A Superfluid-Helium Superthermal Ultracold Neutron Source Embedded in a Cylindrical, High Power Spallation Target

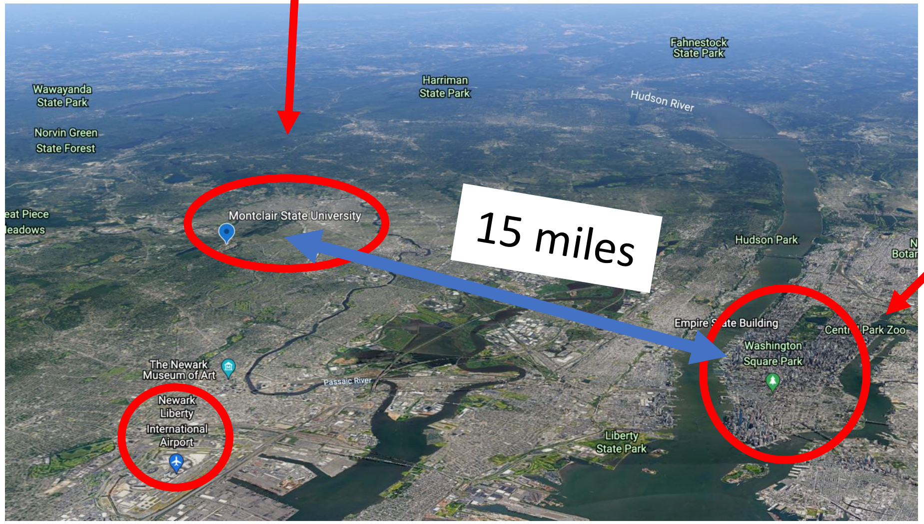
Kent Leung, Günter Muhrer, and Albert Young

MONTCLAIR STATE UNIVERSITY

EUROPEAN SPALLATION SOURCE

NC STATE UNIVERSITY

MONTCLAIR STATE UNIVERSITY

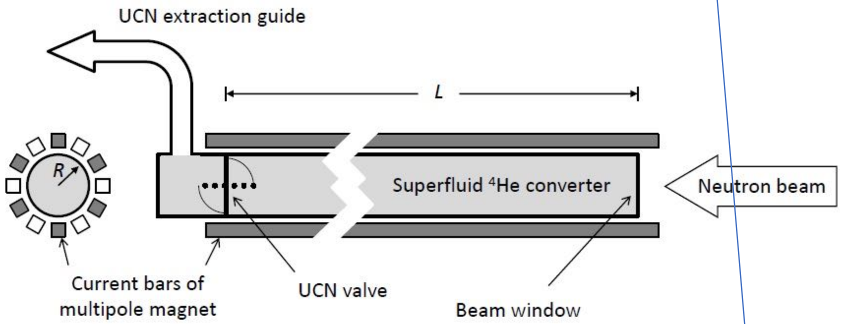


UCN density optimized vs. UCN current optimized

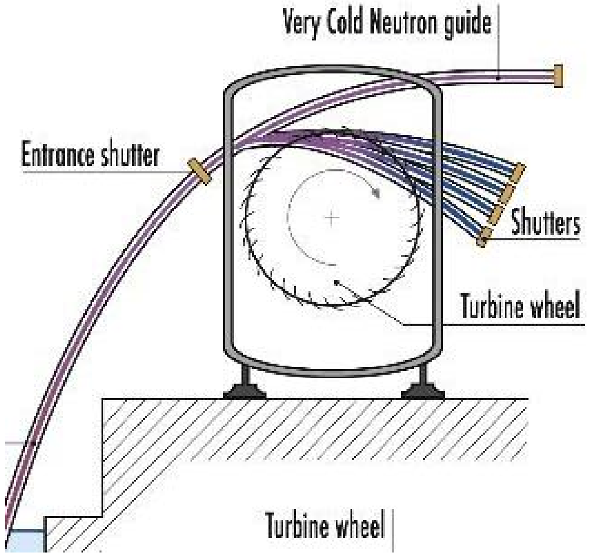
UCN density [UCN/cm^3]

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

PF2
“Steyerl
turbine”

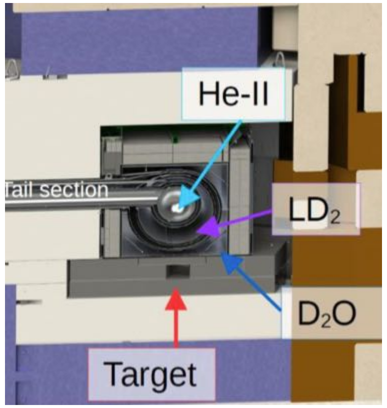


SUN-series in-beam 4He (~0.5 K)



Also a VCN source…

TRIUMF in-pile 4He (~1 K)



PNPI in-pile 4He (~1.3 K)

UCN density optimized vs. UCN current optimized

UCN density [UCN/cm^3]

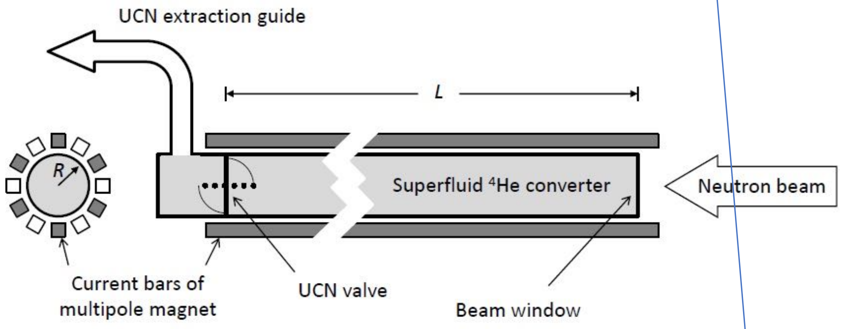
UCN current [UCN/s]
(or “integrated flux”)

PF2
“Steyerl
turbine”

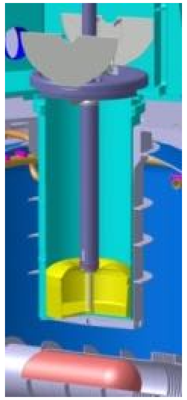
PSI sD2

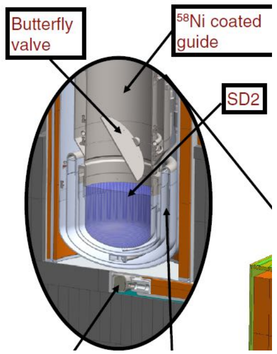
LANL sD2

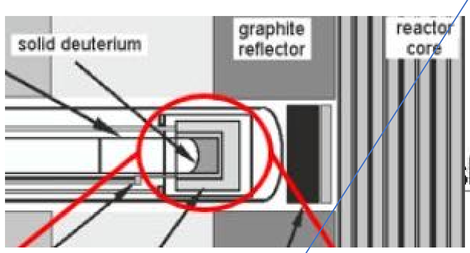
Mainz sD2

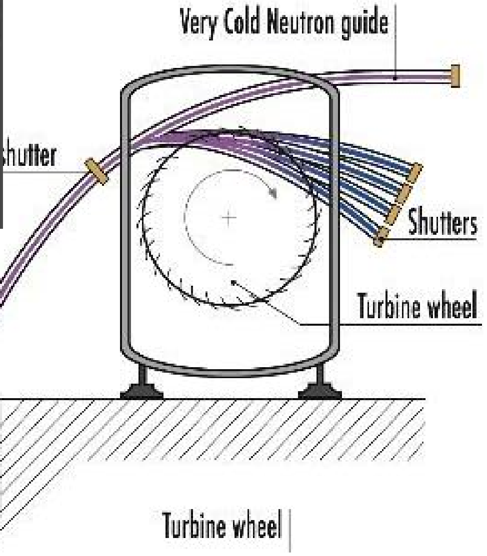


SUN-series in-beam 4He (~0.5 K)

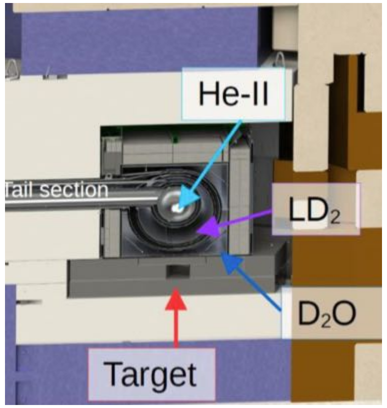




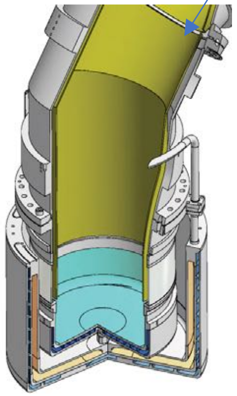




TRIUMF in-pile 4He (~1 K)



PNPI in-pile 4He (~1.3 K)



NCSU sD2

Munich sD2

Also a VCN source…

JPARC

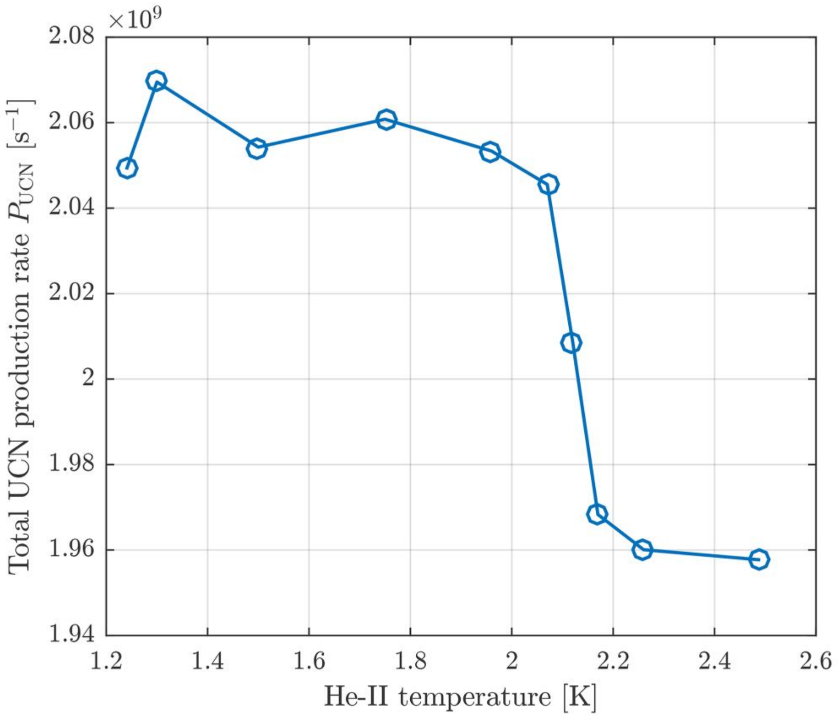
What if we use warmer SF-^{4}He in a UCN source?

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

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

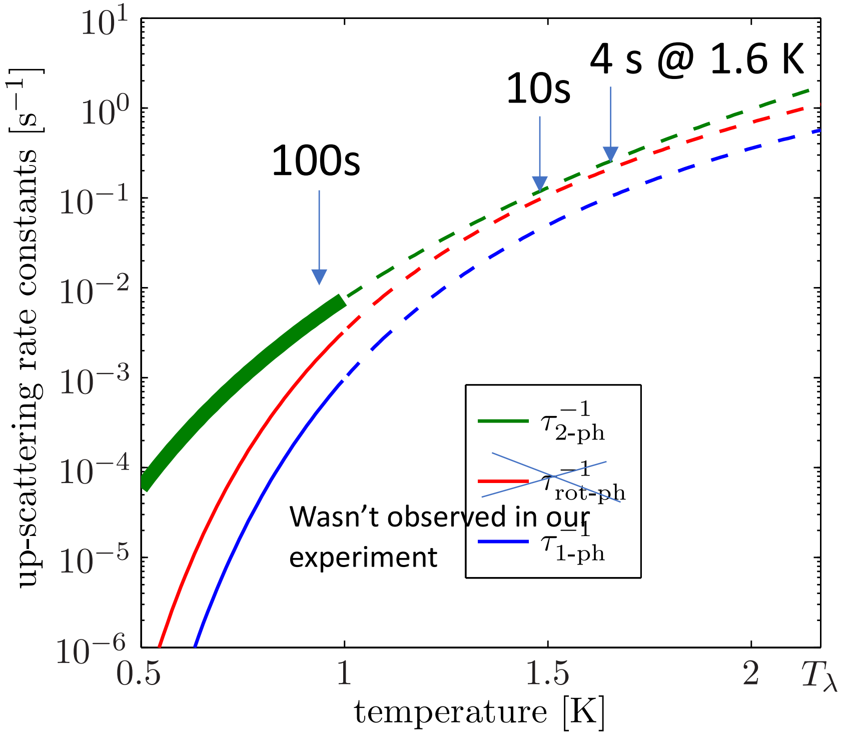
K. K. H. Leung,[1,2] S. Ivanov,[1] F. M. Piegsa,[1,3] M. Simson,[1] and O. Zimmer[1]

Little impact on UCN production rate



(This is for our CN spectrum)

UCN "up-scattering loss" increases



Wasn't observed in our experiment

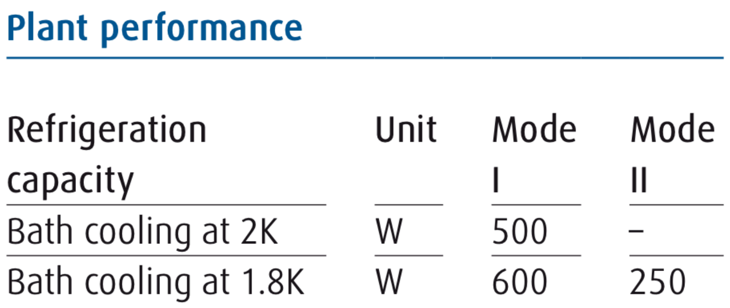
Increase in allowed heat load

Dilution Fridge: ≲ 100 mW @ ≲ 0.4 K

3He evap: ≲ 10 W @ 0.4 – 1.1 K

4He evap: ≲ 60 W @ 1.1 – 1.4 K

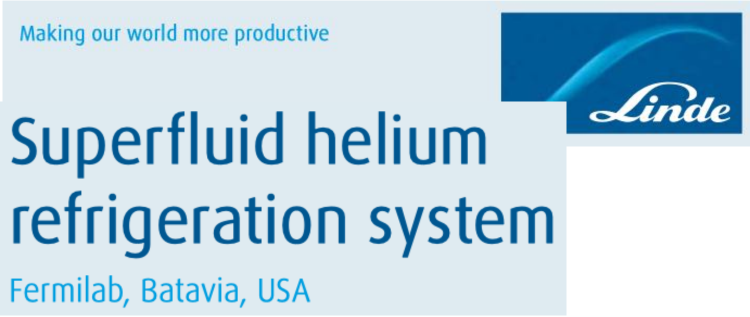
Sub-cooled 4He ("off-the-shelf"):



Plant performance

Refrigeration capacity	Unit	Mode I	Mode II
Bath cooling at 2K	W	500	–
Bath cooling at 1.8K	W	600	250

Sub-cooled ^{4}He technology



Making our world more productive

Superfluid helium refrigeration system

Fermilab, Batavia, USA

Key technology are cold compressors

Plant performance

Refrigeration capacity	Unit	Mode I	Mode II
Bath cooling at 2K	W	500	–
Bath cooling at 1.8K	W	600	250

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

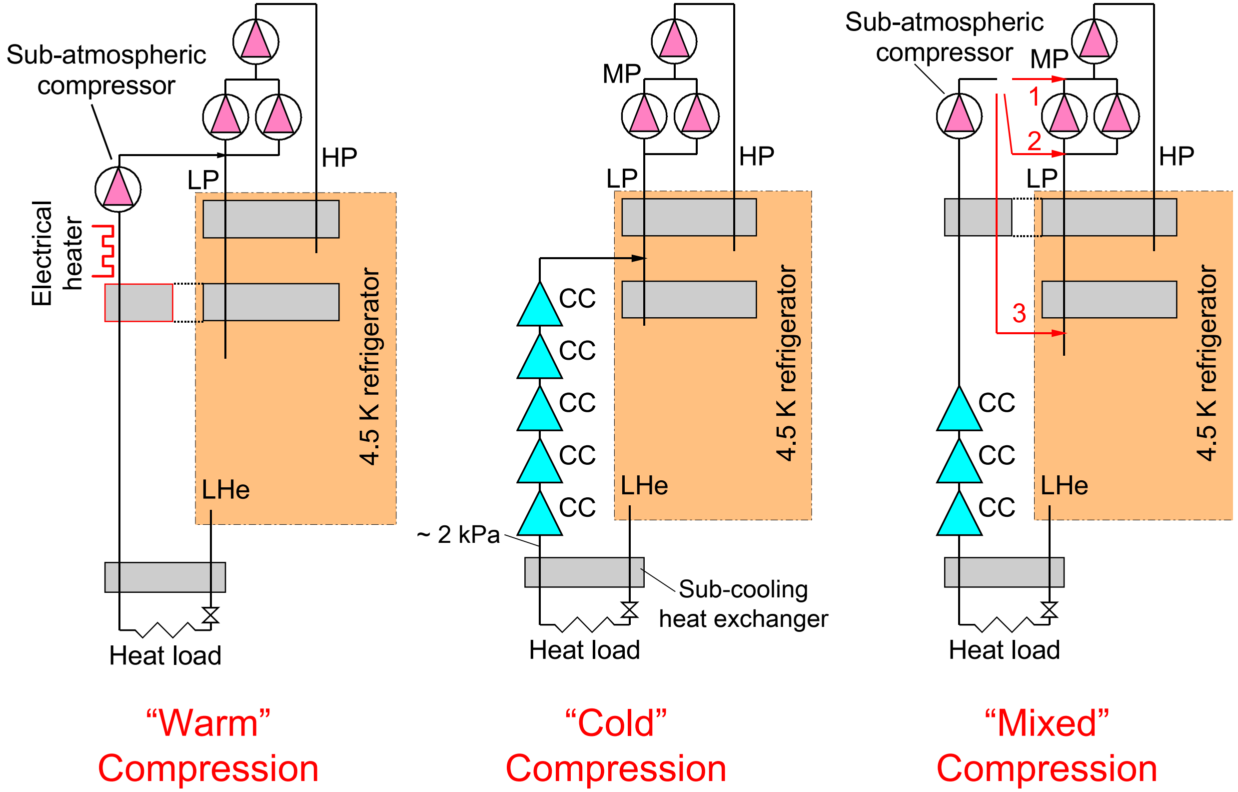


Fig. 13: Generic process cycles for refrigeration below 2 K

- Generally used for > 10 g/s flow => ~ 200 W. (Prob need to add heat!)
- Generally lowest temp ~ 1.8 K, which requires 4 cold compressors in series
- To get to 1.6K (1.4K) need to have 5 (6) CC in series.
- Price estimates ~150k euros per CC stage (plus some overhead when sold integrated with the coldbox)

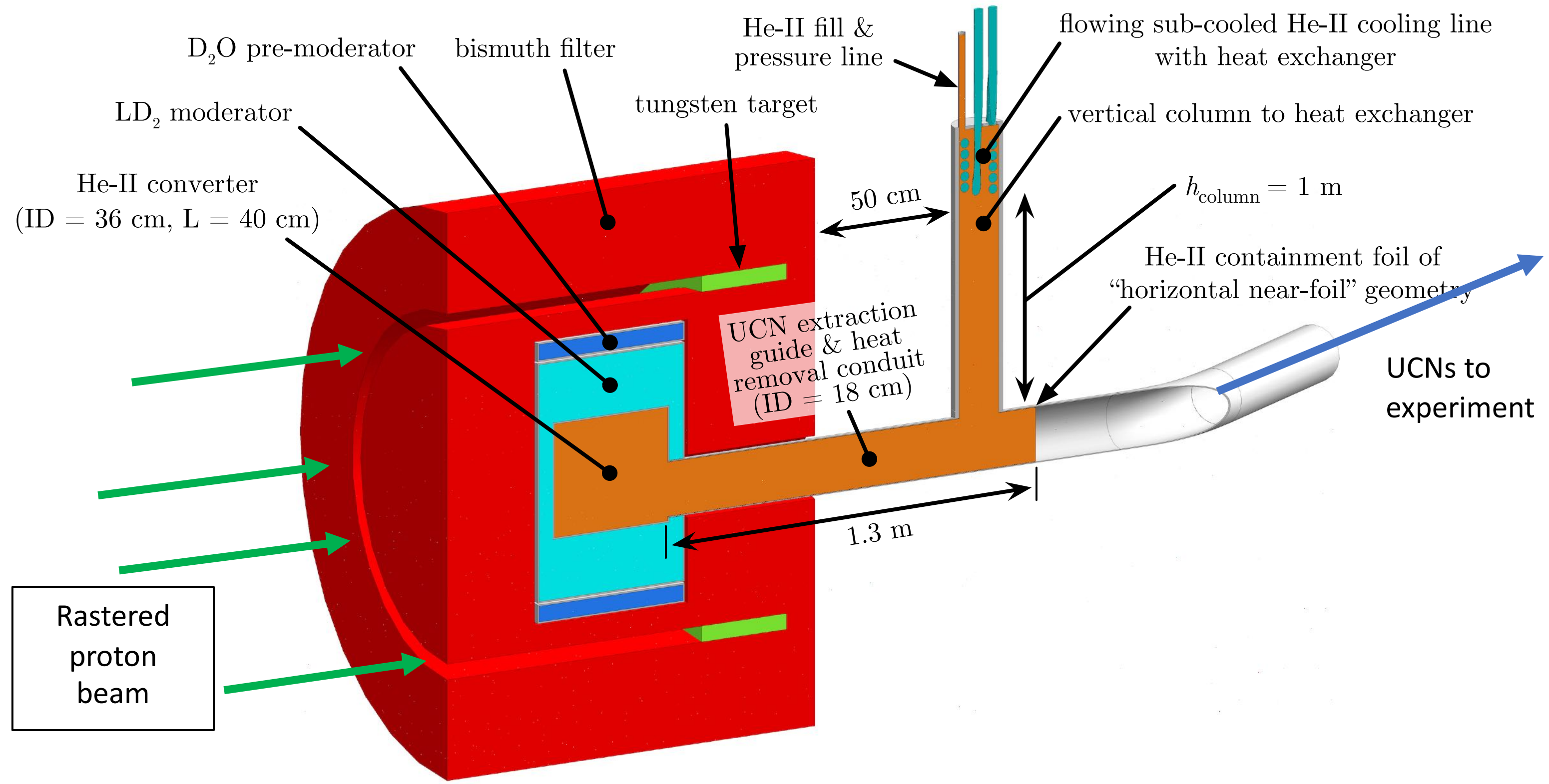
A next-generation inverse-geometry spallation-driven ultracold neutron source

Cite as: J. Appl. Phys. **126**, 224901 (2019); https://doi.org/10.1063/1.5109879
Submitted: 13 May 2019 . Accepted: 01 November 2019 . Published Online: 09 December 2019

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

COLLECTIONS

F This paper was selected as Featured

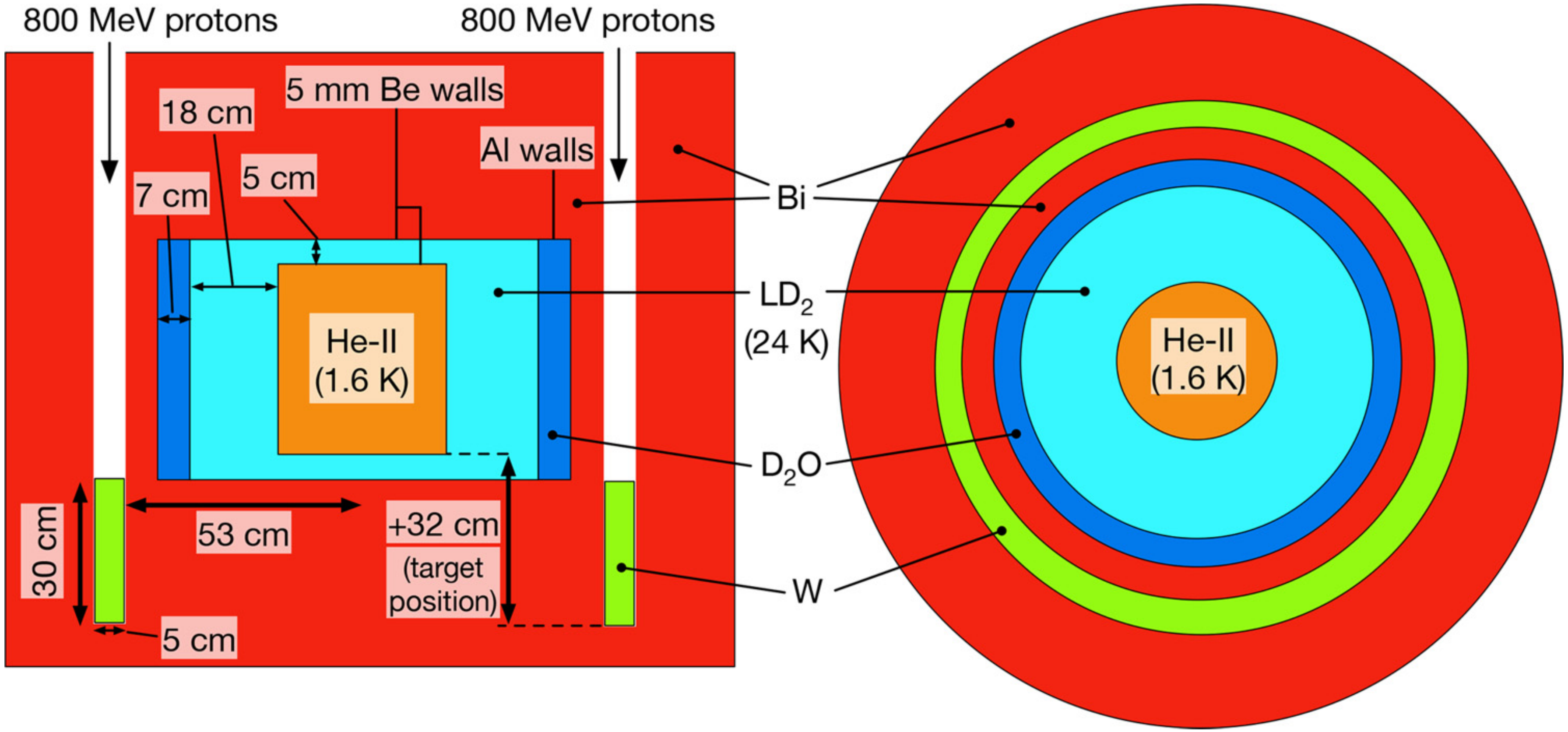


Our in-pile ^{4}He UCN source parameters

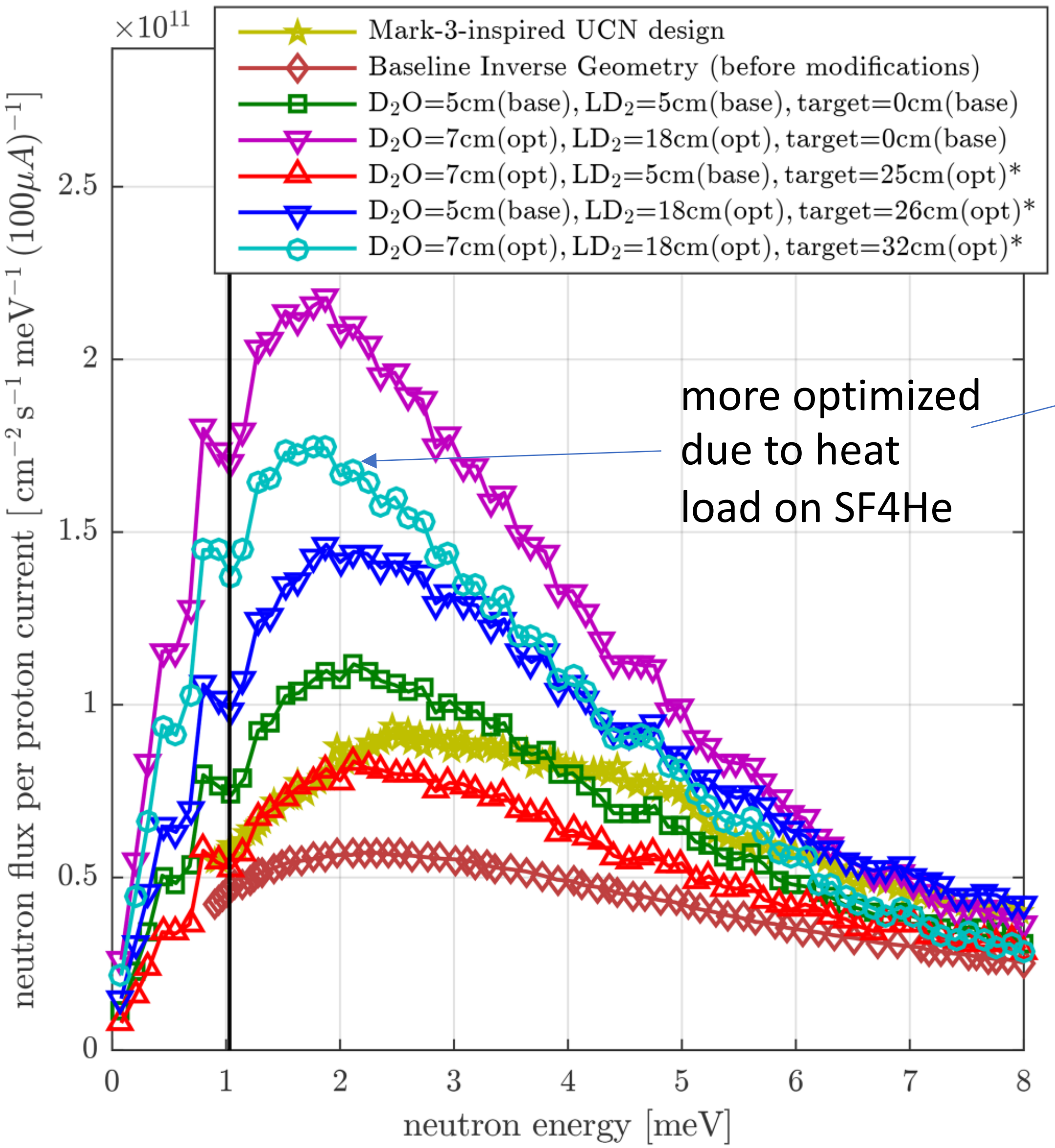
- Optimized for 1 MW proton beam power (@ 800 MeV)
- Water-cooling of spallation target
- Heat load on SF-4He 100 W maximum at 1.6 K
- Single-passage UCN extraction efficiency optimized along with cryogenic heat removal requirements

Maximizing flux of 8.9Å / 1 meV neutrons

- Rastered proton beam to distribute heating over cylinderical tungsten target => allows water edge cooling
- MCNP calculations bench-marked with Los Alamos’ Lujan Center Mark-3 target
- Place 40-L volume of superfluid ^{4}He embedded inside the target, pre-moderator, and moderator in “inverse geometry”
- Optimized for D2O premoderator thickness, LD_2 moderator thickness, and “target location”

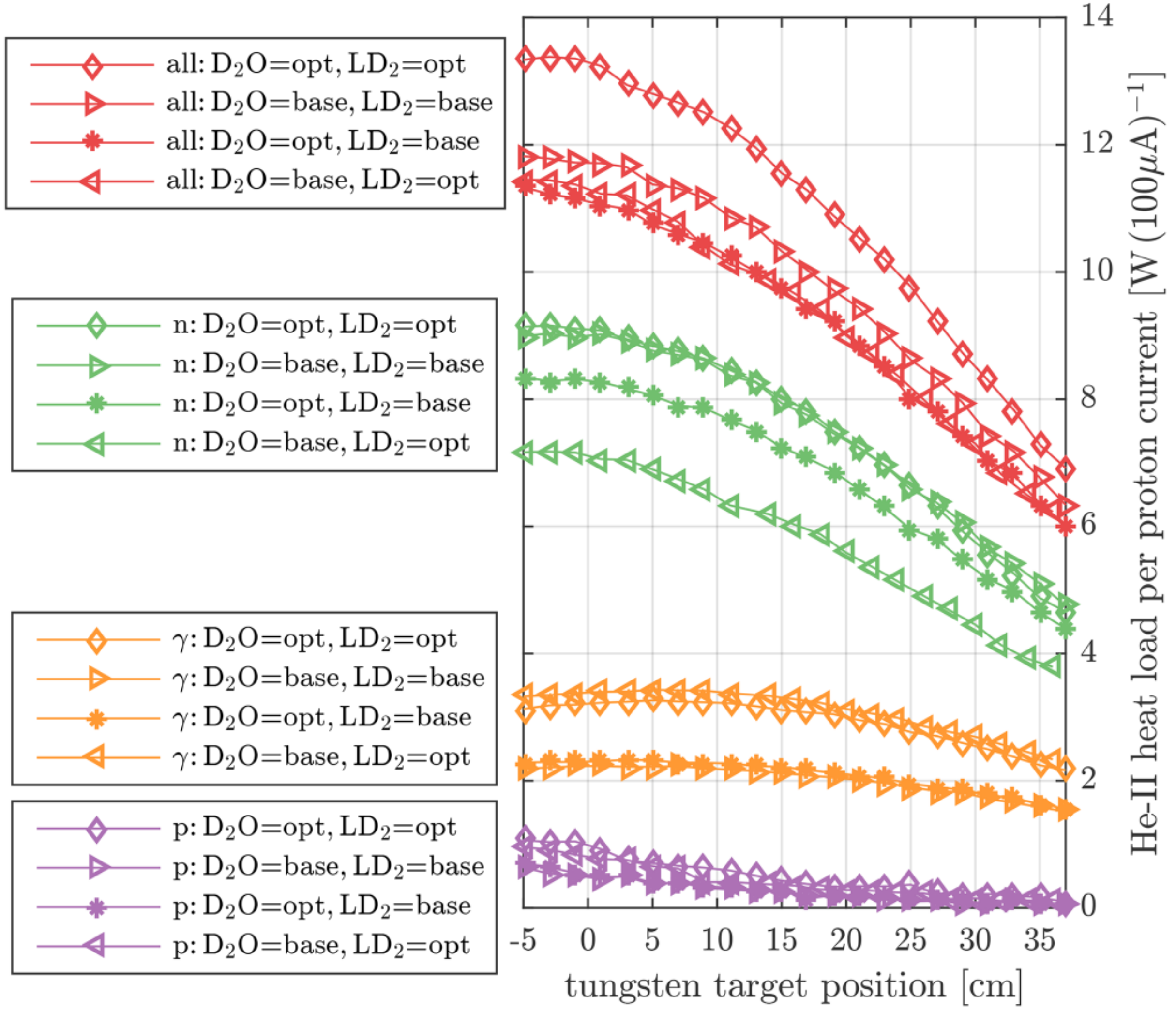


The neutron flux at SF-4He per 80 kW protons:



more optimized due to heat load on SF4He

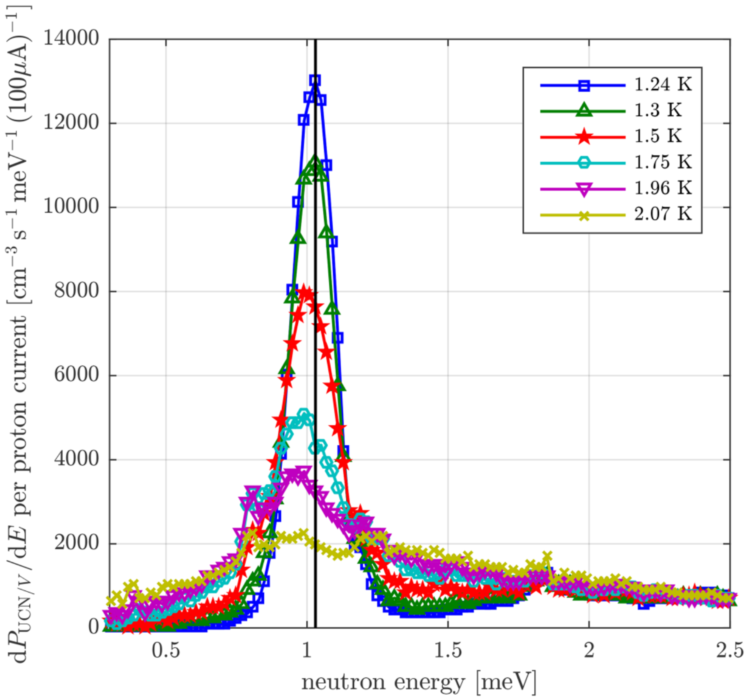
The SF-4He heat load per 80 kW protons:



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

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

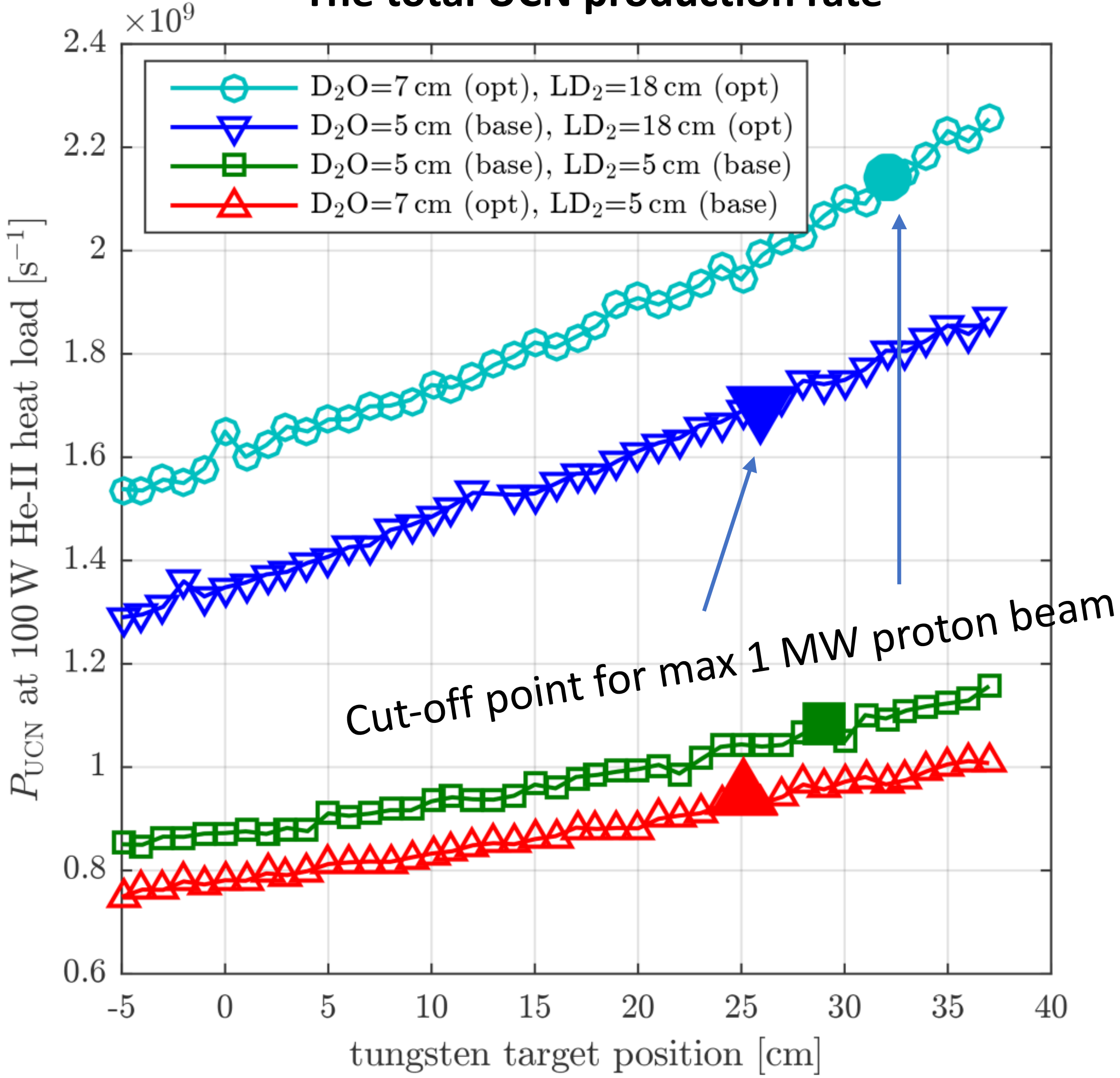
The CN-energy-differential UCN production rate (i.e. with multi-phonon UCN production)



Thanks to Ken Andersen’s data from 1994.

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

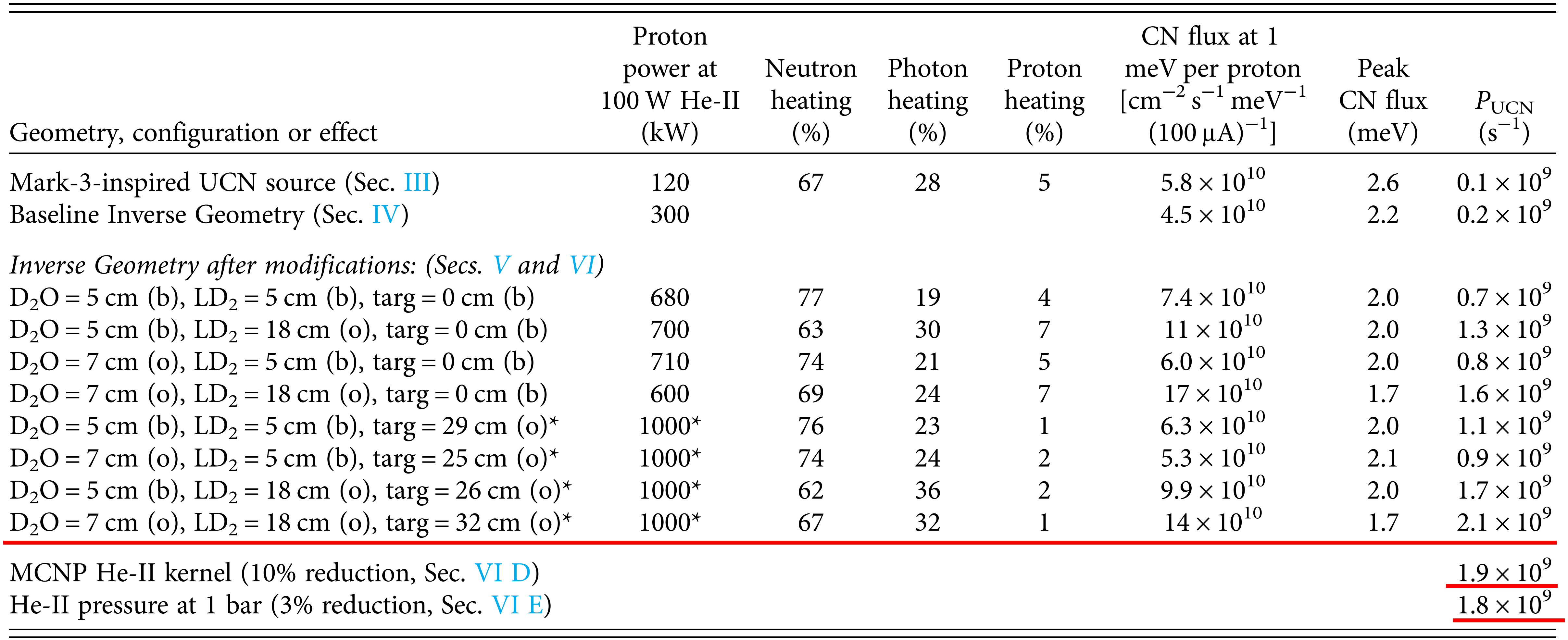
The total UCN production rate



Cut-off point for max 1 MW proton beam

- If greater proton beam power (e.g. 2 MW) then can move SF4He further upstream from target.
- The total UCN production rate for our boundary conditions is 2.1E9 UCN/s (before -15% reduction, see next)

Summary and additional effects on total UCN production rate

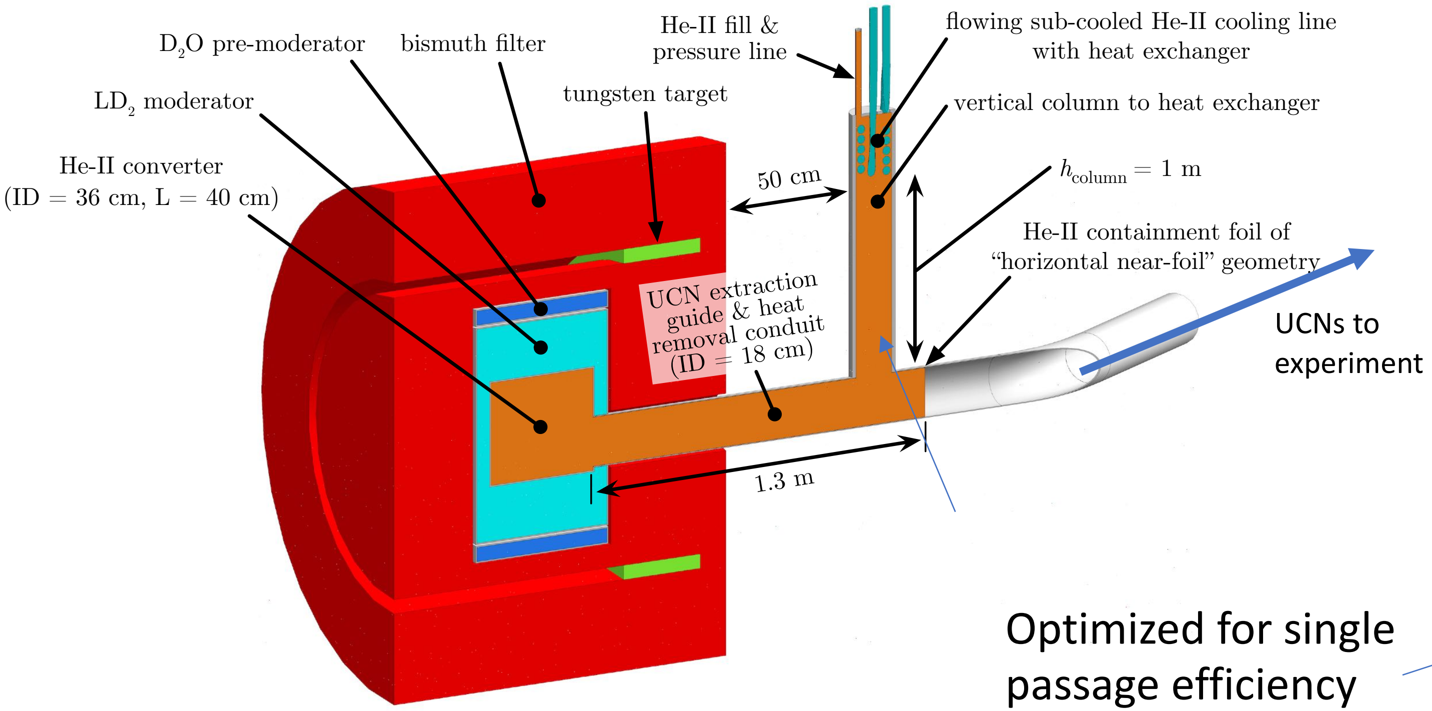


Geometry, configuration or effect	Proton power at 100 W He-II (kW)	Neutron heating (%)	Photon heating (%)	Proton heating (%)	CN flux at 1 meV per proton [$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{meV}^{-1}$ $(100\,\mu\mathrm{A})^{-1}$]	Peak CN flux (meV)	P_{UCN} (s^{-1})
Mark-3-inspired UCN source (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

Single-passage UCN extraction efficiency

- UCN extraction design allows 100 W heat extraction to produce ΔT < 50 mK (need > 18 cm Ø conduit) Our heat flux falls in the Gorter-Mellink regime (mutual friction between normal and superfluid components)
- Have 18 cm Ø Tee to heat exchanger. UCNs that reach heat exchanger assumed to be 100% loss
- Found adding diffuse reflections in some places helped (can be produced by macroscopic bumps or ridges)
- Horizontal extraction found to be best. SF4He 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 SF4He loss is ~55% of total.



Optimized for single passage efficiency

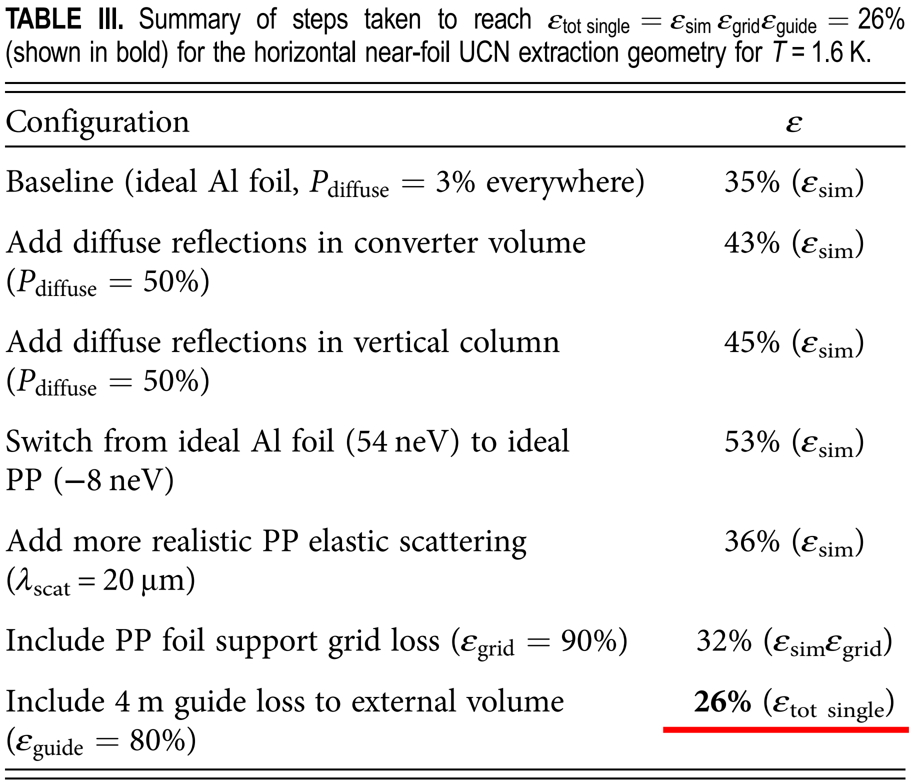


TABLE III. Summary of steps taken to reach $\varepsilon_{\text{tot single}} = \varepsilon_{\text{sim}}\varepsilon_{\text{grid}}\varepsilon_{\text{guide}} = 26\%$ (shown in bold) for the horizontal near-foil UCN extraction geometry for $T = 1.6$ K.

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 ($\lambda_{\text{scat}} = 20\ \mu\text{m}$)	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.**
- The UCN density inside the source is ~ 5 x 10^4 UCN/cm^3. (Not useful as density is not optimized.)
- If the 5 x 10^8 UCN/s current is used to fill an external "bottle" **assuming the no return approximation:**

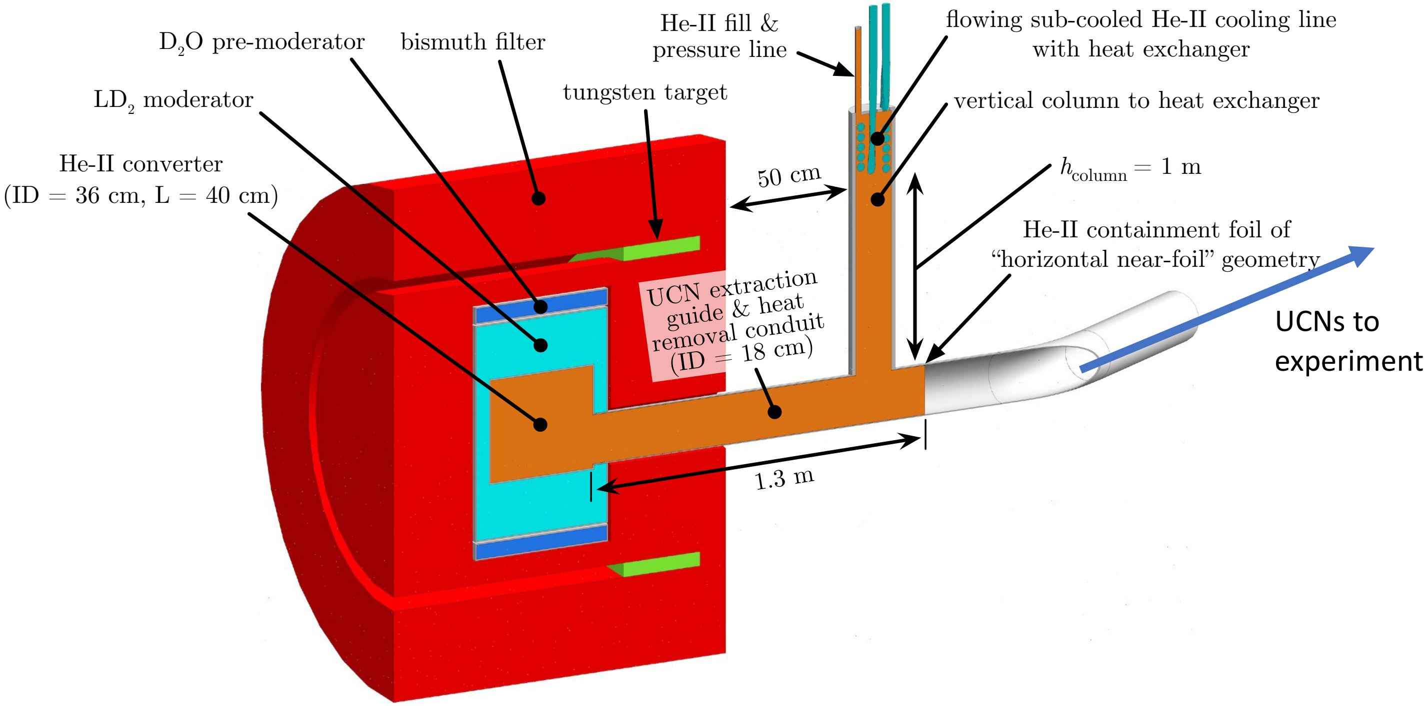
$V_{\rm bottle}$ (l)	5	50	500	5×10^3	5×10^4
$\rho_{\rm bottle}$ ($\times 10^4$ UCN cm^{-3})	1.12	1.11	1.05	0.80	0.31
$\tau_{\rm bottle}$ (s)	0.11	1.1	10	80	315

UCN density loaded into bottle

- 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)
- 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 $\sim (\epsilon_{\rm single\ passage})^{\rm average\ no.\ of\ passages}$

(This is why in-situ UCN experiments, where UCNs do not need to be transported, are so nice…)

Summary



- 40 L vessel SF4He @ 1.6 K with 100 W cooling
- 1 MW proton beam
- 1.8 x 10^9 UCN/s production rate
- Optimize for single-passage extraction to get 5 x 10^8 UCN/s current 4m away
- Ideal for filling large volume or flow-through UCN experiments
- Could offer very high VCN currents
- With 2 MW proton beam, optimum location of 4He vessel is further upstream of p-beam
- System works if proton beam hits the same spot (if cooling can be overcome, e.g. rotating wheel), then filter, moderator & pre-moderator would not need to be axially-symmetry