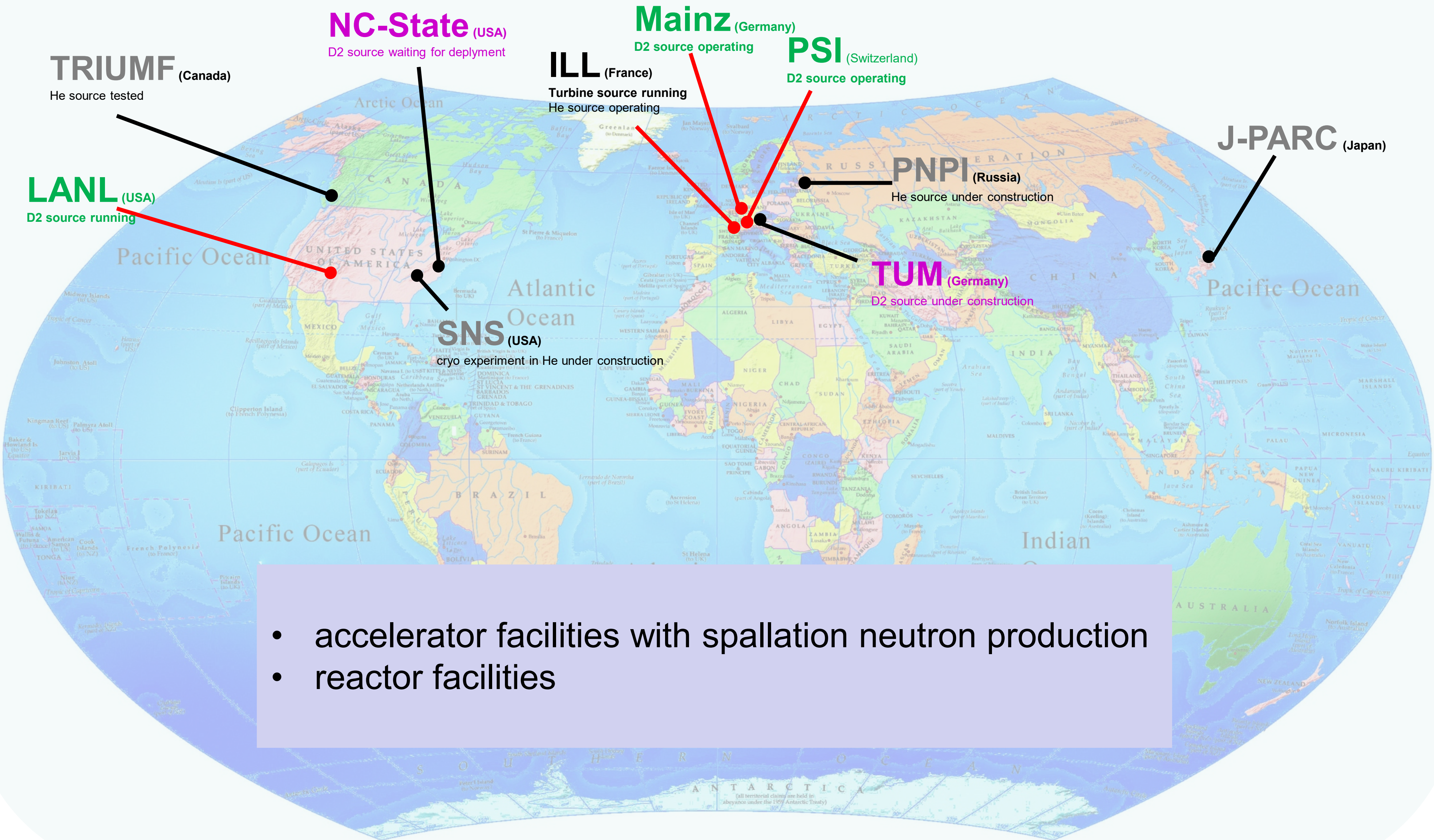
Ultracold neutron sources based on solid deuterium

Bernhard Lauss
Paul Scherrer Institute

Feb. 2022

ULTRACOLD NEUTRON SOURCES



- accelerator facilities with spallation neutron production
- reactor facilities

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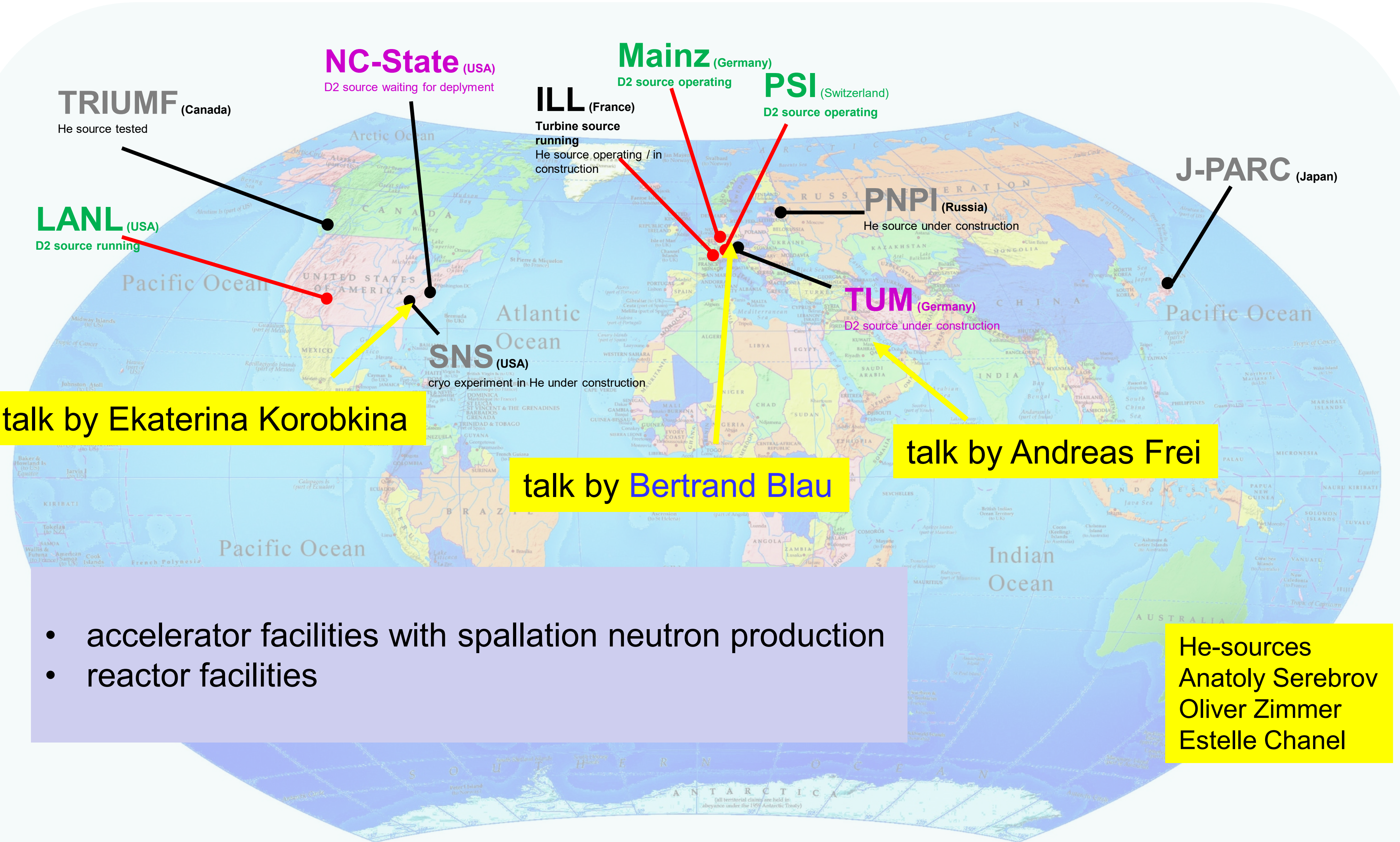
ULTRACOLD NEUTRON SOURCES

Ultra Cold Neutron Source



- accelerator facilities with spallation neutron production
- reactor facilities

D2 properties

UCN production

a neutron creates a phonon and looses almost all its energy

R. Golub, K.Boening, Z.Phys.B 51 (1983) 95
New type of low temperature source of ultracold neutrons and production of continuous beams of UCN

Z.-Ch.Yu, S.S.Malik, R.Golub Z.Phys.B 62 (1986) 137
A thin film source of ultracold neutrons

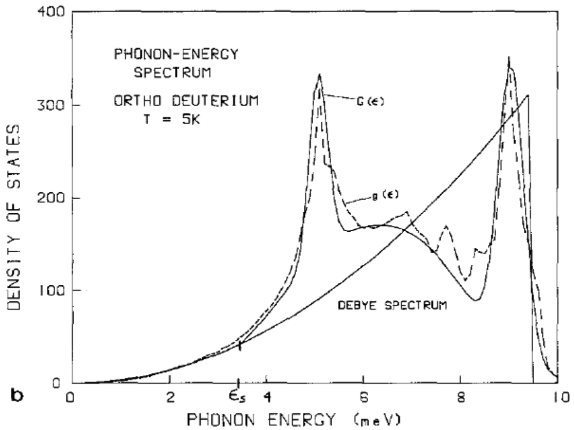
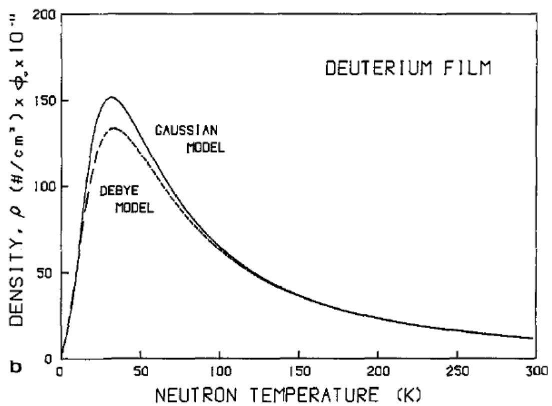


Fig. 1a and b. The two curves in each of the Figs. (**a**) and (**b**) correspond to the density of states. The curves marked $g(\varepsilon)$ were

calculates downscattering cross-section



UCN production per molecule in sD2
multiphonon Debye-Model

F. Atchison et al.

PRL **99,** 262502 (2007) PHYSICAL REV

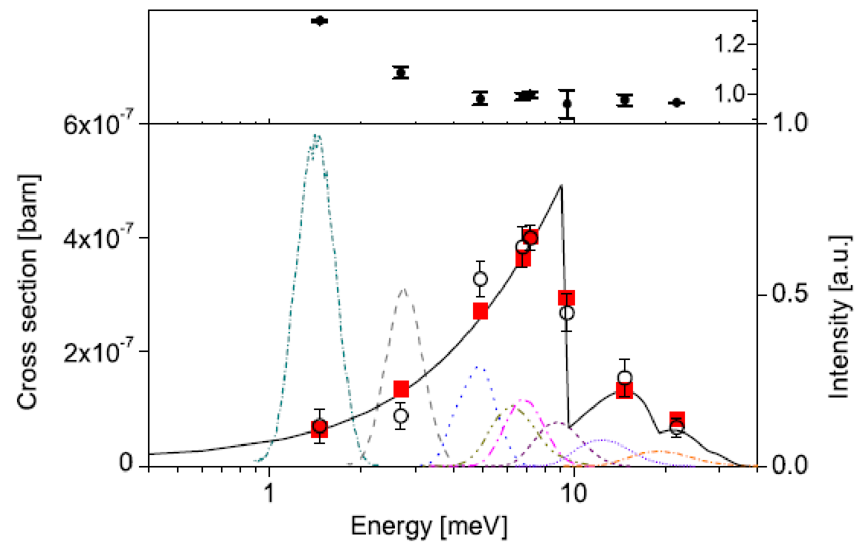
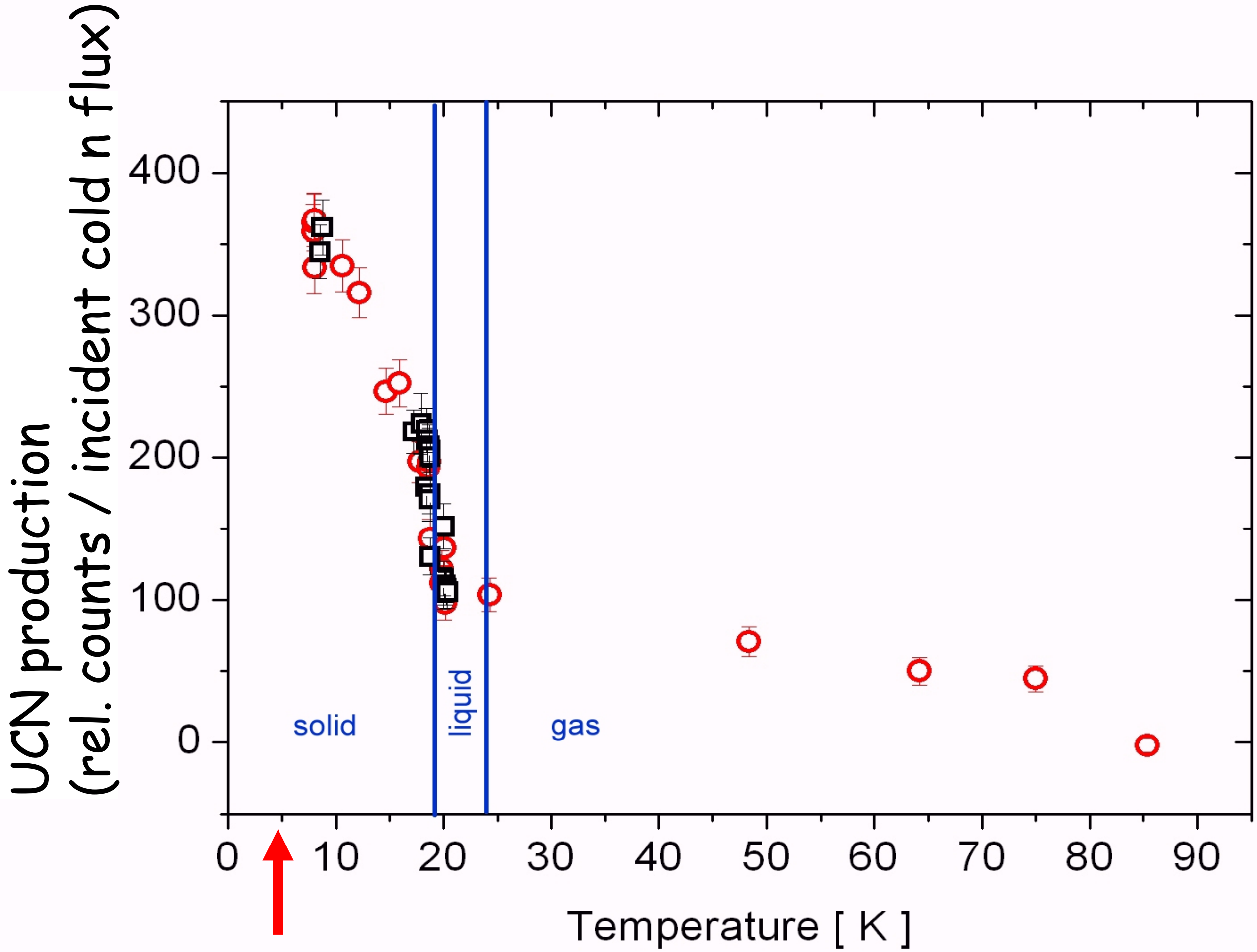


FIG. 4 (color online). Scaled measured (open circles) and calculated UCN production cross sections per molecule (multi-phonon Debye model: continuous black line and red squares; see text) for solid ortho $^2H_2$ at 8 K. The velocity-selected CN

strong dependence of the UCN production rate on state and temperature -> solid deuterium as production medium



operation point for sD2 source

several pioneering experiments in Gatchina by A.Serebrov's Group in 1990'ies demonstrated feasibility and high yield in sD2.

absolut cross section was measured subsequently at PSI

F. Atchison et al., Phys. Rev. C 71 (2005) 054601.
F. Atchison et al., Phys. Rev. Lett. 99 (2007) 262502.

UCN density

$$\rho_{UCN} = \Phi_0 \, R \, \tau_{UCN}$$

- cold neutron flux
- UCN production rate
- UCN lifetime in the moderator

- high neutron production rate
- 5K deuterium
- low losses

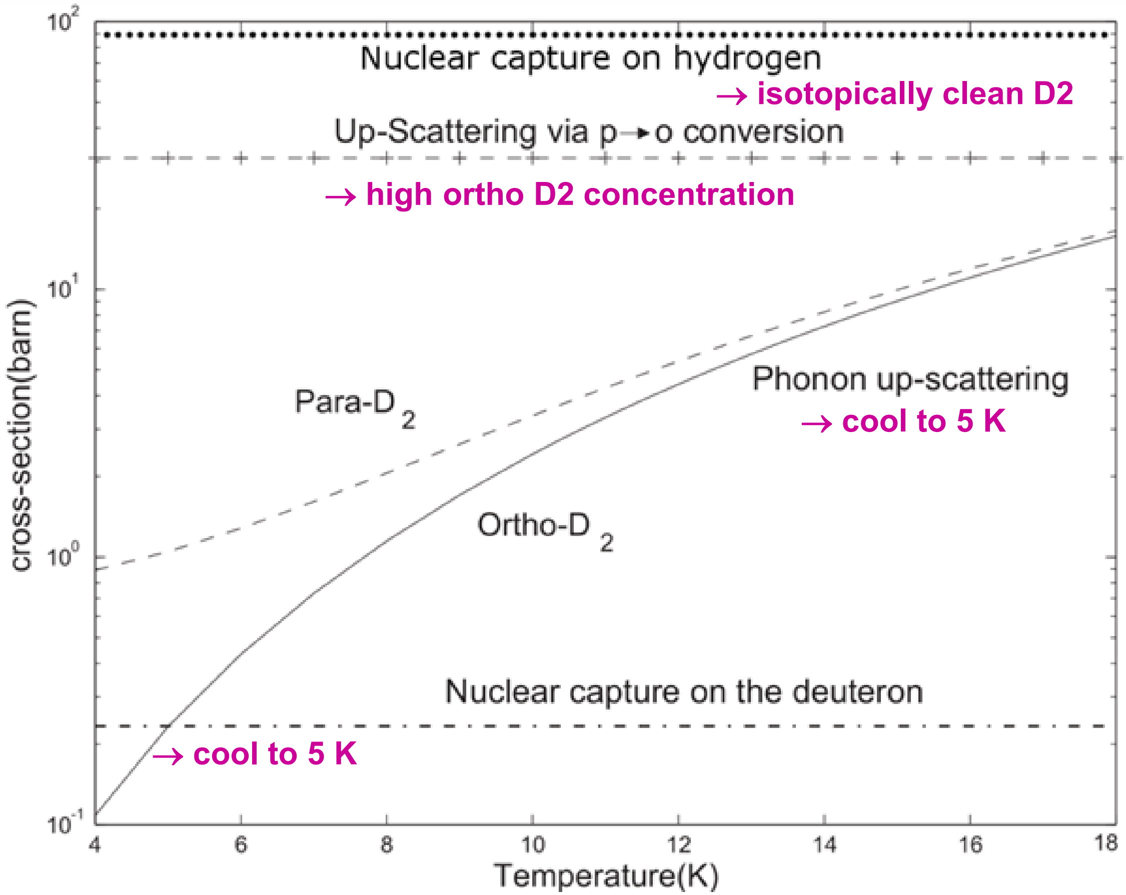
$$\tau_{UCN} = 1 / \sum (\sigma \, v)$$

loss cross sections (σ), velocity (v)

UCN losses

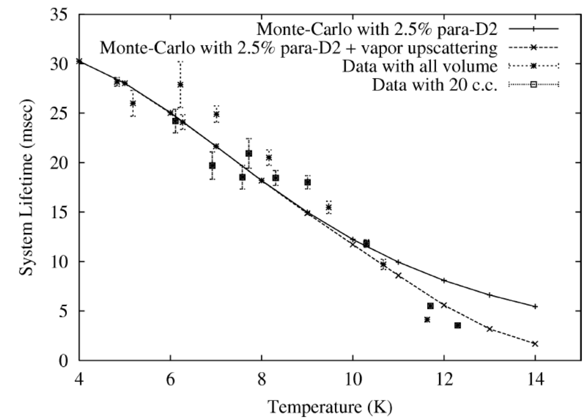
$\tau_{UCN} = 1 / \sum(\sigma v)$

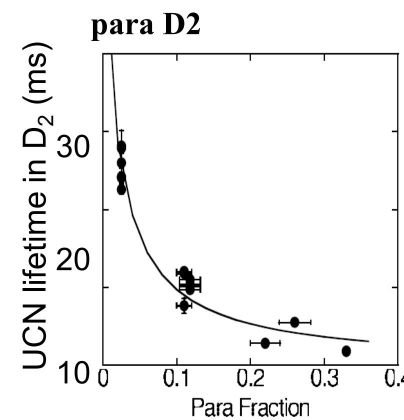
loss cross-sections



Modified plot from
C.-Y.Liu, A. Young, S.K. Lamoreaux, Phys. Rev. B 62 (2000) R3581

UCN lifetime in sD2 with respect to para D2 fraction and temperature
PhD Thesis C.-Y.Liu (2002)





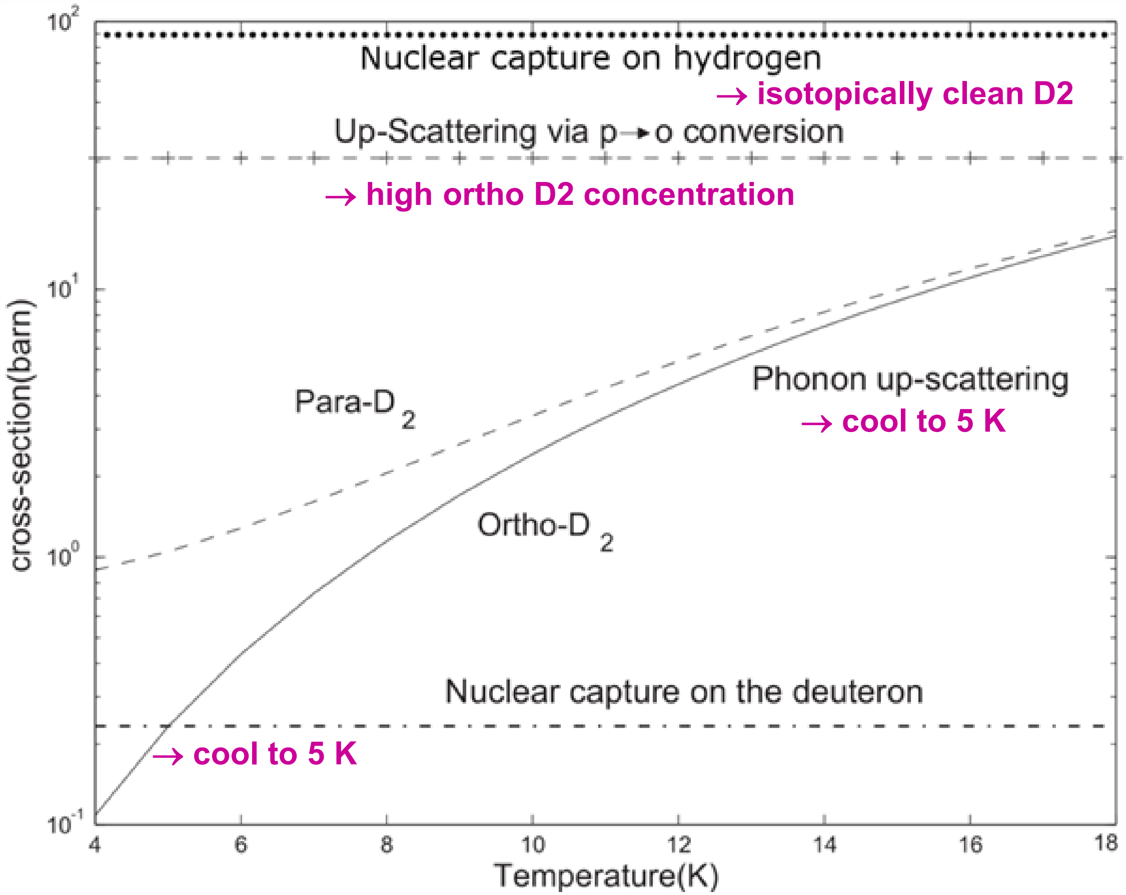
LANL Prototype Source
C.Morris et al, Phys.Rev.Lett.89(2002)272501

+ mechanical losses - gaps

UCN losses

$$\tau_{UCN} = 1 / \sum(\sigma v)$$

loss cross-sections



Modified plot from
C.-Y.Liu, A. Young, S.K. Lamoreaux, Phys. Rev. B 62 (2000) R3581

τ_{ucn} dominated by:
Nuclear capture
factor 640

σ(H) =0.3barn

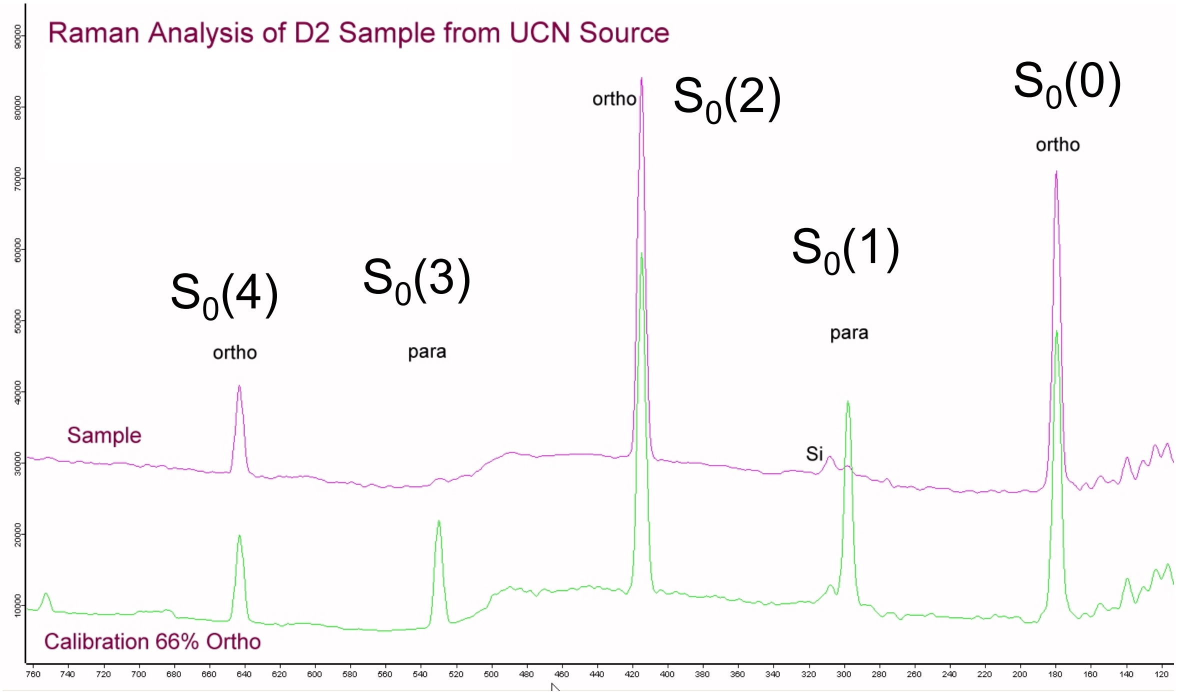
σ (D)=0.0005barn

UCN lifetimes in ortho D2 at 5K finally limited to ~150ms by nuclear capture
-> UCN extraction important

+ mechanical losses - gaps

Check conversion of Ortho- to Para-D2 and hydrogen (HD) concentration

rotational Raman peaks

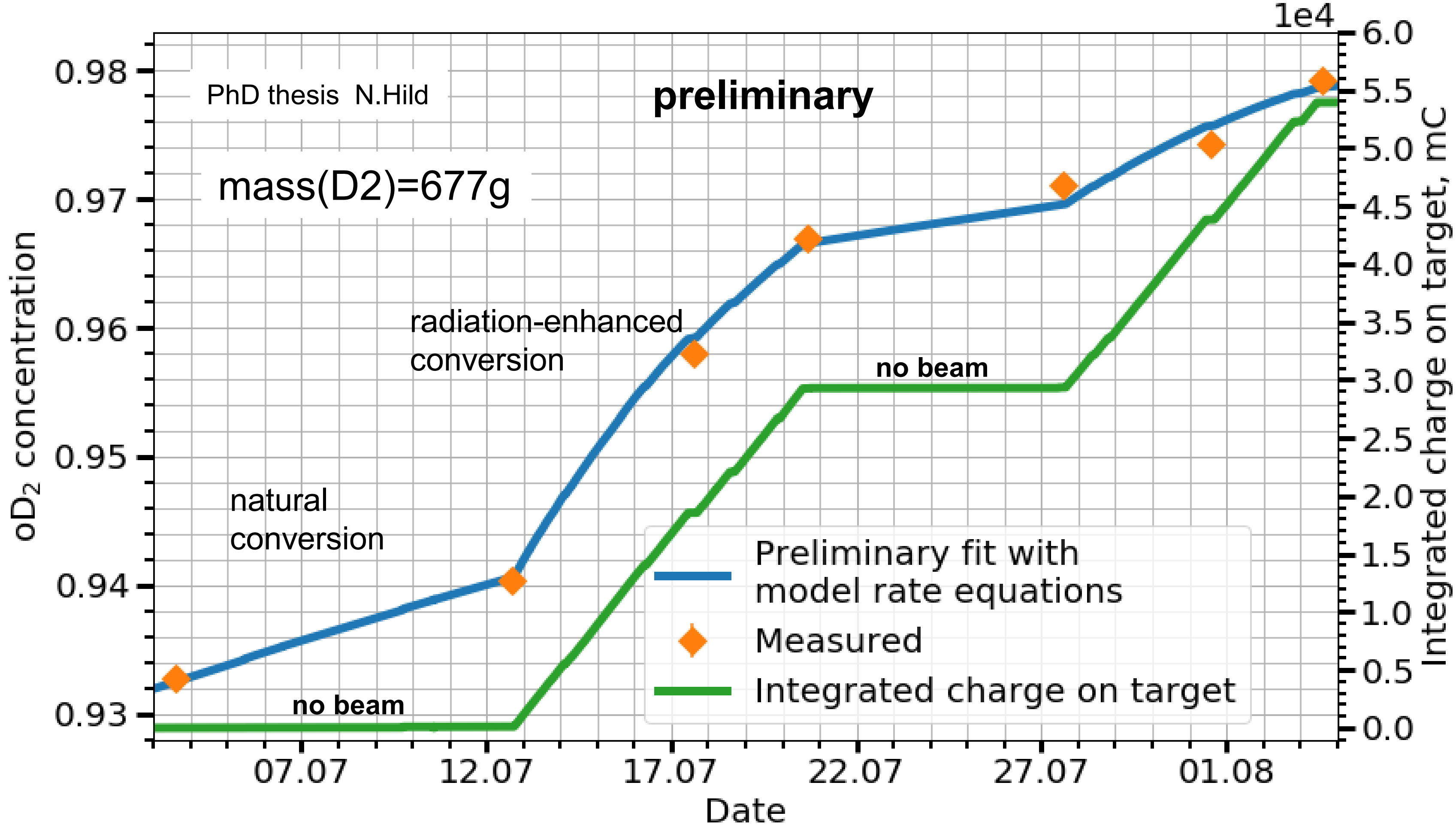


conversion of room-temperature D2 (66% Ortho) to ~96% Ortho in e.g. Oxisorb at liquid D2 temperature.

at PSI observed >99.8 % orthoD2
and <0.2% HD molecular contamination
PhD. Thesis N.Hild ETH (2019)

Radiaton conversion of sD2

at PSI UCN source measured radiation-enhanced conversion



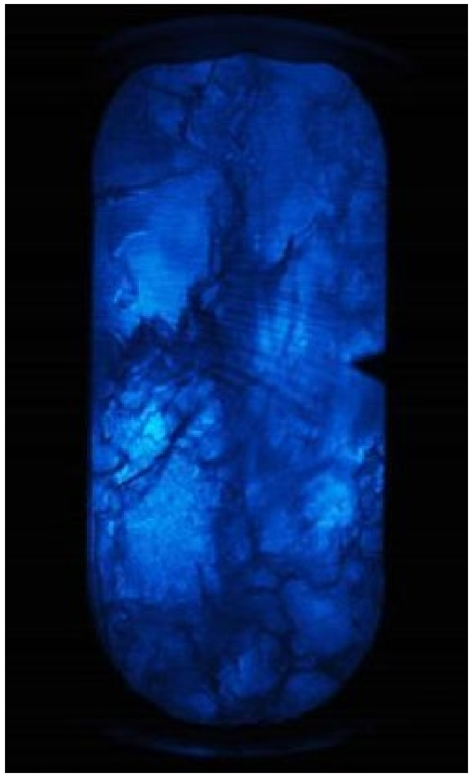
liquid D2 (at SINQ) - 76% ortho D2 equilibrium

F. Atchison et al. Phys Rev.B68 (2003) 094114

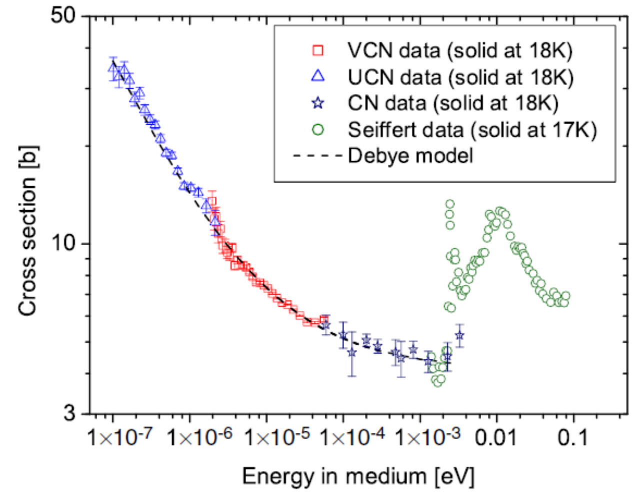
Measured D2 total Cross-Section

slow crystal

fast growing



Photos: PhD thesis M.Kasprzak



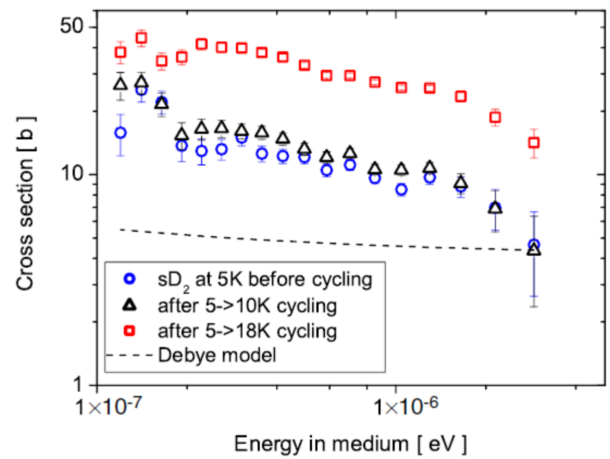


FIG. 2 (color online). Measured cross sections per deuterium molecule for UCN energies. The data sets correspond to the differently treated target crystals measured at 5 K, either after careful cooldown only, or after thermal cycles between 5 and 10 K or between 5 and 18 K. The expected cross section for the ideal crystal can obviously not describe the measured data.

F.Atchison et al., Phys.Rev.Lett. 95 (2005) 182502

Deuterium Fermi Potential

UCN get a kick when exiting the solid deuterium due to the neutron optical potential of 104 neV → minimum velocity favorable for UCN extraction

I.Altarev, ... M.Daum..et al.
Phys.Rev.Lett. **100,** 014801 (2008)

PRL **100,** 014801 (2008) PHYSICAL RE

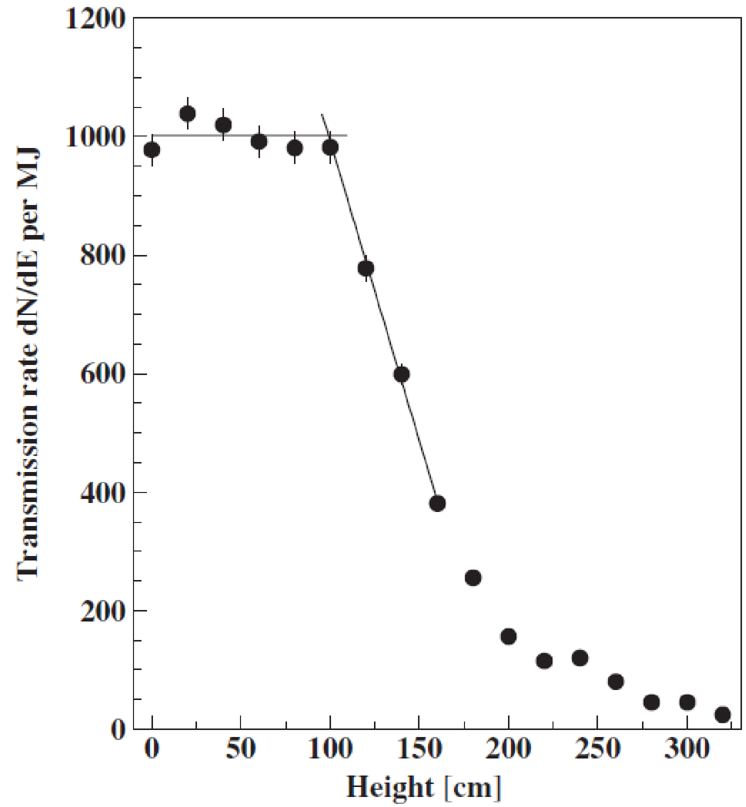


FIG. 2. Data taken with the gravitational spectrometer. The UCN transmission rates per megajoule of the reactor power after background subtraction are plotted against the vertical height of the gravitational spectrometer. The two lines represent the fit to the data, see text.

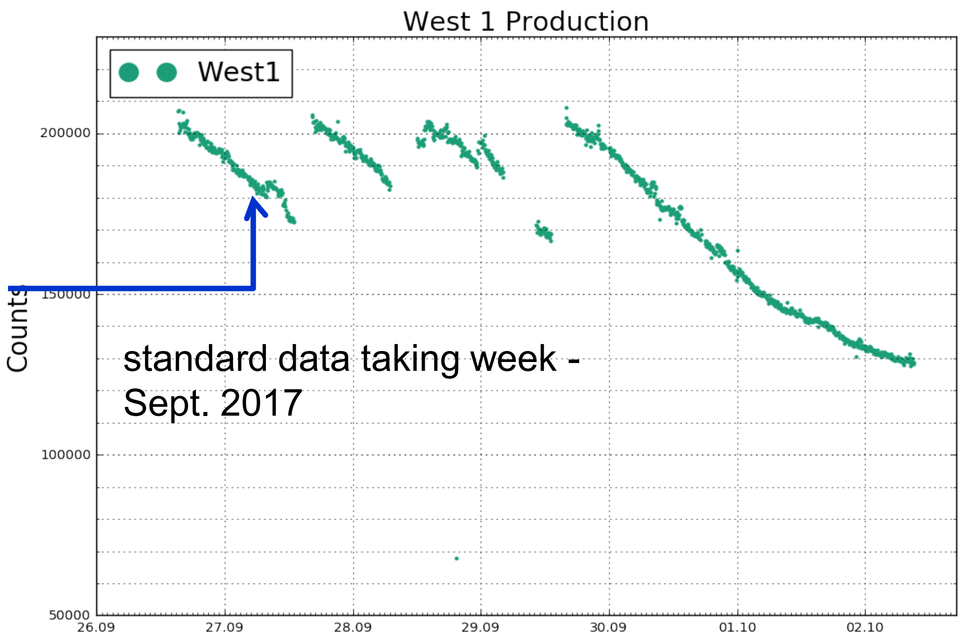
Time behavior of UCN intensity
Frost formation

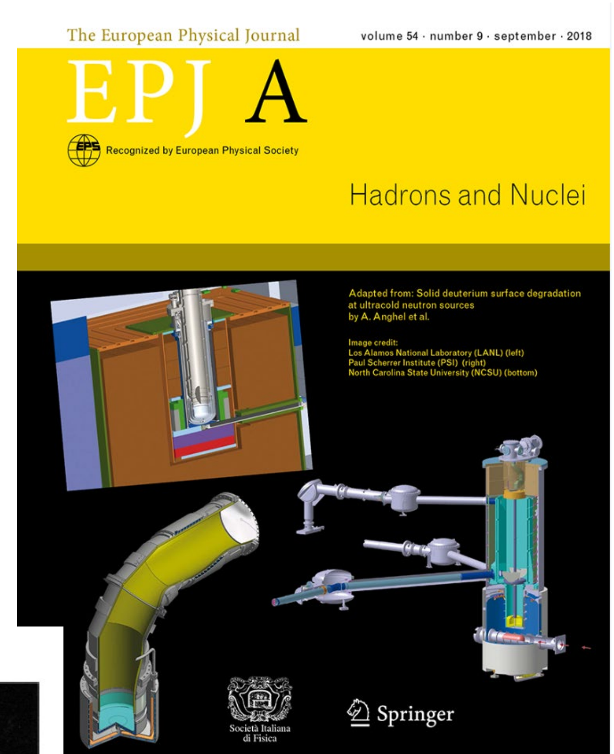
similar effect observed at PSI, LANL and NCSU

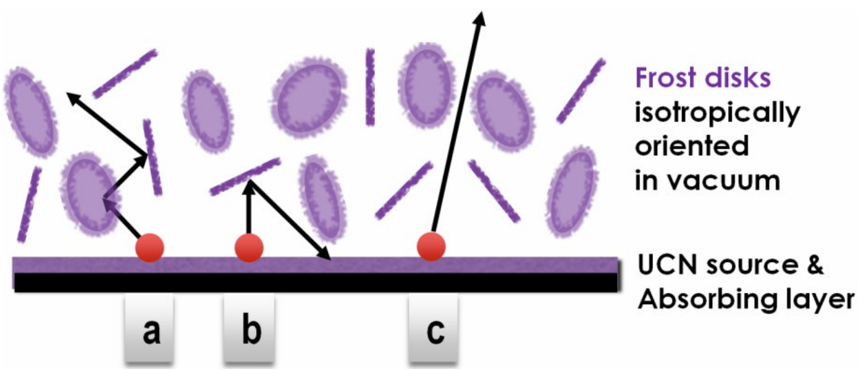
EPJ A Highlight - Solid deuterium surface degradation at ultracold neutron sources

Published on 11 September 2018

conditioning procedure regains full intensity







Eur. Phys. J. A (2018) 54: 148

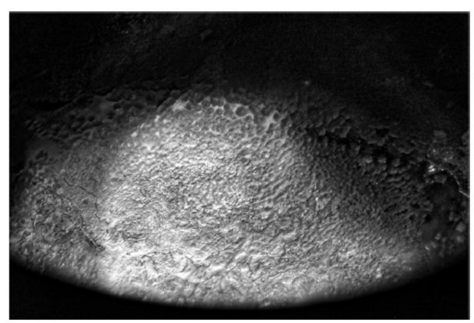
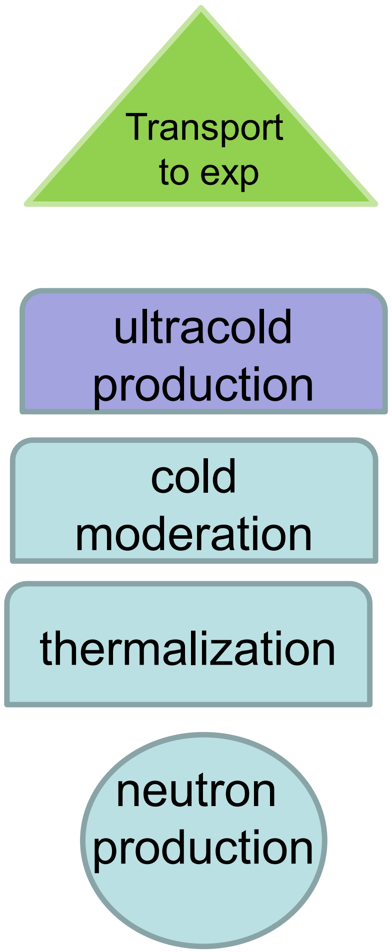


Fig. 15. Zoomed and post-processed image of the sD_2 surface after thermal pulsing.

Talk by Ekaterian Korobkina

Basic components of operating UCN sources



D2

D2 / Plastics

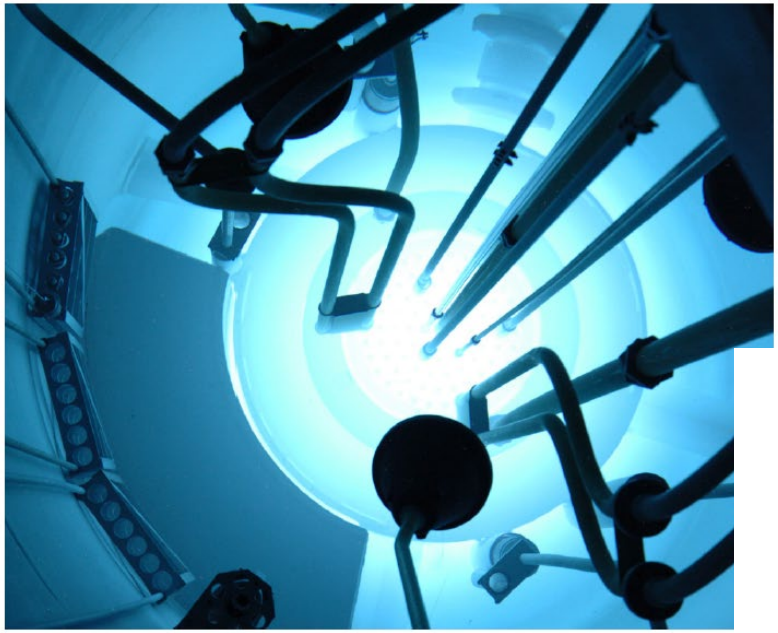
D2O / Plastics

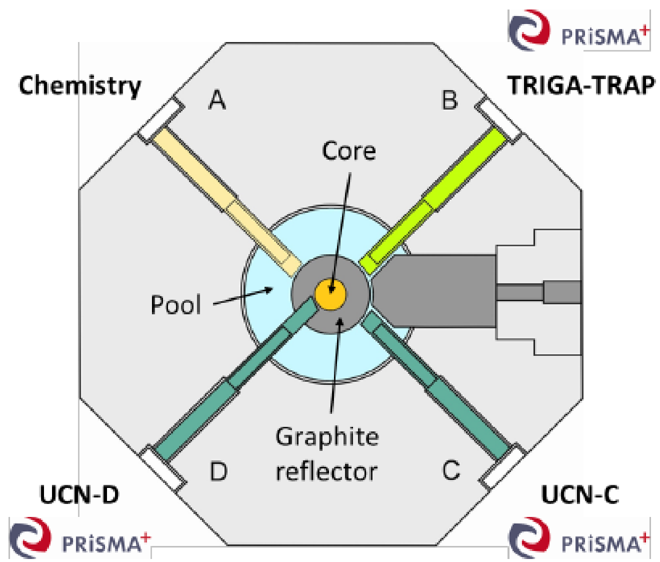
spallation @ accelerator
fission @ reactor

TRIGA - UCN source
Johannes Gutenberg University - Mainz - Germany

TRIGA Mainz

- Pulsed or DC
- Pulse:
  - 30 ms width
  - 250 MW_{th}
  - 10^{15} n/cm^{2}s
  - 5 pulses/h
- 4 side beam ports
- 2 UCN sources





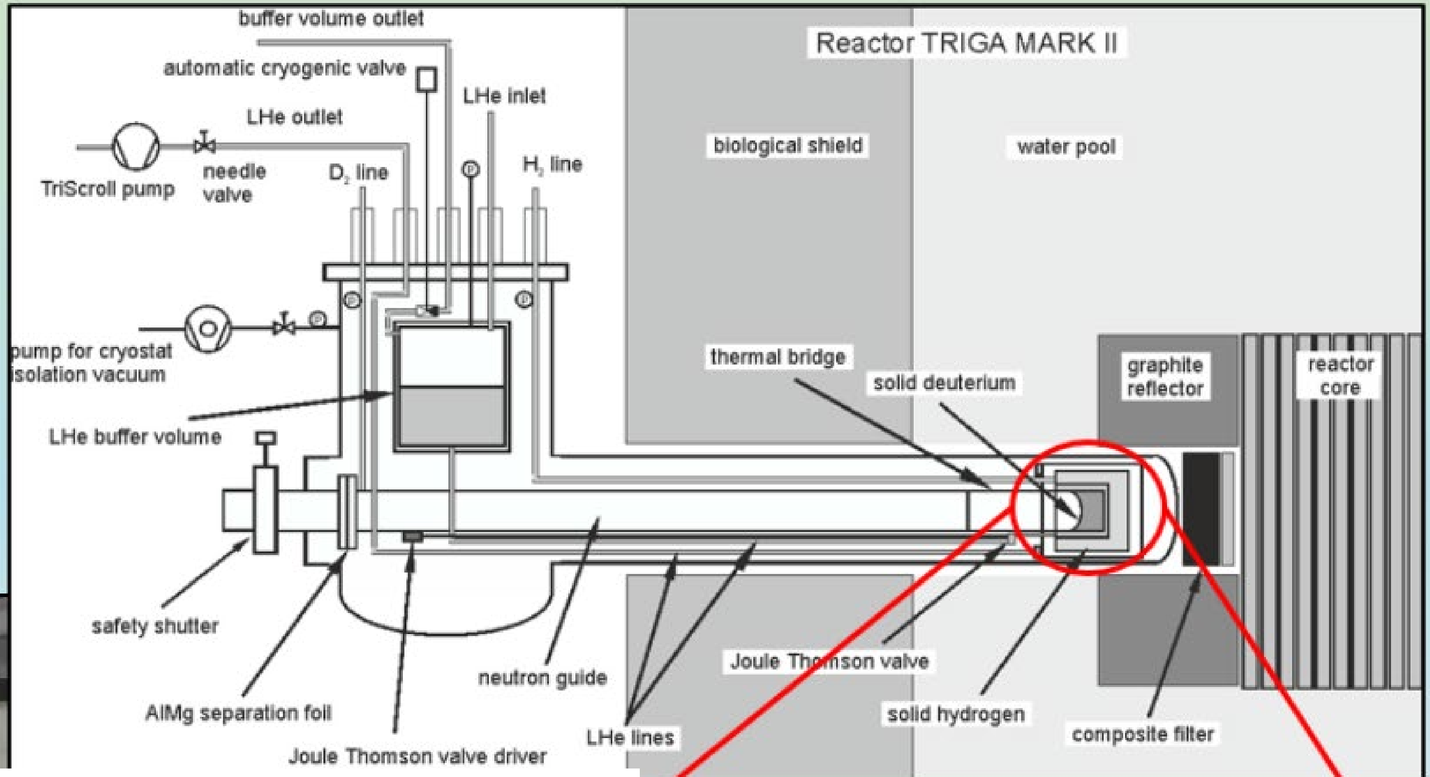
Figures courtesy D. Ries

TRIGA - UCN source

total length: 4.5 m
inner diameter of
beam port: 66 mm

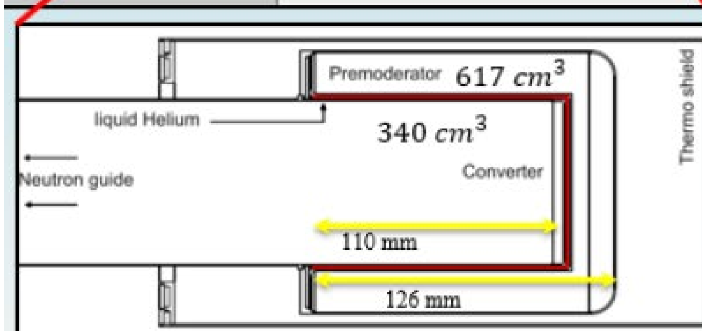
converter: solid D_2
pre-moderator: solid H_2, CH_4

cooling with liquid Helium
He consumption
controlled by scroll pump
(8-10 l/h liquid Helium)



Premoderator	Freeze-out rate (mol/h)	Total amount of gas (mol)	Freeze-out time (typically) (h)	Temperature at the nose during freeze-out (K)
H_2	1.24	≈ 20	≈ 16	7.6
D_2	1.04	≈ 15	≈ 14	7.6
CH_4	0.52	≈ 10	≈ 20[(*)]	≈ 95
D_2 converter	0.51	8	≈ 16	7.1

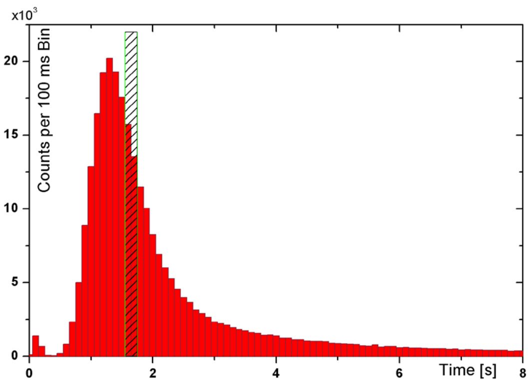
[(a)] The temperature across the sD_2 converter was calculated using the heat transfer simulation tools of COMSOL Multiphysics. It varies from 6 K in the areas towards the *l*He-cooled walls to about 8 K at the crystal's surface facing the thermal bridge.



[Karch et al., doi:10.1140/epja/i2014-14078-9, 2014]

TRIGA - UCN source

reactor pulse 30 ms
--> UCN pulse ~1.5s



gain with premoderator

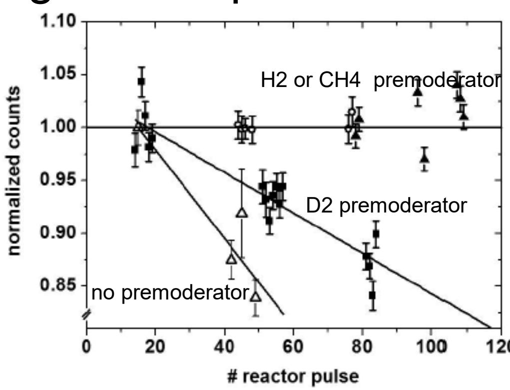


Fig. 5. Normalized UCN&VCN counts measured as a function of the number of reactor pulses. The sequence of flow mode and

J.Kahlenberg et al., Eur.Phys.J. A 53 (2017) 226

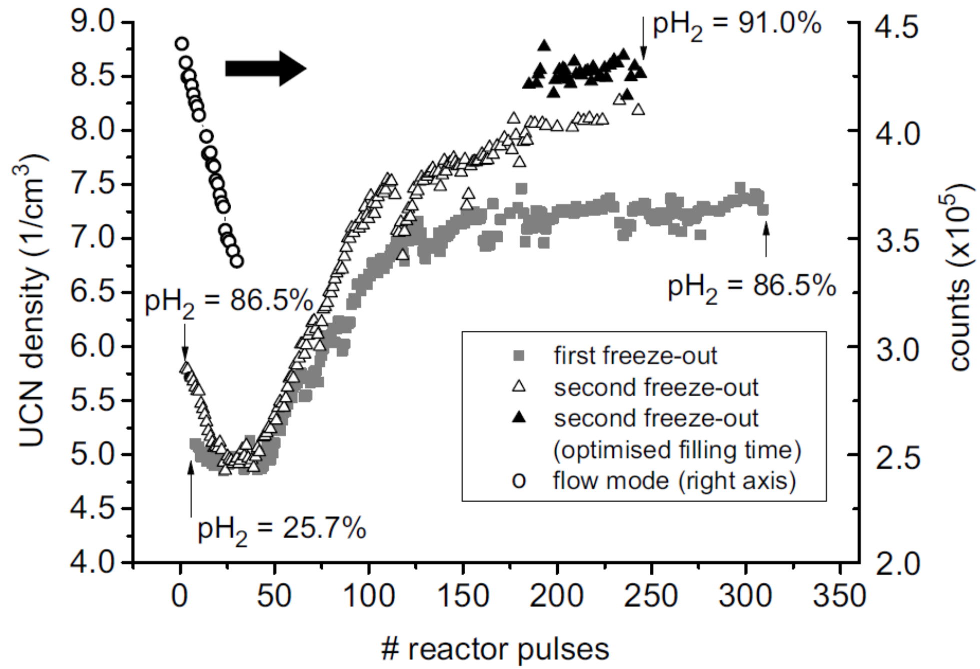


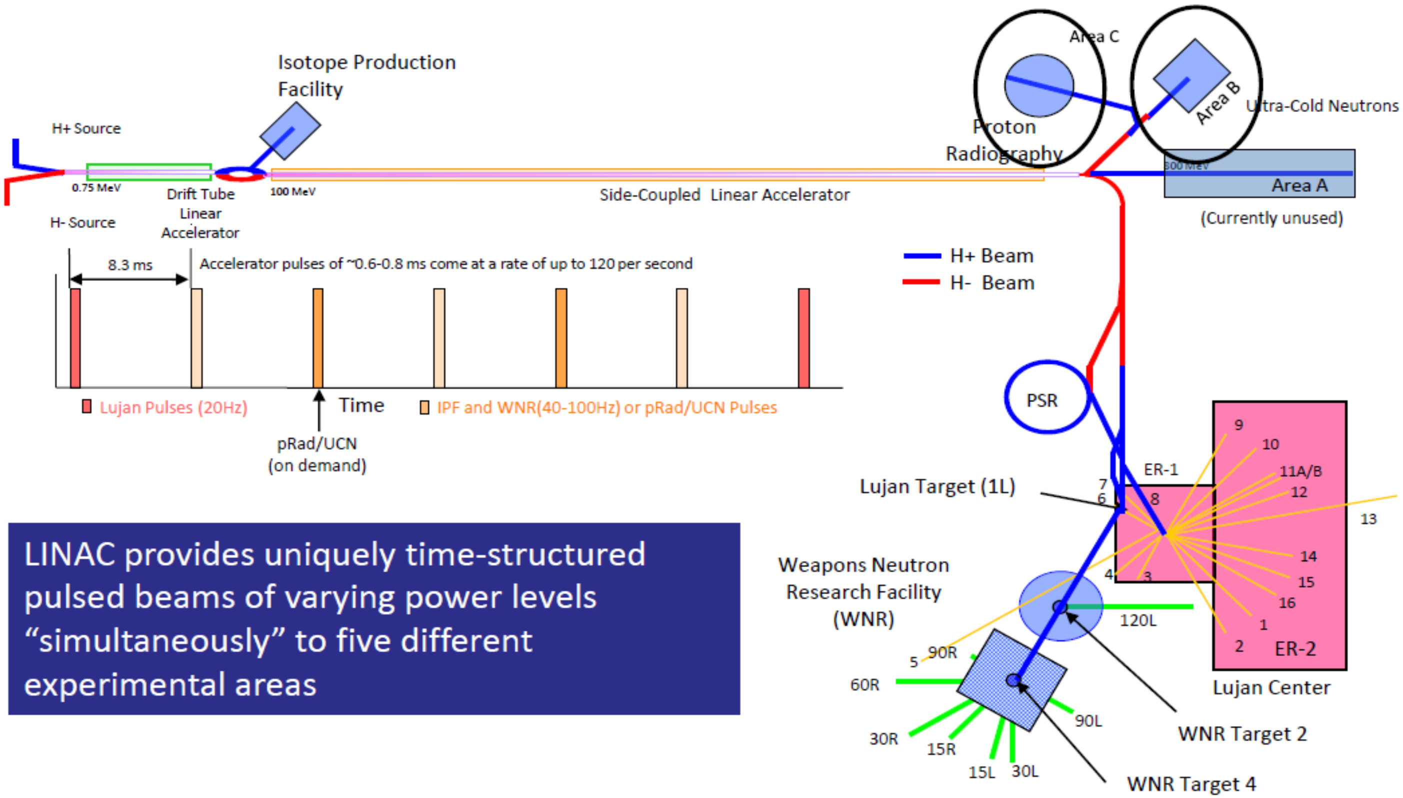
Fig. 4. UCN densities measured in vertical extraction after upgrade a), b), and c) *versus* the number of reactor pulses.

Crystal grown directly from D_2 gas at vapor pressures of 50–130 mbar - typically ~8mol mass

UCN output decrease with operation time(# of puses) (thermal shielding effect) for a few pulses and then stays high

UCN source
Los Alamos National Laboratory

pulsed 800 MeV proton beam - 120 Hz, 0.6/0.8 ms pulse width -> 20 Hz to UCN target



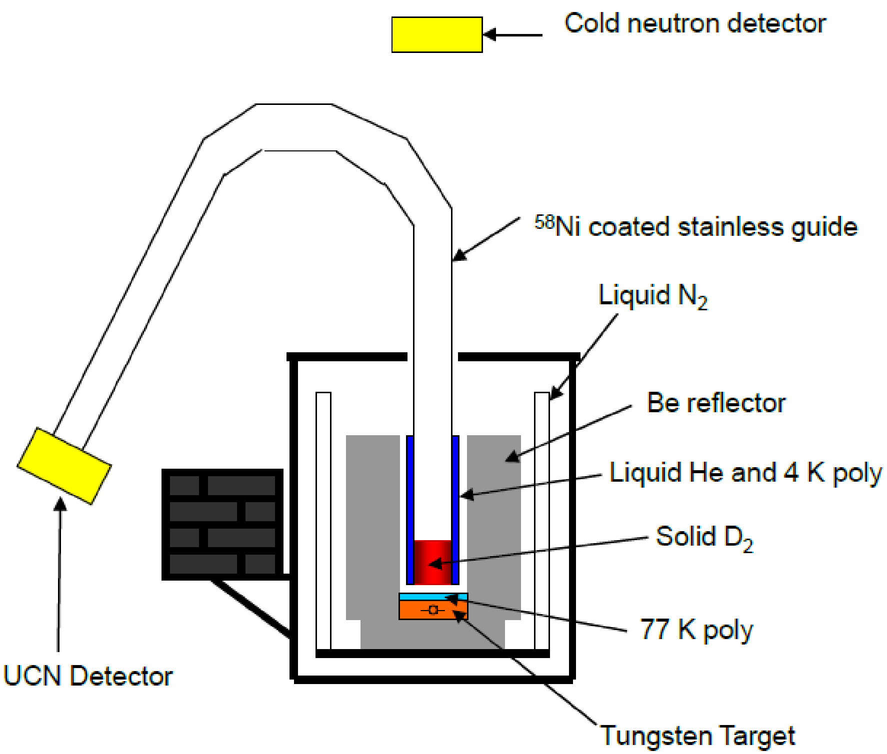
LINAC provides uniquely time-structured pulsed beams of varying power levels “simultaneously” to five different experimental areas

- peak proton current 12 mA,
- bursts of 10 pulses each 625μs long at 20 Hz,
- gap between bursts of 5 s
- total charge per burst ~45 μC in 0.45 s.
- time averaged current ~9 μA.

T.M.Ito et al., Phys.Rev.C97 (2018) 012501

Figure C.Morris

LANL
first spallation-based operating sD2 UCN source

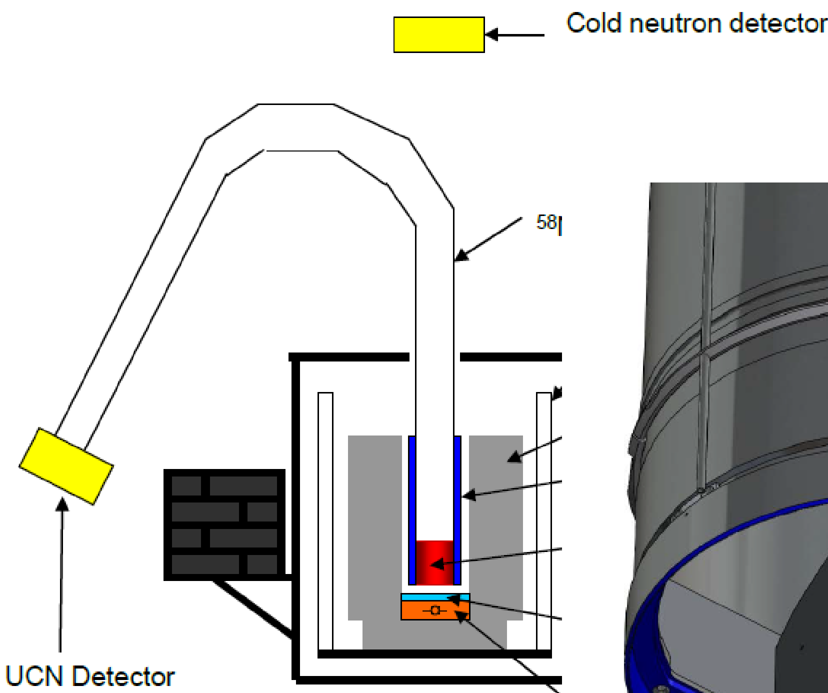


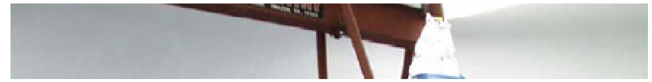
P-25 Nuclear and Particle Physics
LOS ALAMOS NATIONAL LABORATORY

10 vertical extraction
-> UCN fall back

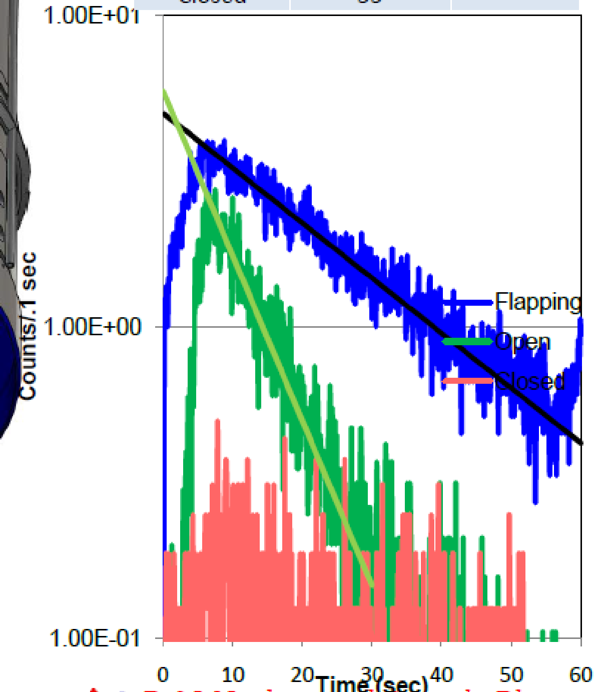
Figure C.Morris

LANL
first spallation-based operating sD2 UCN source





Column1	Counts	Tau
	/5 pulses	sec
Flapping	992	26+/-.2
Open	269	8.1+/-.1
Closed	53	



P-25 Nuclear and Particle Physics
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Figure C.Morris

LANL - UCN facility

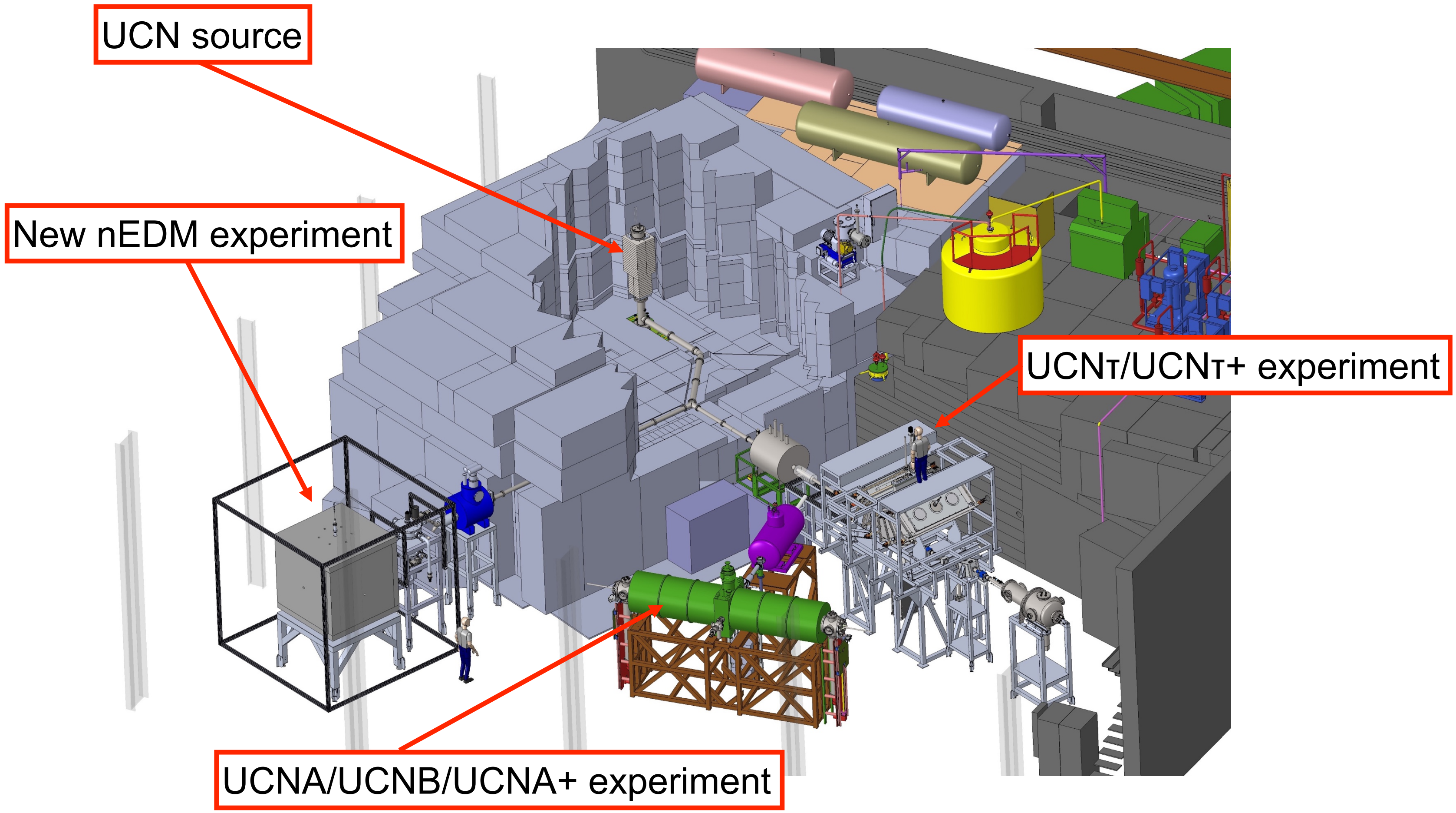
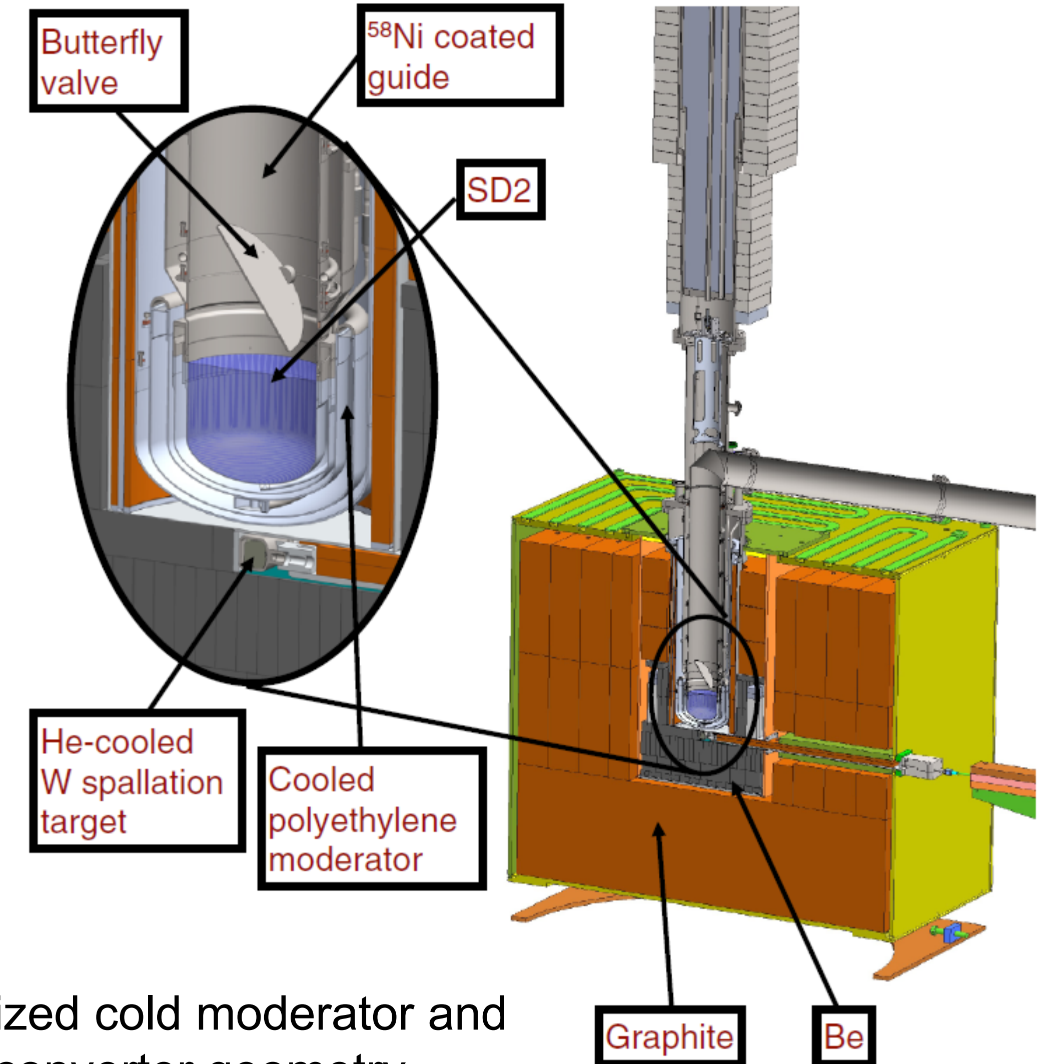


Figure T.Ito

LANL - upgraded UCN source

T.M.Ito et al., Phys.Rev.C97 (2018)012501



Spallation neutrons from W target
~ 2 MeV

↓

Thermal neutrons in Be and graphite moderator
~ 25 meV

↓

Cold neutrons in polyethylene cold moderator
~ 6 meV

↓

Ultracold neutrons in SD2 converter
~ 100 neV

optimized cold moderator and UCN converter geometry

~factor 4 improvement

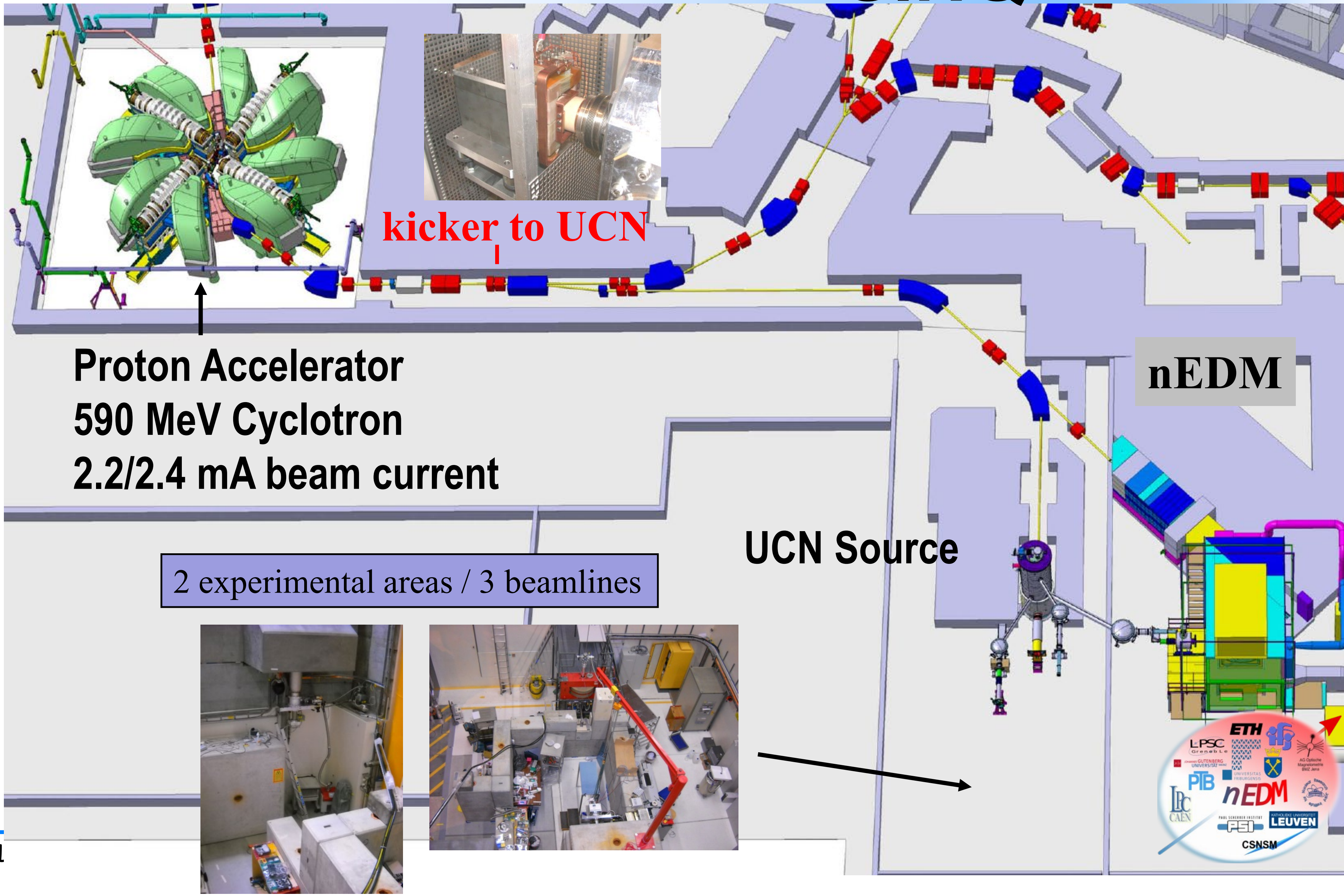
Figure T.Ito

UCN source
Paul Scherrer Institut

PAUL SCHERRER INSTITUT PSI

High Intensity Proton Accelerator (HIPA) complex

Ultra Cold Neutron Source



The PSI UCN source

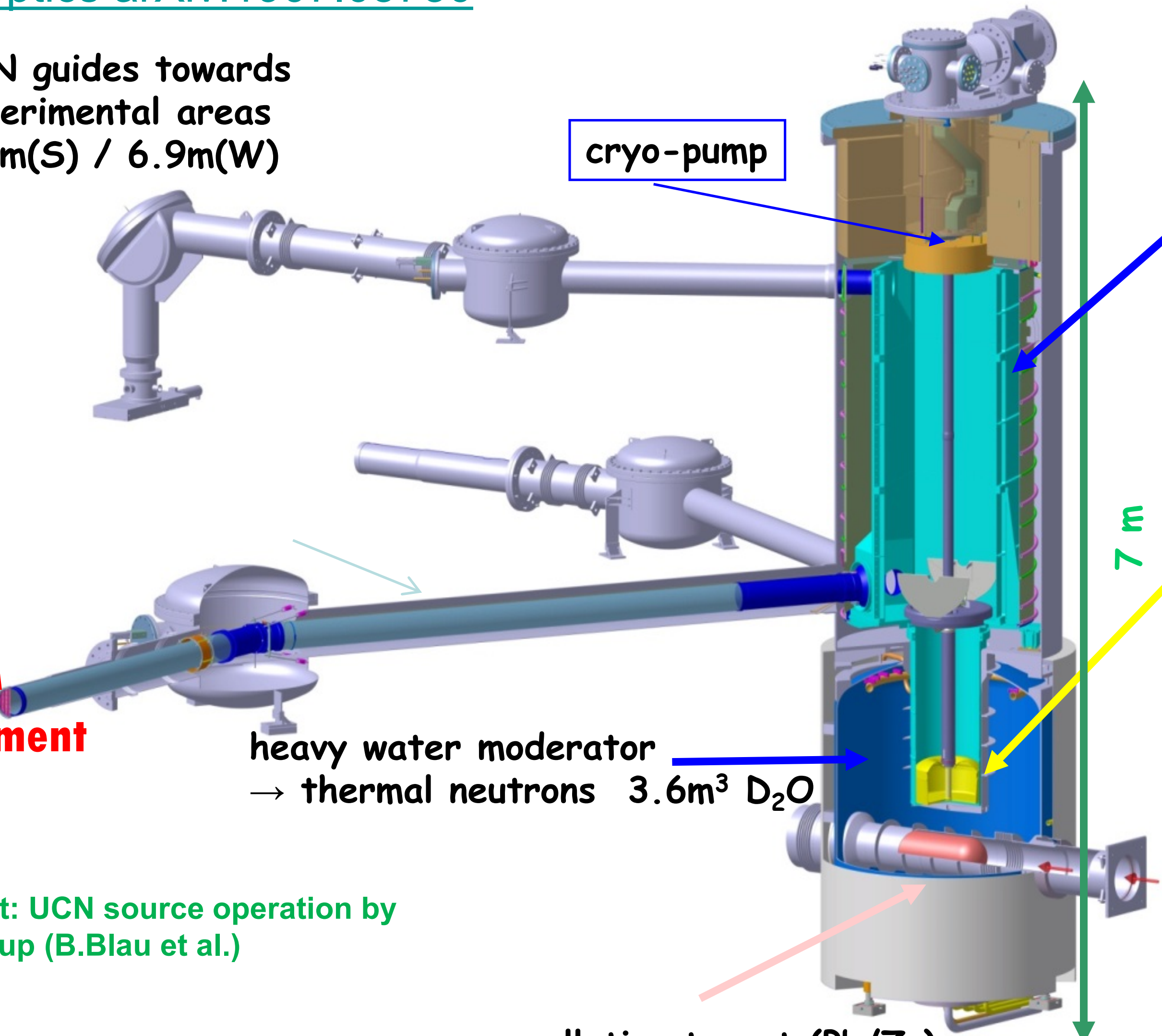
UCN optics arXiv:1907.05730

UCN guides towards experimental areas 8.6m(S) / 6.9m(W)

cryo-pump

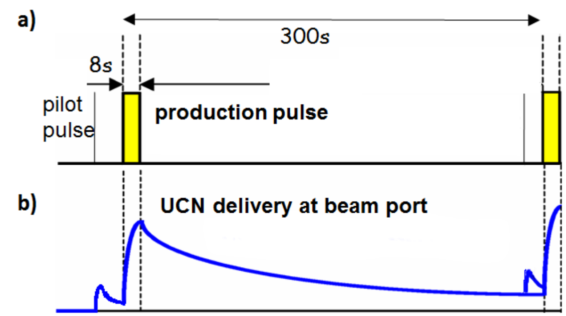
DLC coated UCN storage vessel height 2.5 m, ~ 2 m^3

cold UCN-converter 5 kg solid D_2 at 5 K



n2EDM experiment

heavy water moderator → thermal neutrons 3.6m^3 D_2O



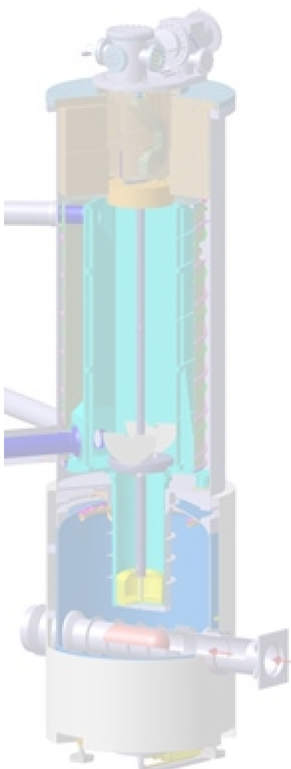
important: UCN source operation by ASQ Group (B.Blau et al.)

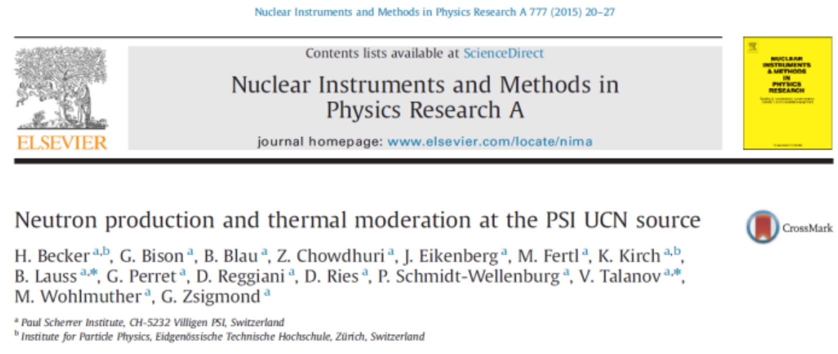
pulsed 1.3 MW p-beam 590 MeV, 2.2 mA, 1% duty cycle

spallation target (Pb/Zr) (~ 8 neutrons/proton)

Understanding the thermal neutron flux

- Fully detailed MCNP-X model and simulation by Vadim Talanov & Michael Wohlmuther
- comparison to gold foil measurements




Nuclear Instruments and Methods in Physics Research A 777 (2015) 20–27

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

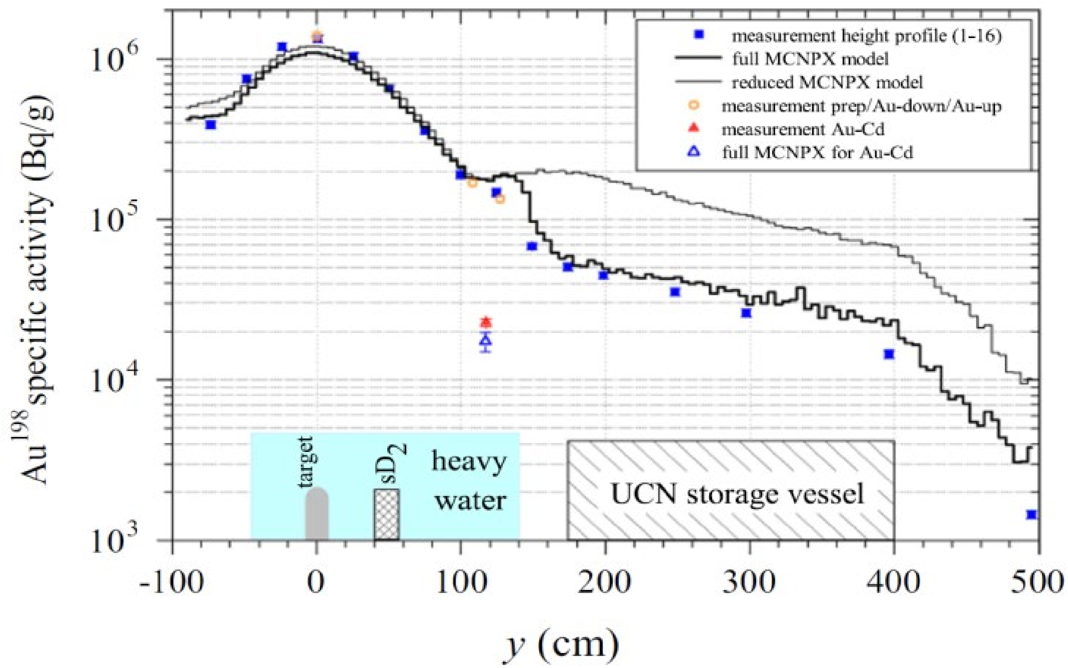
journal homepage: www.elsevier.com/locate/nima

Neutron production and thermal moderation at the PSI UCN source

H. Becker[a,b], G. Bison[a], B. Blau[a], Z. Chowdhuri[a], J. Eikenberg[a], M. Fertl[a], K. Kirch[a,b], B. Lauss[a,*], G. Perret[a], D. Reggiani[a], D. Ries[a], P. Schmidt-Wellenburg[a], V. Talanov[a,*], M. Wohlmuther[a], G. Zsigmond[a]

[a] Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[b] Institute for Particle Physics, Eidgenössische Technische Hochschule, Zürich, Switzerland

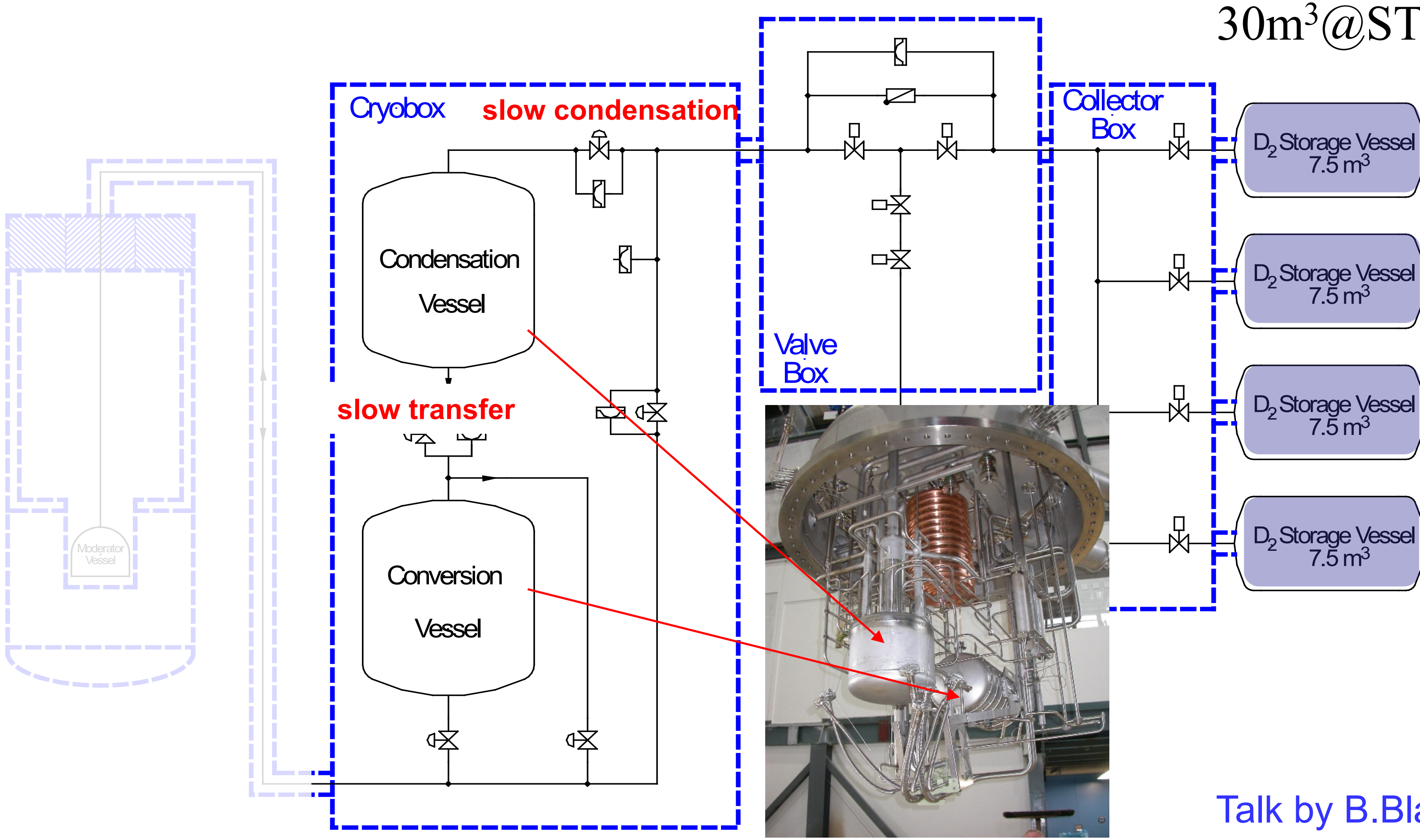
756 Zr/Pb Canelloni Target
~7.5 n/p



Preparation of the deuterium

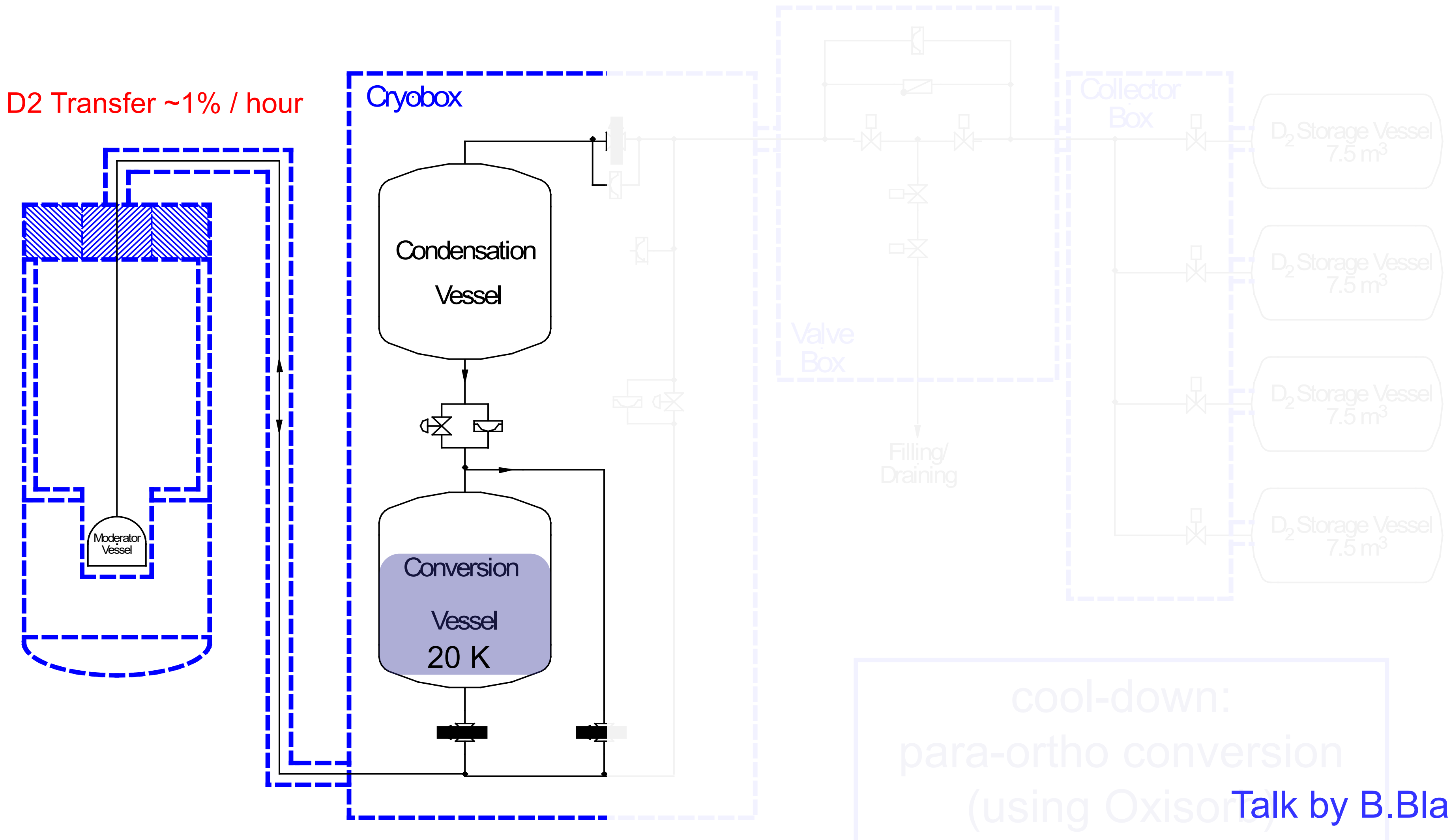
He-refrigerator cooling power: 370W @4.2K and 2500W @ 80K

30m³@STP



Talk by B.Blau

Preparation of the deuterium

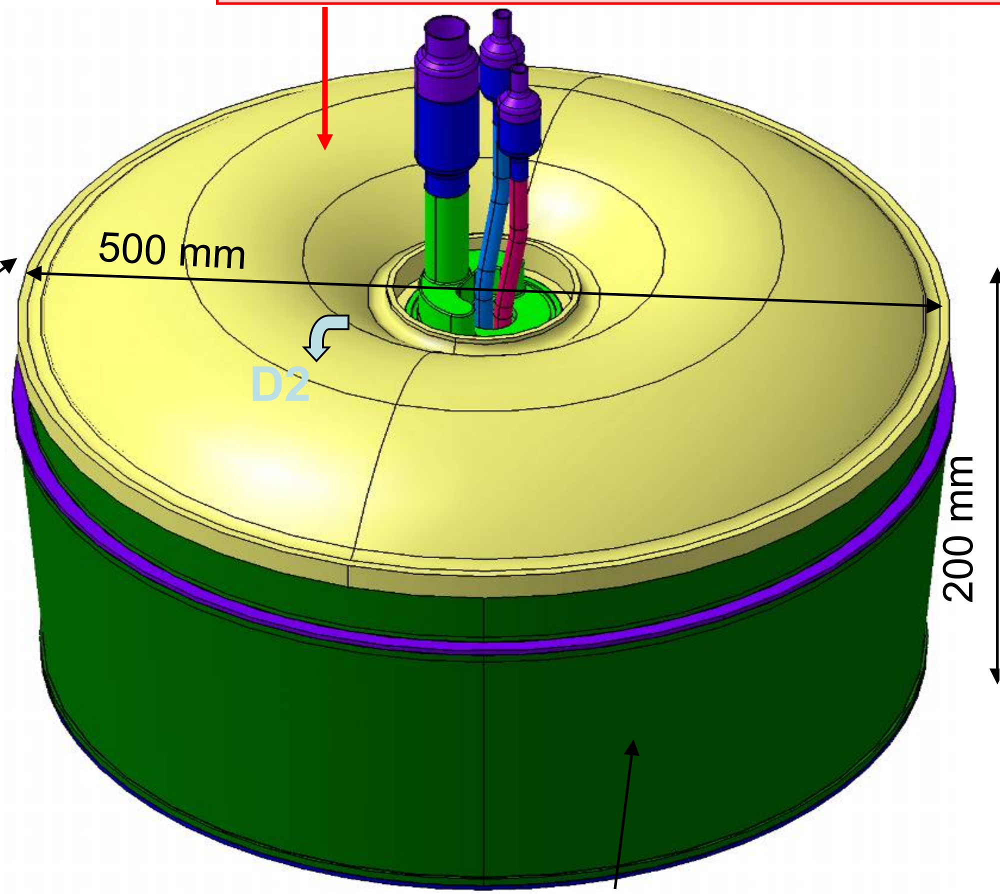


Talk by B.Blau

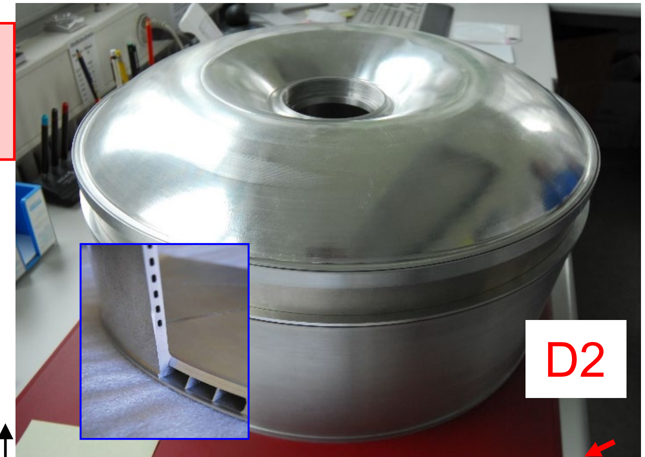
Solid deuterium at 5K

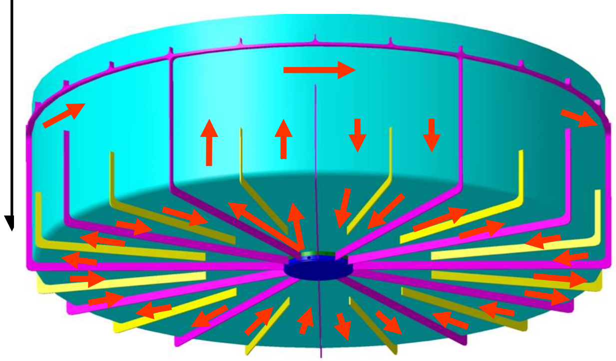
talk by B.Blau

saturated vapor pressure indicates D2 temperature



0.5 mm AlMg3



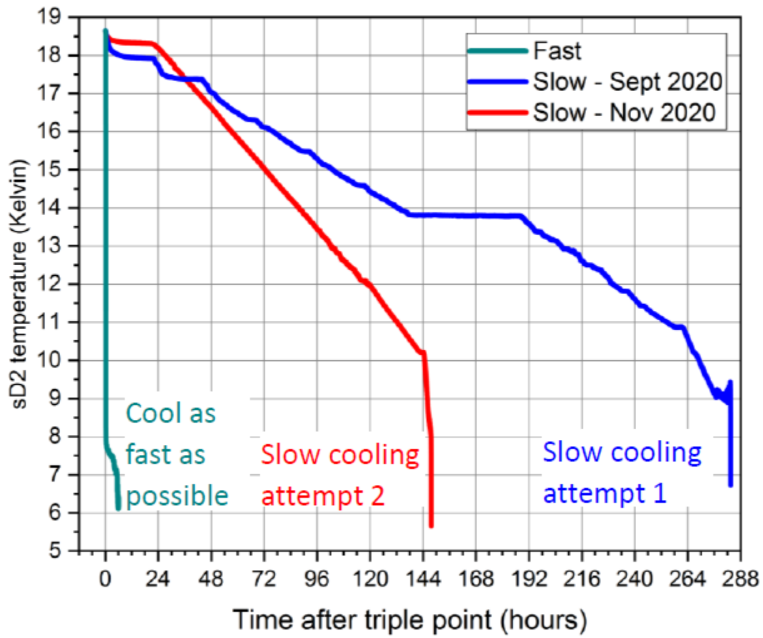


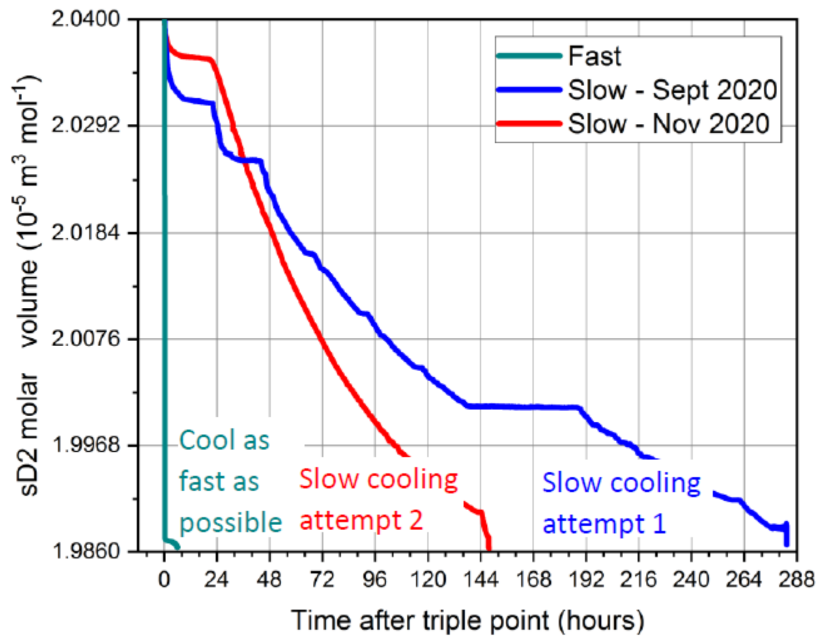
Cooling Agent:
Supercritical Helium

Talk by B.Blau

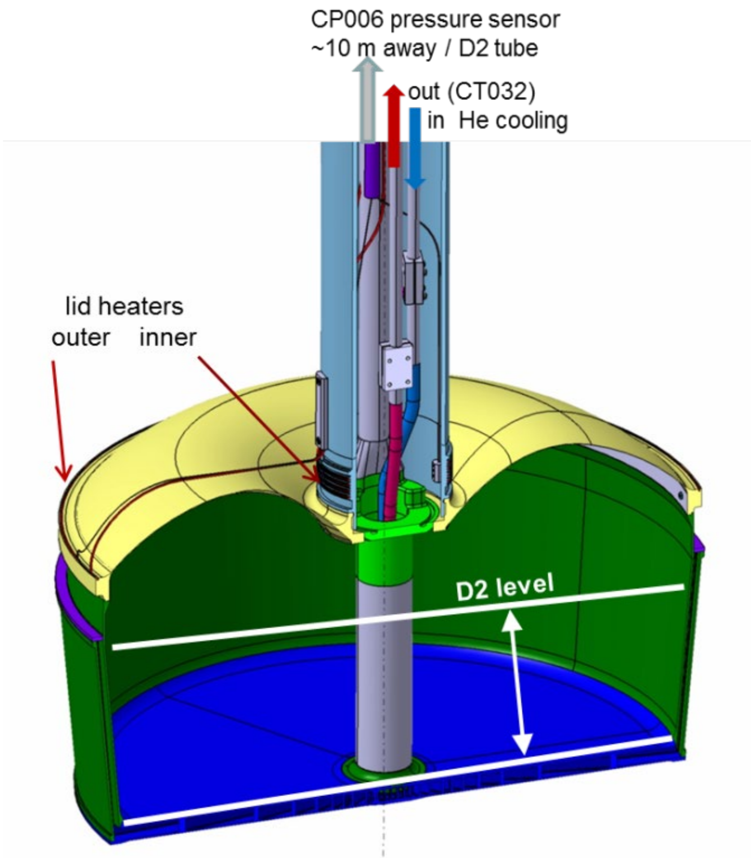
Slow freezing procedure

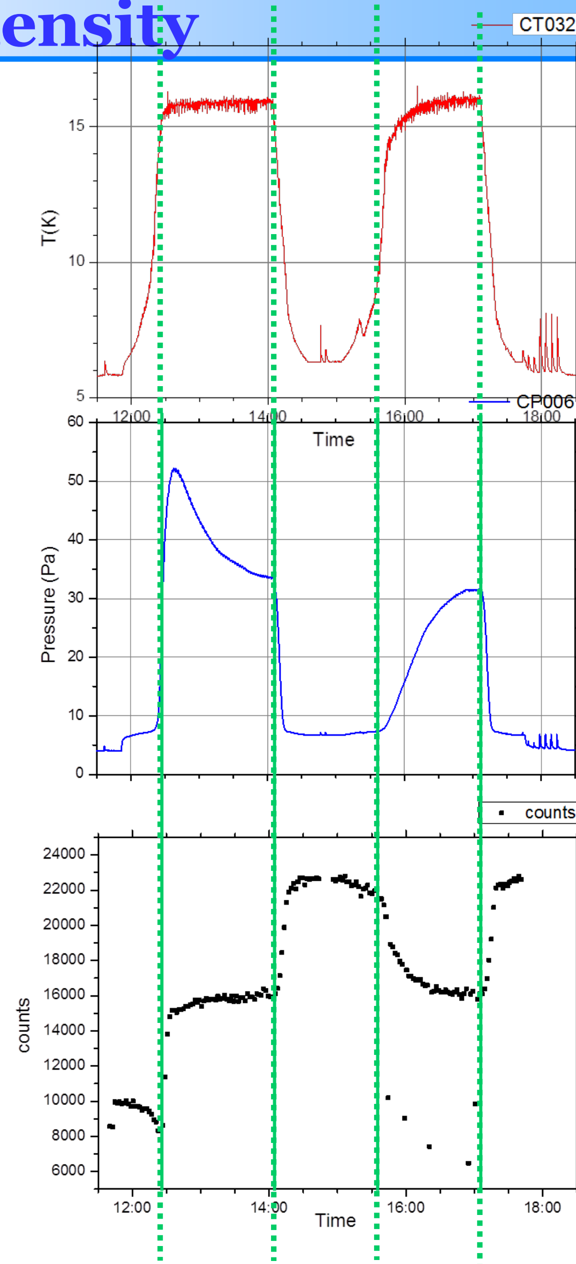
sD2 vapor pressure ↔ sD2 temperature ↔ sD2 molar volume





Conditioning: regaining the full UCN intensity





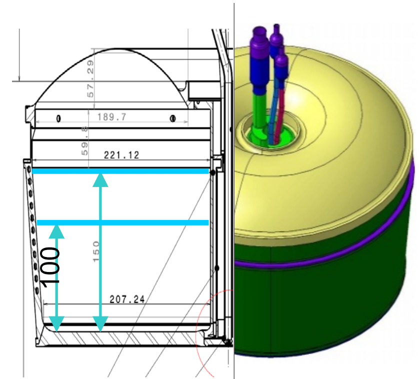
Recreation of solid thin-film D2 source
A 'calibrated' source of UCN

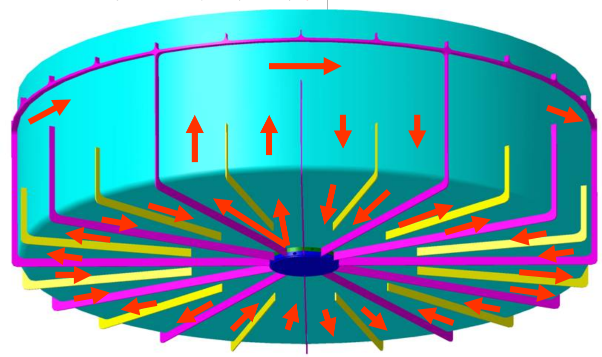
D2 fills with gas → exact D2 mass known

→ freeze to make a solid thin-film D2 source

starting at a few grams - 1300 g
→ thickness 100 mu - a few mm

→ no UCN losses occurring within the solid D2 (lifetime is long enough that UCN exit also after multiple scattering)





- established thermal flux
- simulated /checked cold flux
- established UCN production cross-section from
Golub/Boenig 1983, Yu/Malik/Golub 1985
Atchison et al, PRC71, 2005
Atchison et al, PRL99, 2007

- established UCN transport trom sD2 surface to detector
Bison et al . arXiv:1907.05730 and arXiv:2110.12988

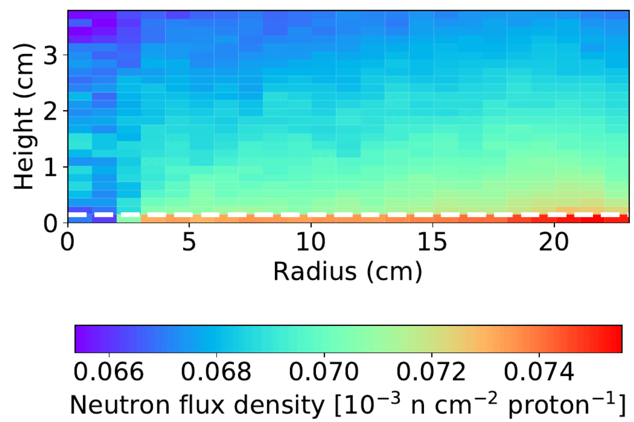
mass (g)	Measurement UCN counts	Simulation UCN Counts
5.77±0.2	28’100±1300	30’000
2.82±0.2	16’070±500	15’000

PhD Thesis I.Rienäcker

Thin film sD2 UCN source

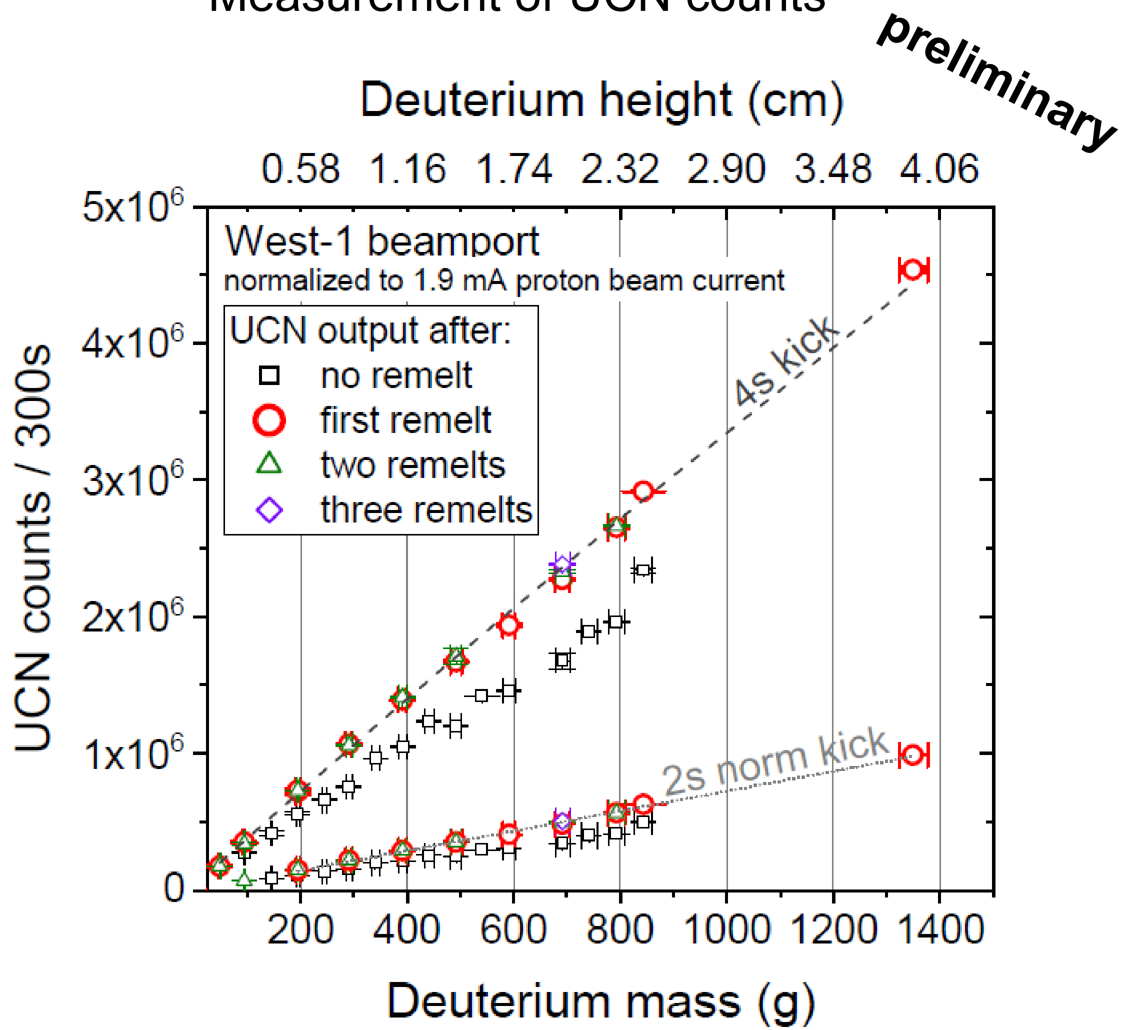
- at larger masses moderation and sD2 extraction become relevant

Simulation of cold-neutron flux



PhD Thesis I.Rienäcker

Measurement of UCN counts

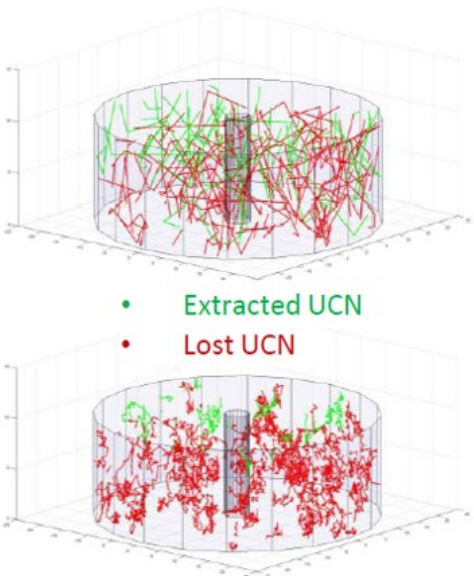


Thin film sD2 UCN source -> UCN extraction from sD2

Our measurements and UCN transport simulations indicate that the solid deuterium "crystal quality" is crucial for UCN extraction

«good» crystal

«bad» crystal



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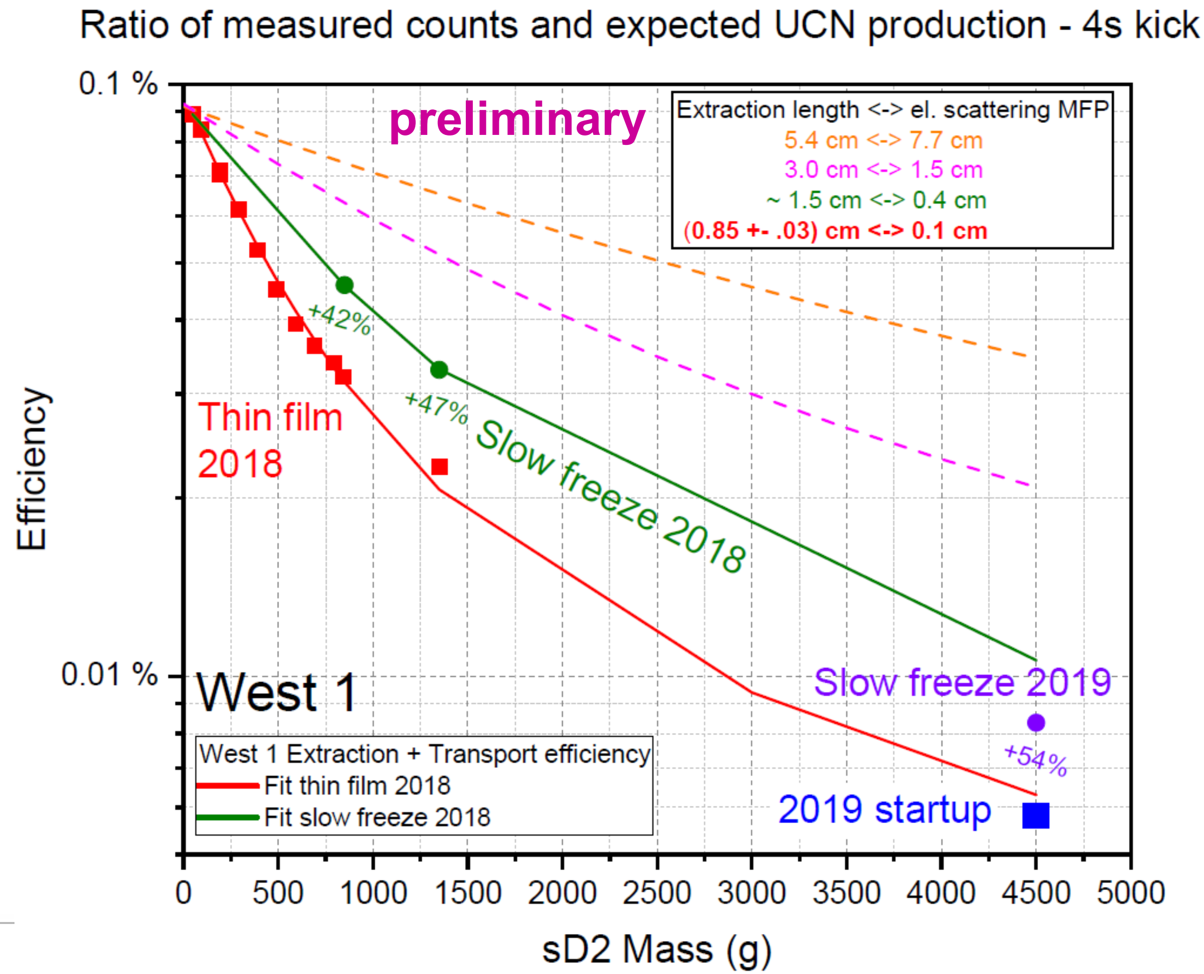
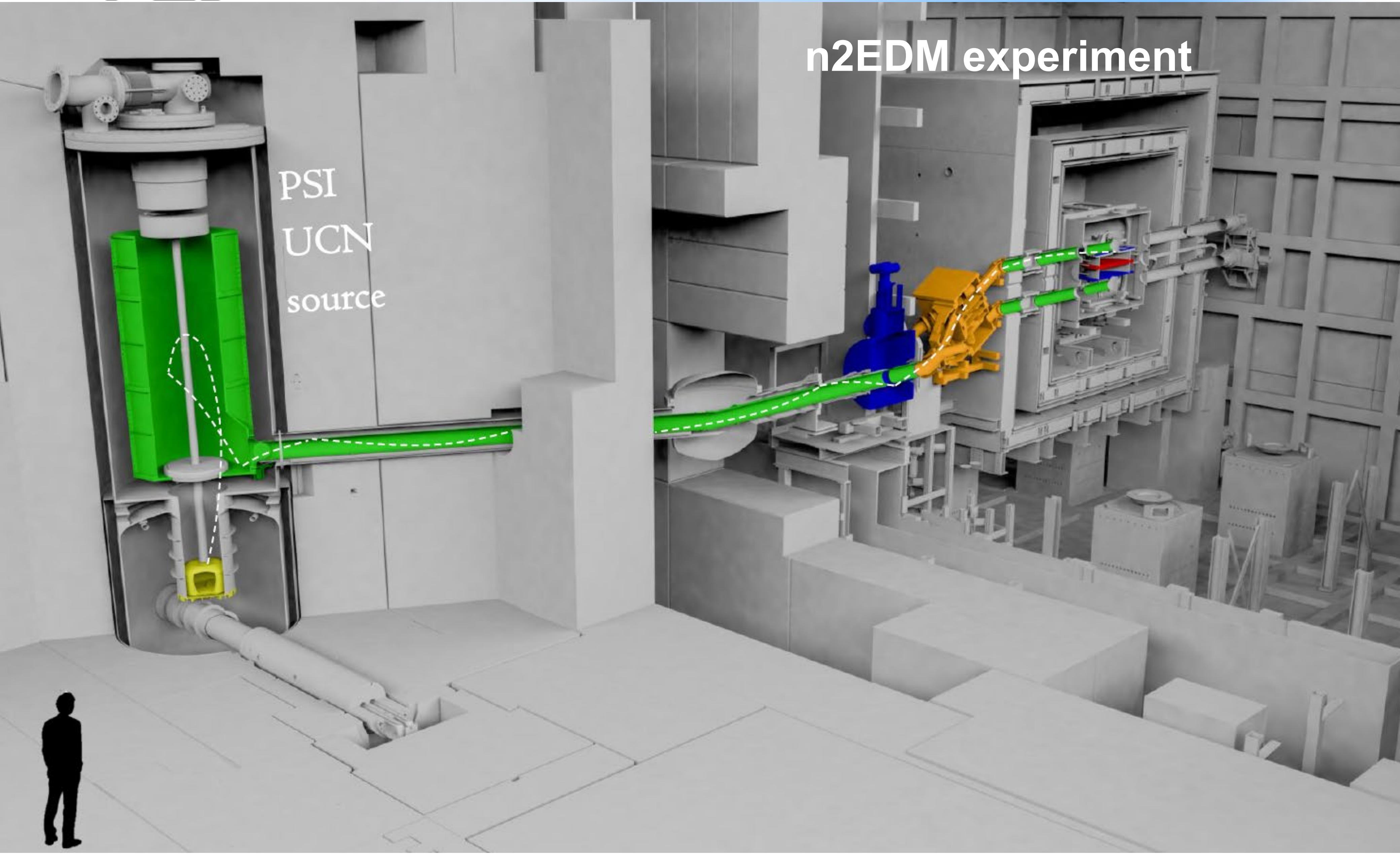
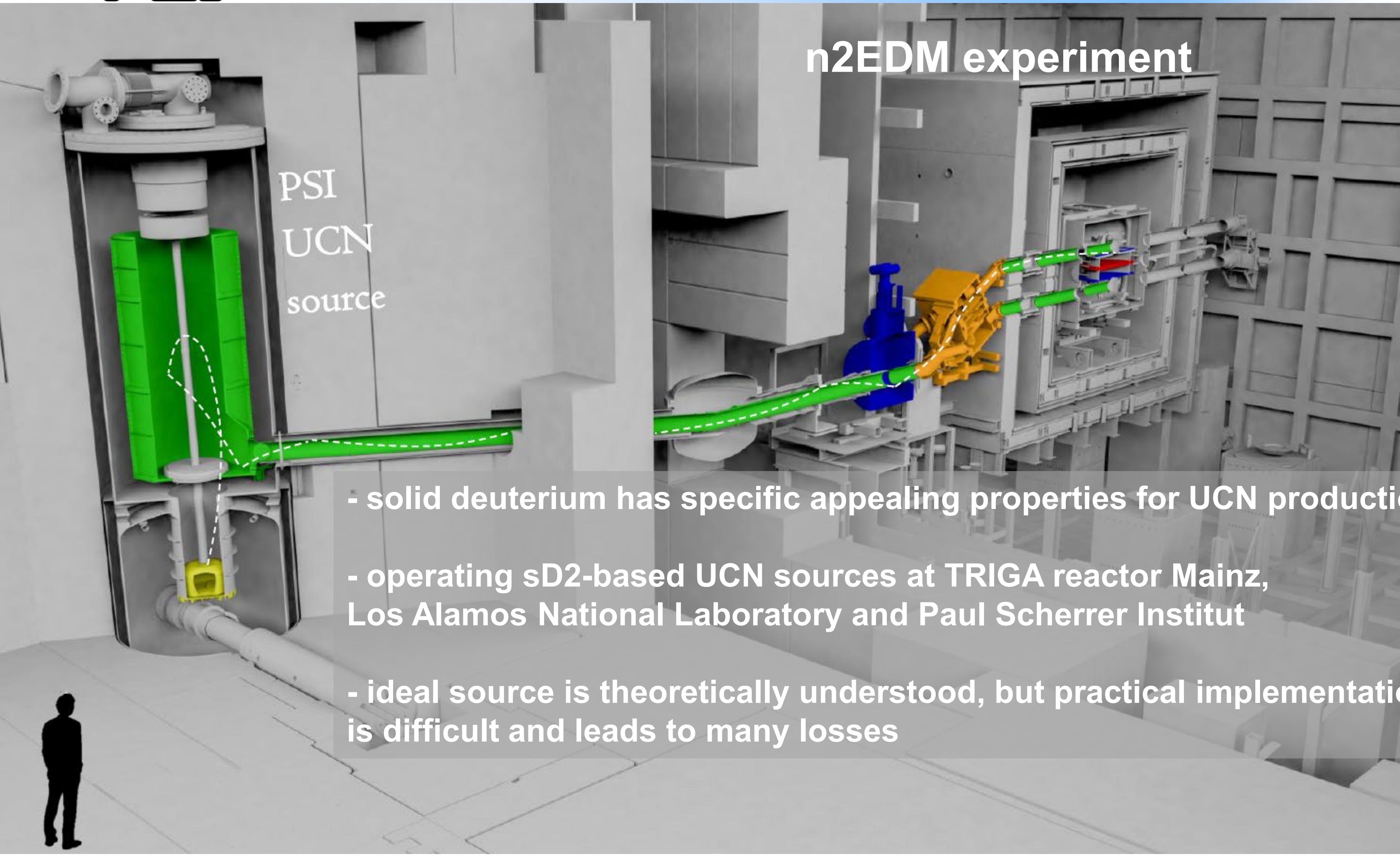


Extraction simulation
PhD Thesis T.Brys 2007

Artistic view of experimental hall



Summary



- solid deuterium has specific appealing properties for UCN producti

- operating sD2-based UCN sources at TRIGA reactor Mainz, Los Alamos National Laboratory and Paul Scherrer Institut

- ideal source is theoretically understood, but practical implementati is difficult and leads to many losses


thanks for your attention
thanks to all colleagues for transparencies and inputs
UCN