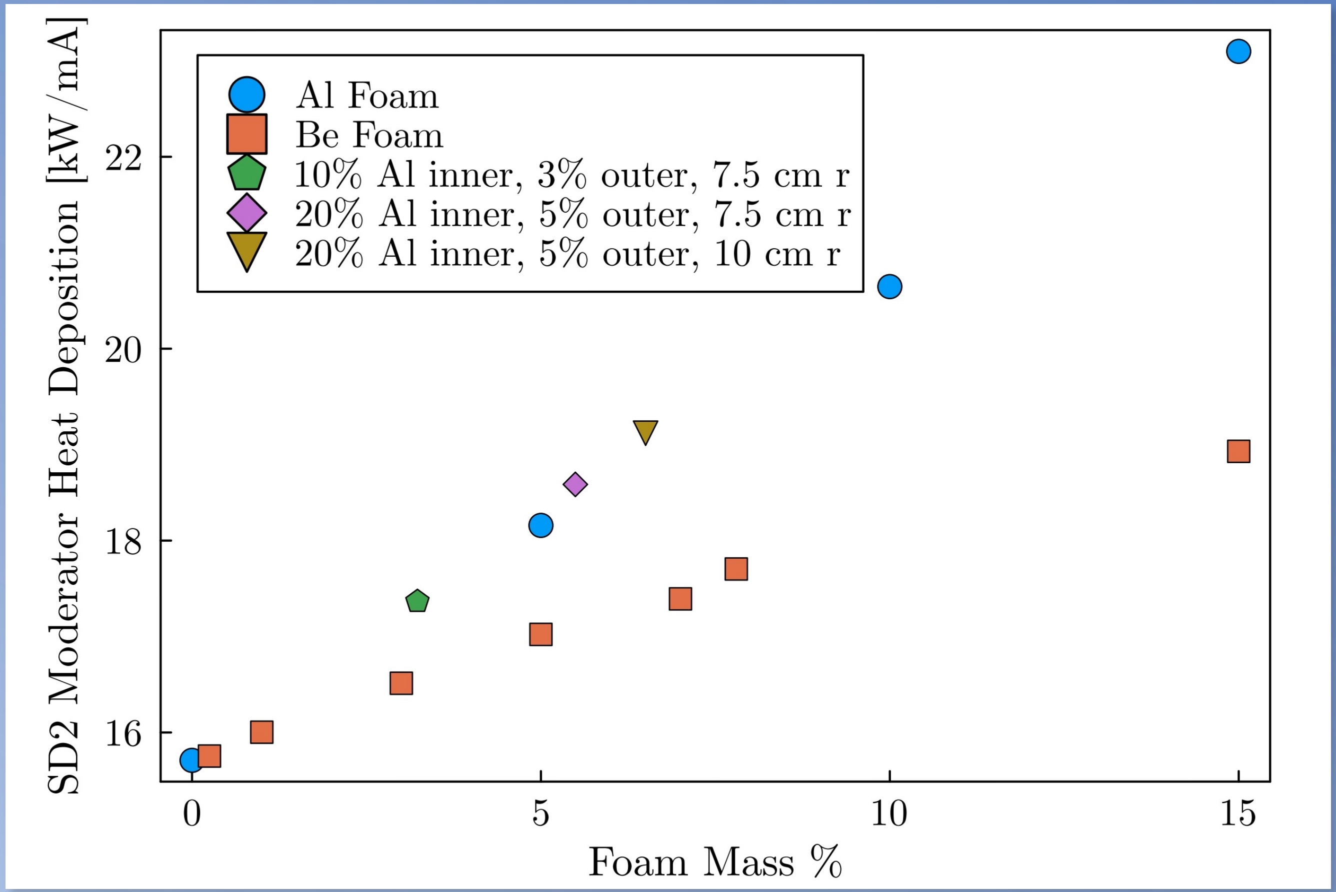
How do we plan to cool it?

- Preliminary calculations show that it is possible to cool the SD2 volume within the ESS environment **at 2 MW** beam power by use of aluminum foam and conventional liquid-He channeling.
- Beryllium performs better in terms of both self-heating and neutronics, further testing is needed to determine its viability at 5 MW, with a heatload of ~40 kW.





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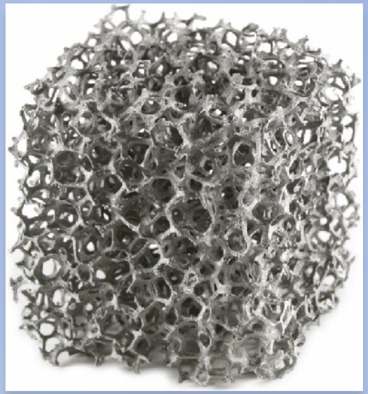


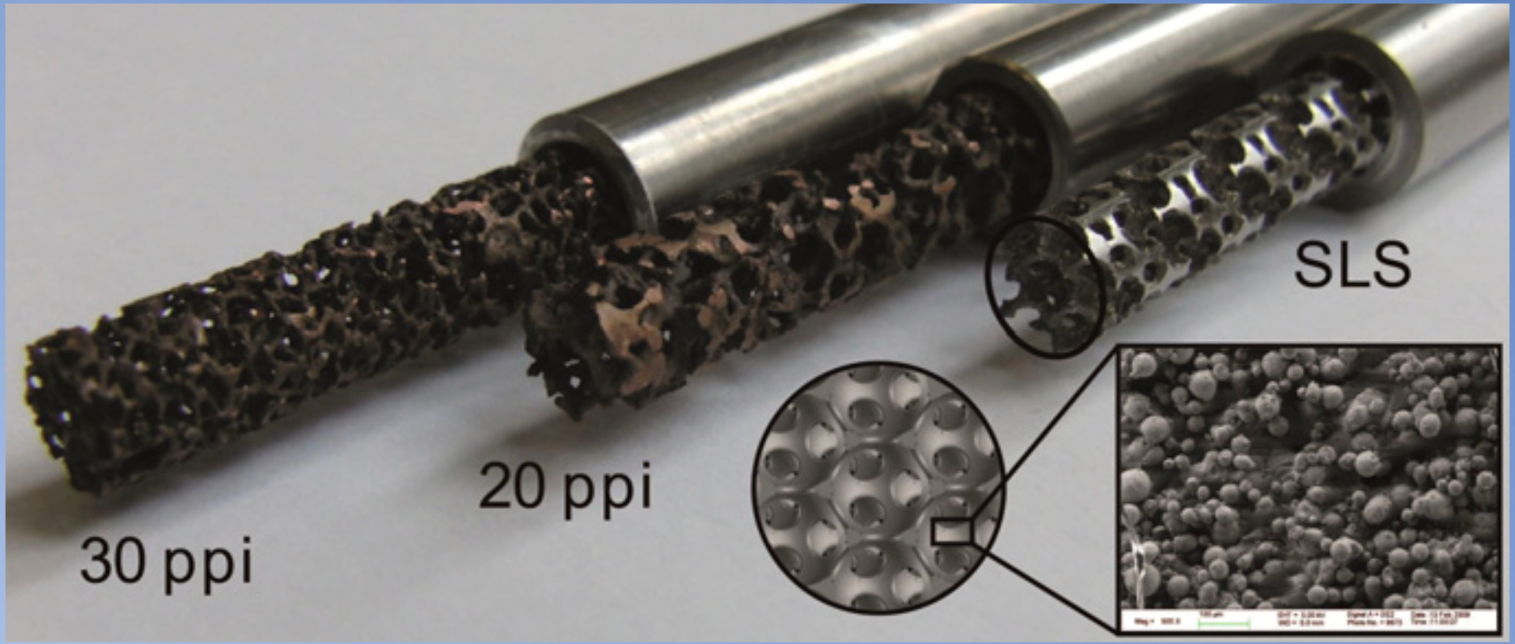
	Al %	> 40 Å	10 Å to 40 Å	4 Å to 10 Å	2.5 Å to 4 Å
WP7	15%	3	0.95	0.67	0.57
	15/7 %	4.73	1.54	0.93	0.63
NNBAR	15%	1.9	0.96	0.71	0.48
	15/7 %	4.74	1.50	0.94	0.54

	Be %	> 40 Å	10 Å to 40 Å	4 Å to 10 Å	2.5 Å to 4 Å
WP7	15%	11.9	2.12	1.10	0.64
	15/7 %	16	2.36	1.21	0.70
NNBAR	15%	10.45	1.93	1.10	0.56
	15/7 %	14.2	2.26	1.21	0.60

Conventional vs. SLS (3D printed) foams

- SLS has better heat extraction in some applications. May be prohibitively expensive with beryllium due to toxicity measures. Additionally, the outer surface is left porous after fabrication.

- With conventional foaming-agent production, density and porosity can be tuned homogeneously. This is a more mature technology and may be more feasible for beryllium.



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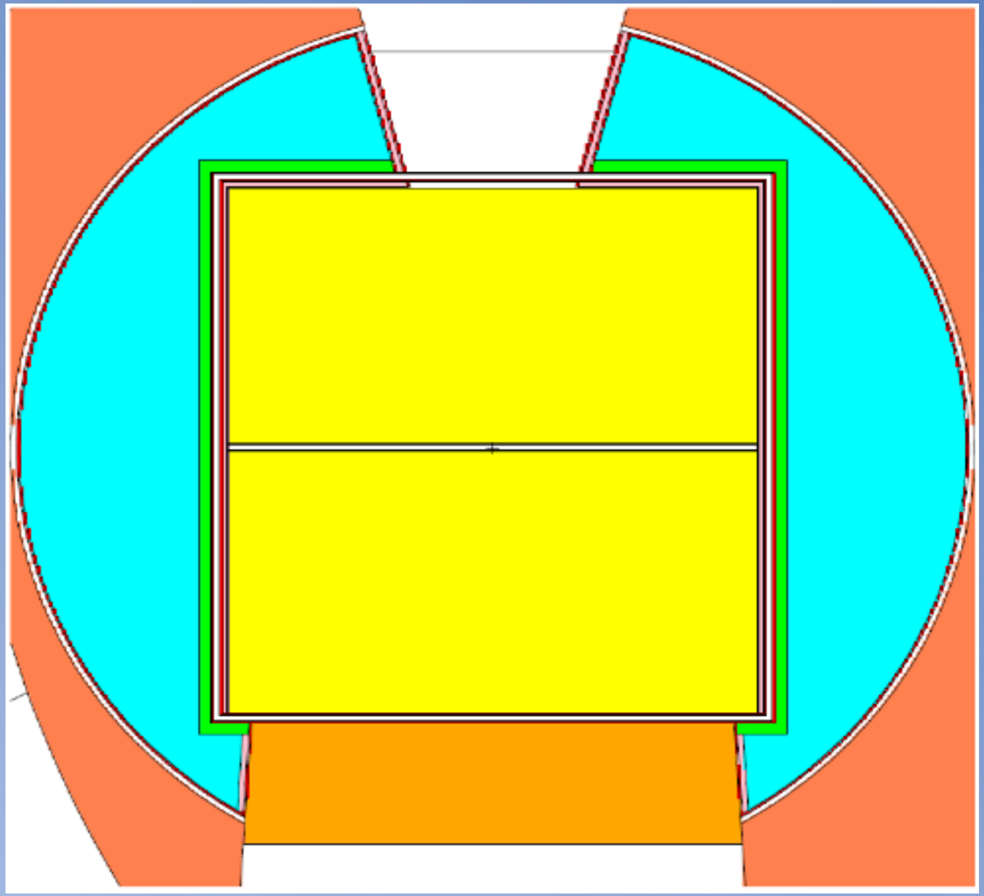
Cooling Channel Tests

Inserting a single aluminum-walled liquid-helium pipe through the center dramatically improves cooling capability and has negligible impact on neutronics performance.

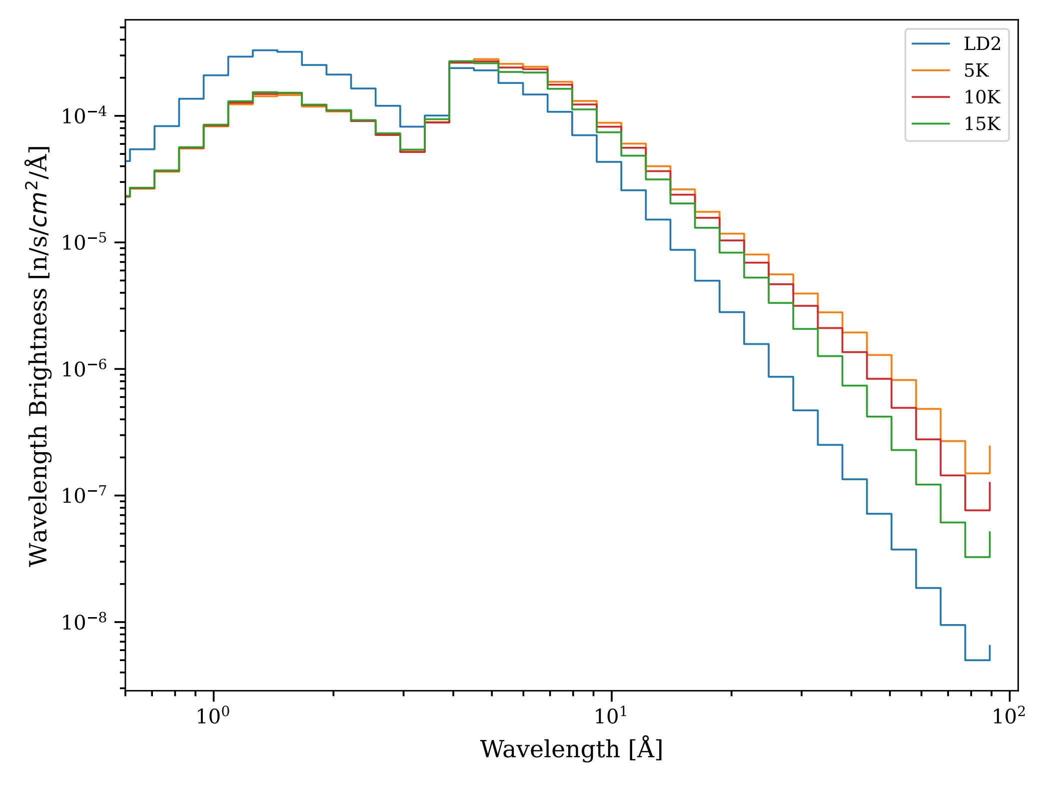
(WP7)

n/nps @ 2m	λ>40Å		10Å<λ<40Å		4Å<λ<10Å	
	Value	Rel.err.	Value	Rel.err.	Value	Rel.err.
	6.55E-07	0.0777	2.53E-05	0.0042	1.57E-04	0.0035
Gain over Baseline	26.4		2.3		1.1	
Gain over 0% Al SD2	1.0		1.0		1.0	



VCN production with SD_2 temperature

- Early studies show a limit of 10 K is optimal to avoid cracks in the SD2 crystal.
- Thermal conductivity for SD2 drops by a factor of 30 from 5K to 12K [7]. This may present engineering constraints.



(WP7 Side)

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Conclusions

- We found that solid-D_2 could be used to build a high-intensity VCN source.
- Nanodiamonds are almost transparent in transmission for cold neutrons, but at lower energies they show optimal properties as reflector material.
- Nanodiamond fabrication for VCNs has improved in the last few years; nanodiamond reflector performance is thus likely to exceed our current estimates.
- Cooling is going to be challenging, but:
  1. A VCN source could operate at higher temperature than 5 K
  2. We should not give up on the possibility to innovate
- In any case, solid-D_2 could play a role in the future of the ESS. With the right effort and expertise, there is fertile ground for designing the first high-intensity VCN source.

Thank you
for your attention

References

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