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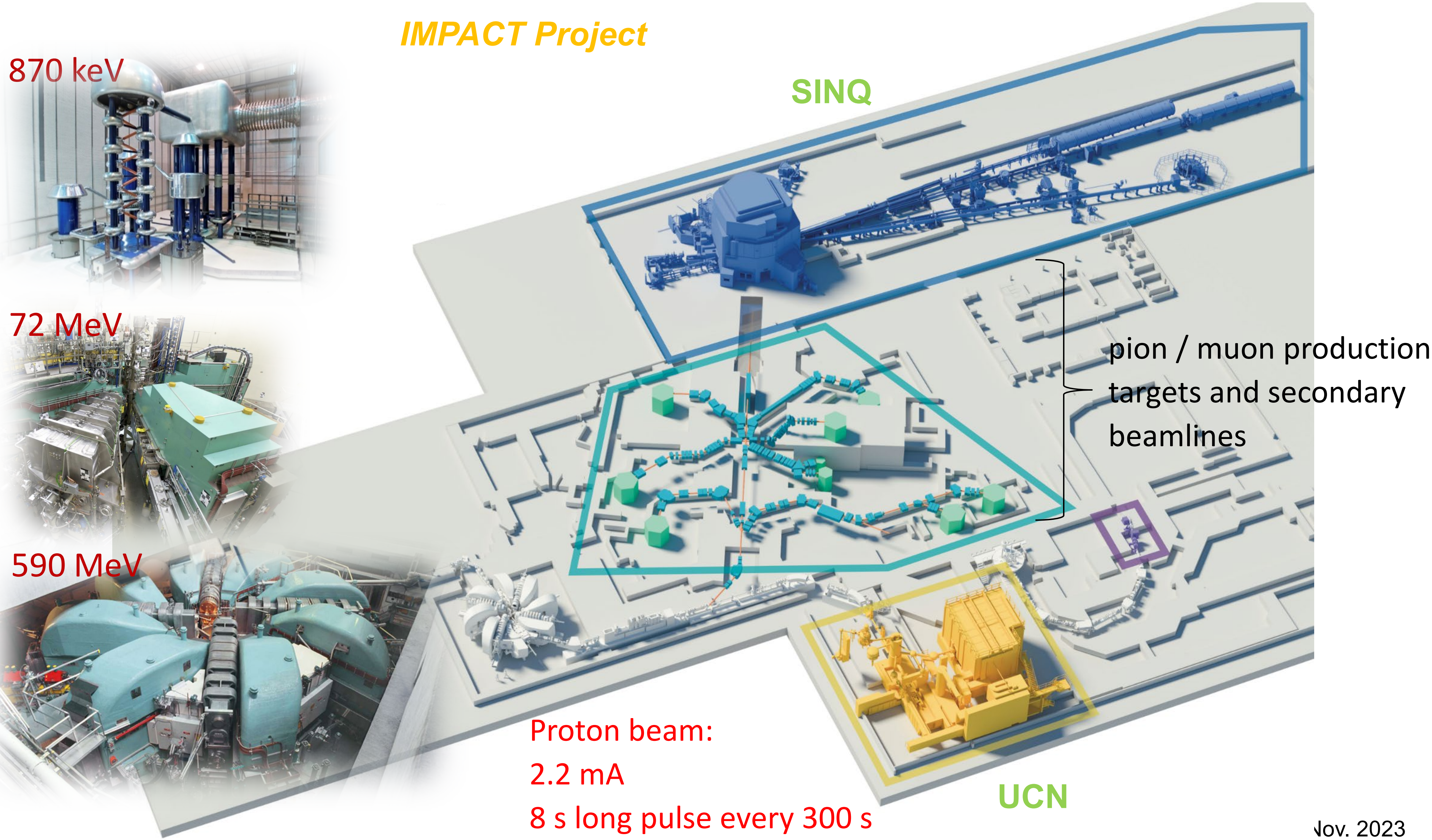
Status of the PSI ultracold neutron source

Bernhard Lauss
Paul Scherrer Institute

High intensity proton beam - ultracold neutron source UCN at PSI



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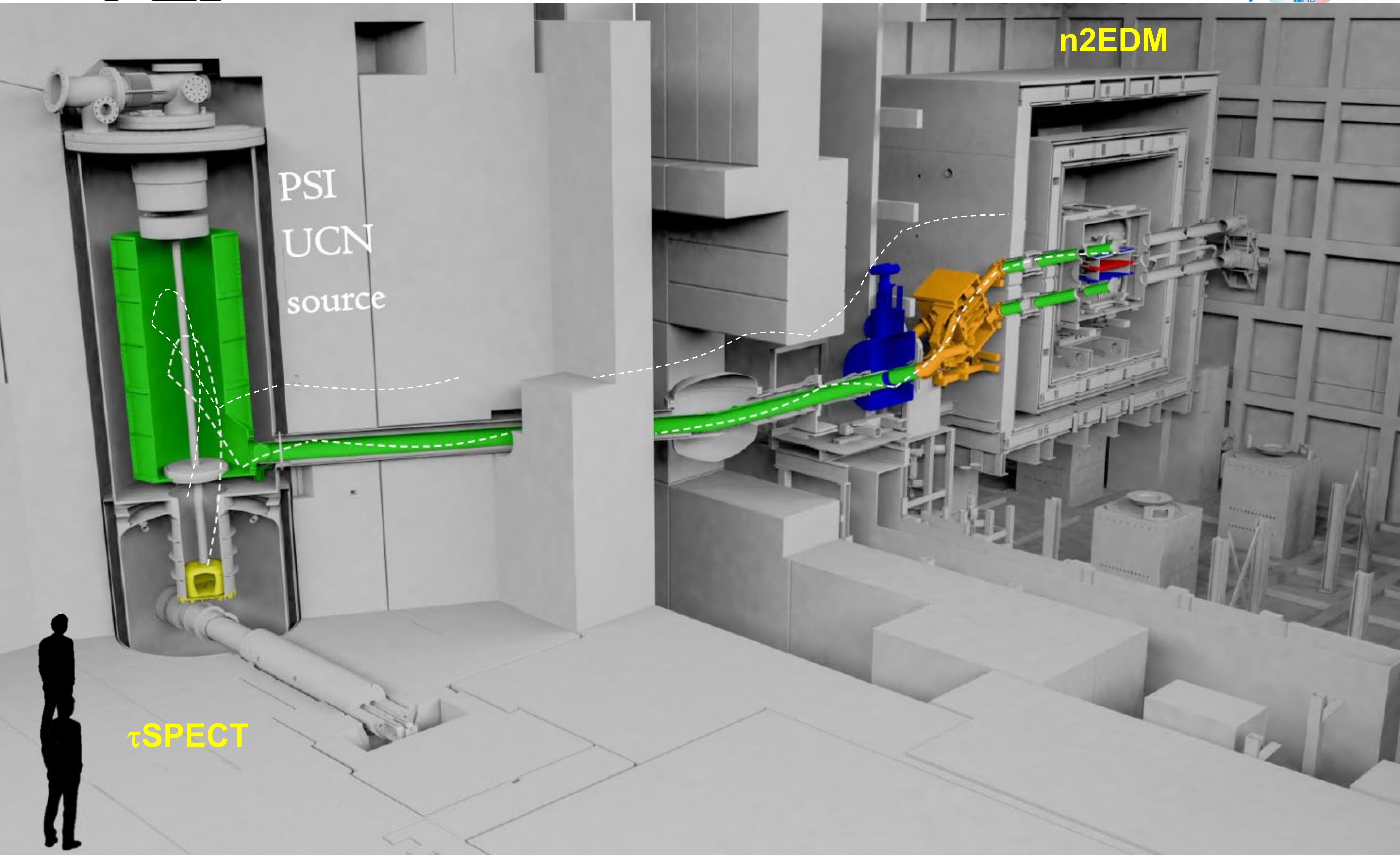
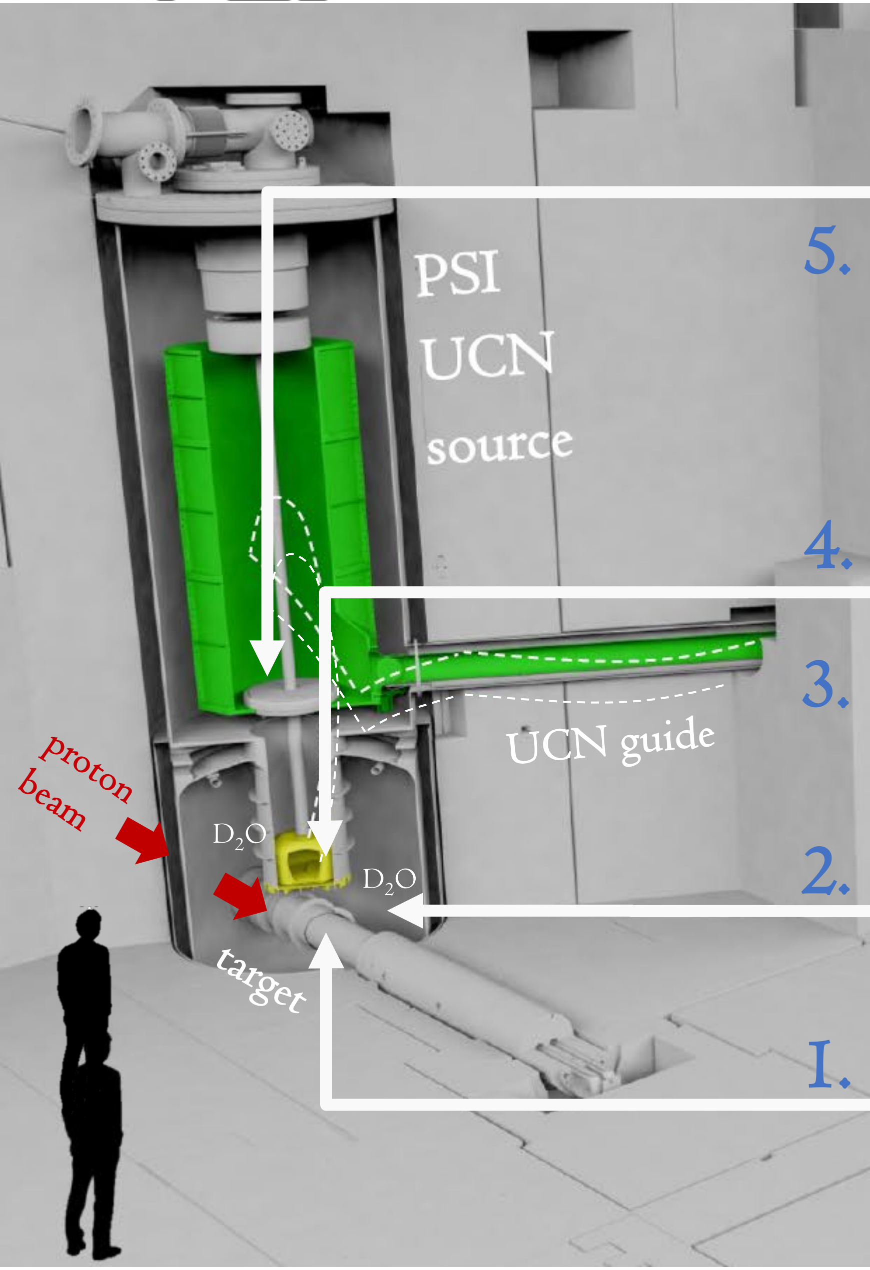
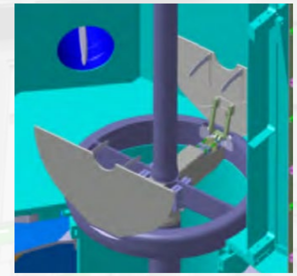
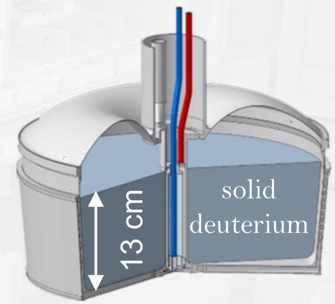




5. Two storage flaps close to confine the UCN in the storage volume



4. Conversion to UCN by phonon excitation in solid deuterium



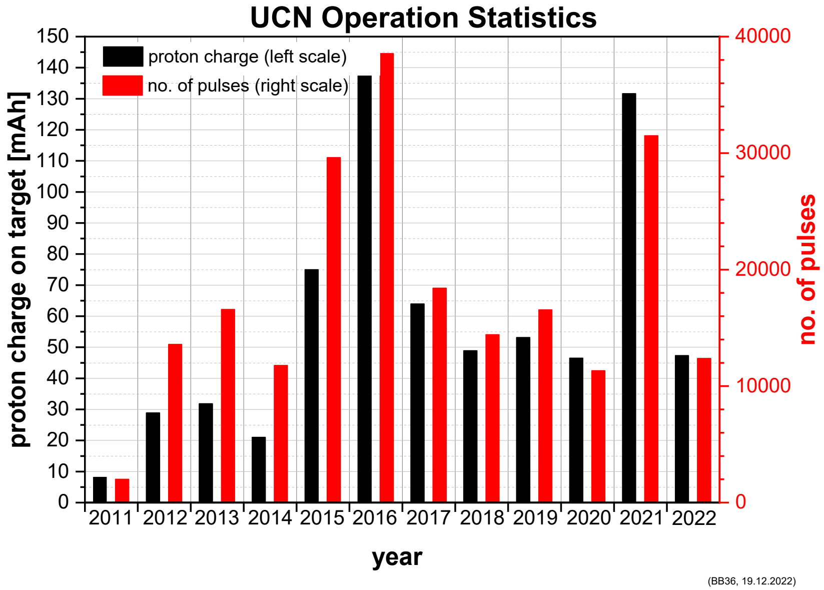
3. Cold neutron flux from moderation in solid deuterium at 5 Kelvin

2. Moderation in heavy water thermalizes neutrons at room temperature

1. HIPA beam on Pb spallation target (up to 8s) produces ~8 free neutrons per proton

– UCN operation

UCN opertion and output improvement



nEDM data taking

nn' data taking

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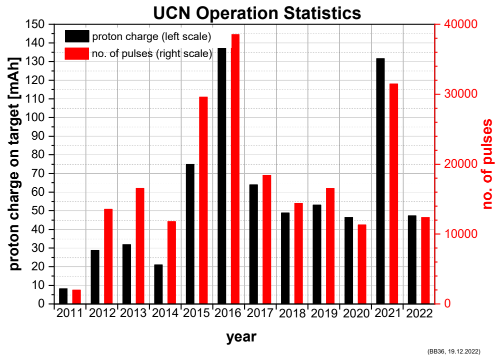
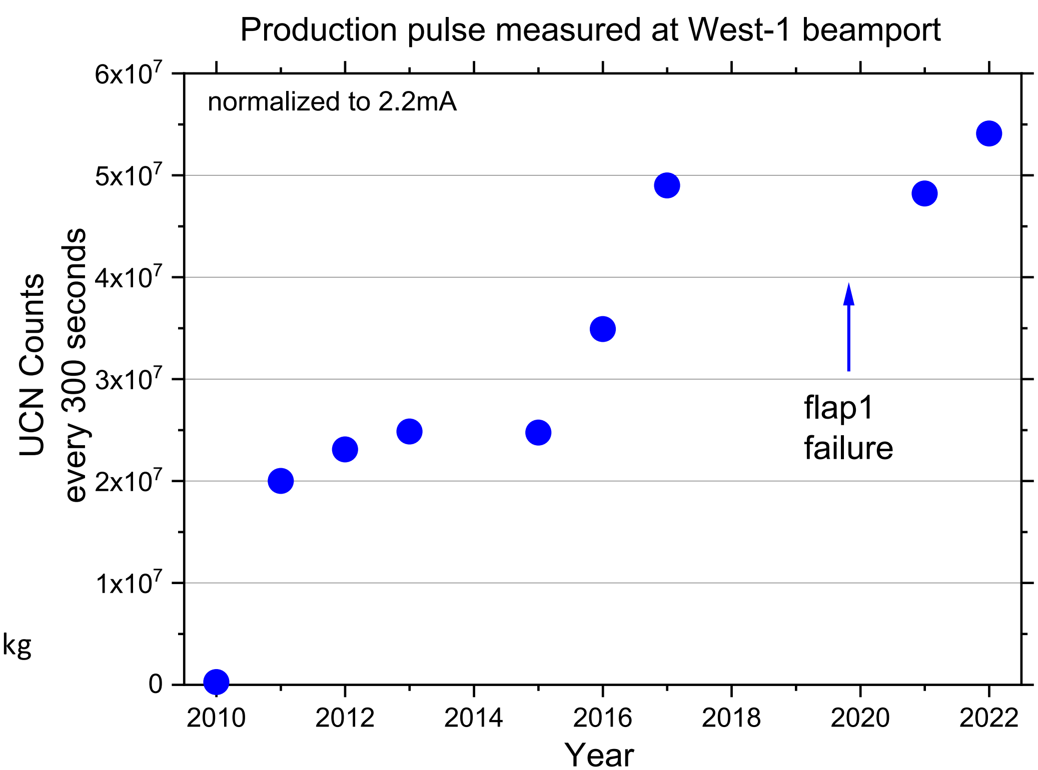
UCN opertion and output improvement





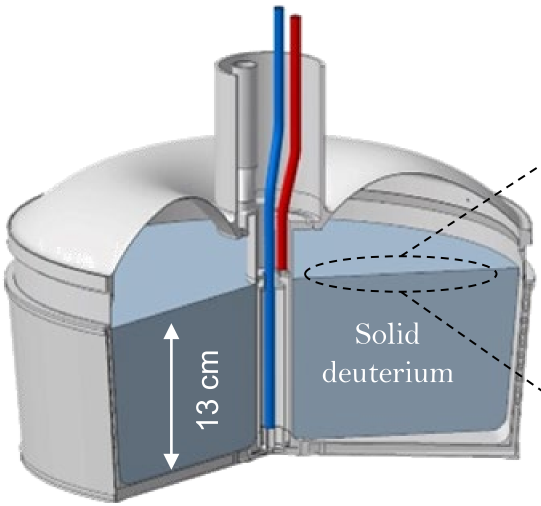
Operation in 2022 with largest D2 mass = 5.677 kg

Understanding the source performance

- sD2 Frost

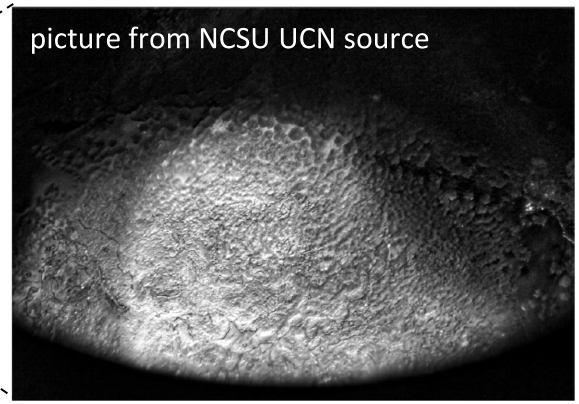
Solid deuterium surface degradation

Sublimation:
Heat deposition during proton beam pulse causes sublimation of D2 vapor

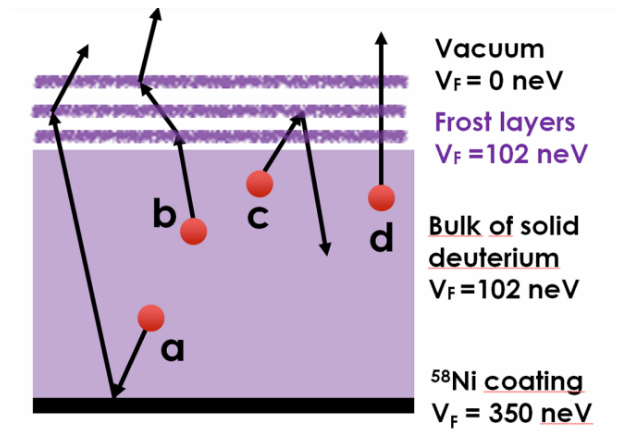


Frost deposition:
After the proton beam pulse the D2 vapor is deposited on the cold sD2 surface and forms an opaque frost layer

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



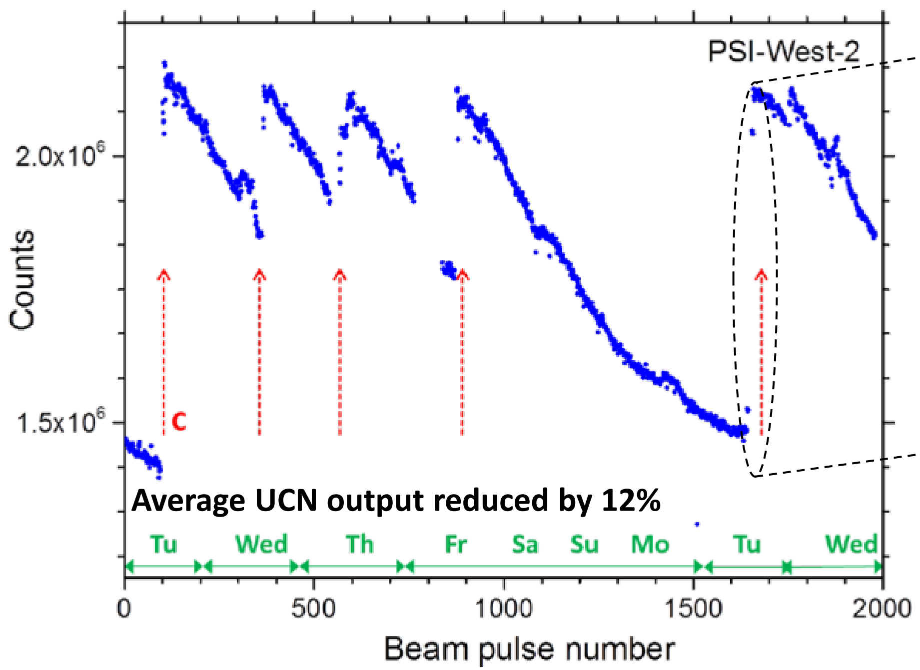
Albedo reflection:
Frost layer causes Albedo reflection of UCN back into the sD2 bulk where they are lost due to upscattering and absorption



conditioning procedure - 'surface heating' - regains full UCN output

sD_2 conditioning procedure

A regular conditioning procedure anneals the sD2 surface and recovers UCN output



Conditioning:

- Stop proton beam pulses
- Decrease cooling power
- Turn on heating elements on moderator vessel for approx. 2 hours

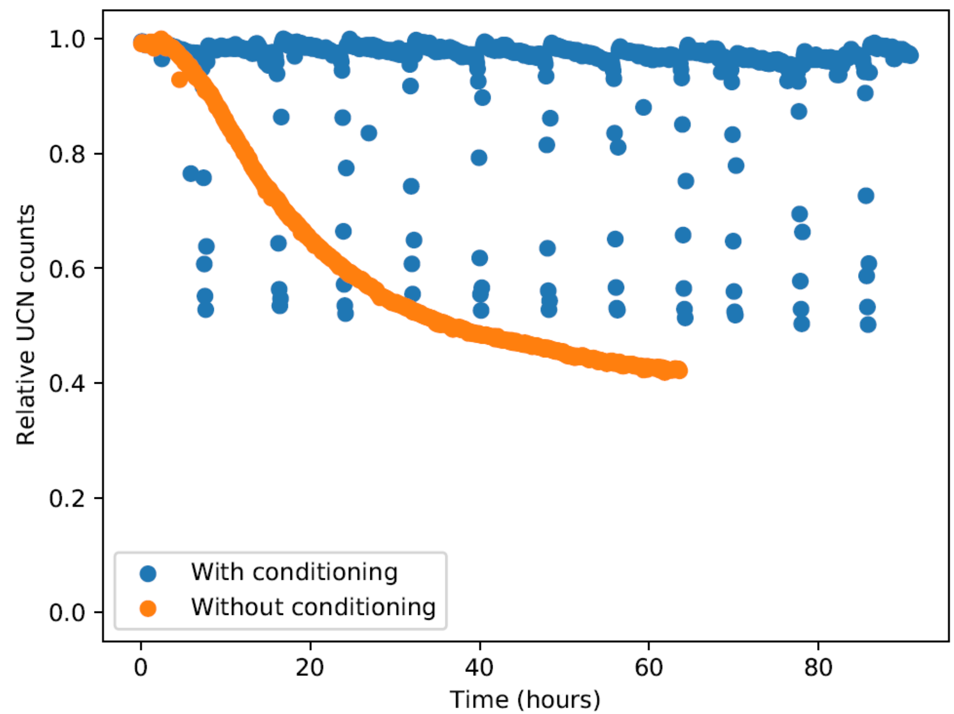
2 hours / 24 hours = 8% of the time no UCN production

sD_2 conditioning procedure

The new conditioning procedure recovers the UCN output just as the standard conditioning for all cases investigated until now

Estimated gain on average UCN output: ≈ 20%
- important for n2EDM statistics

automated conditioning



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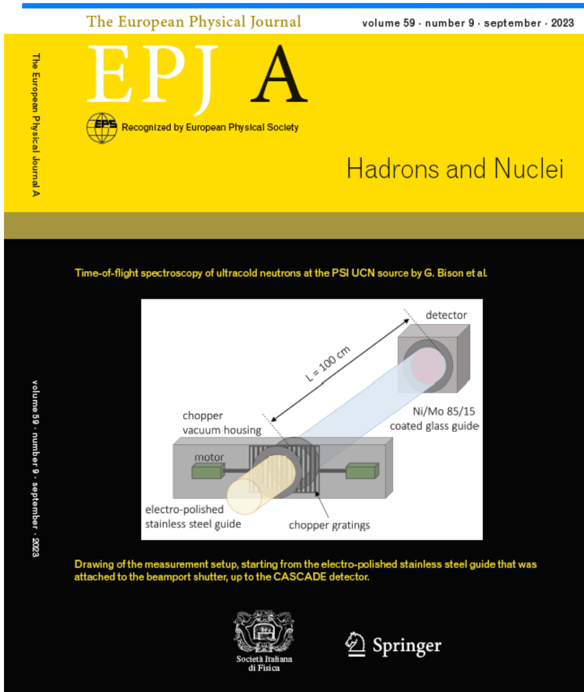
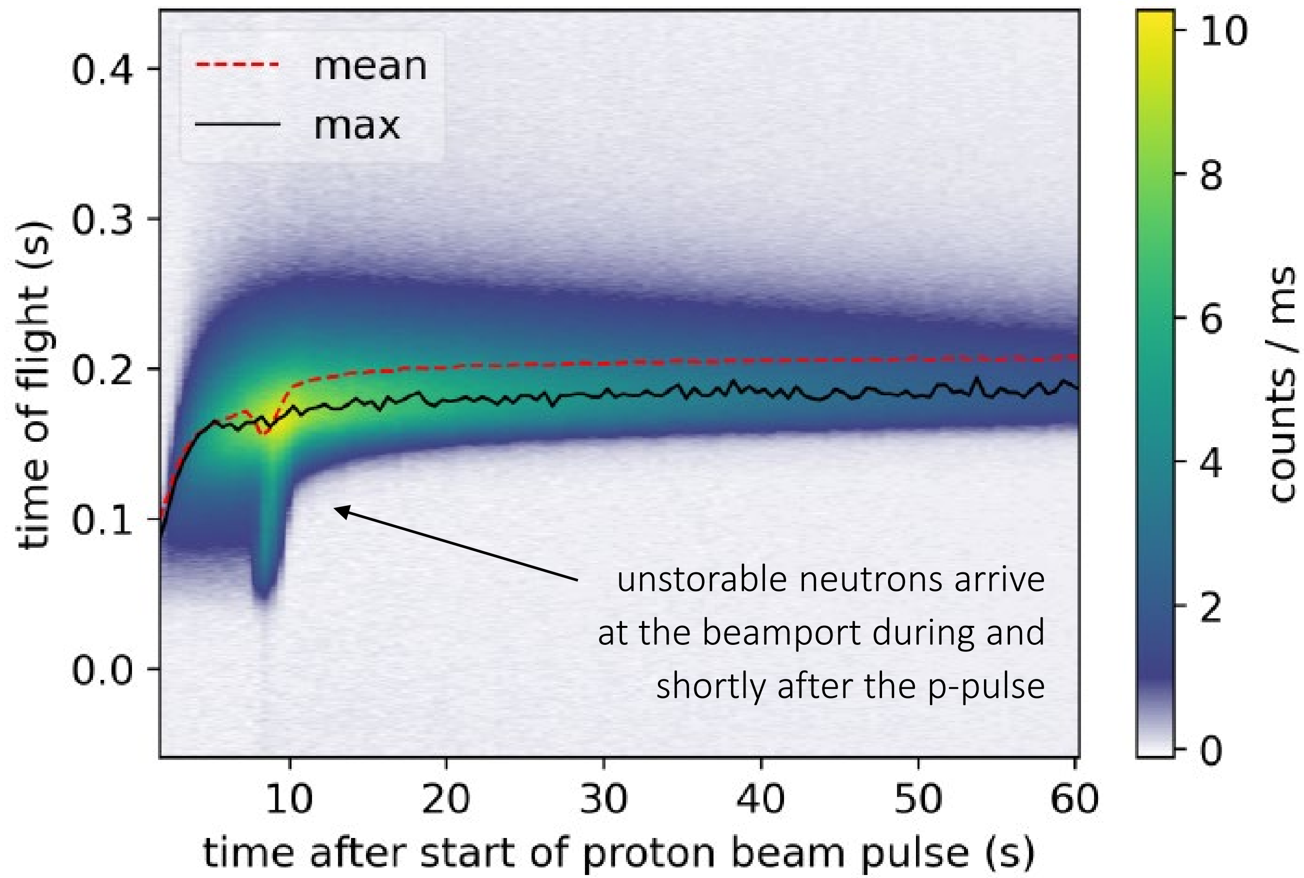
– UCN mean energy measurement

Measured time of flight spectra



chopper opened/closed the beamline continuously at 2 Hz (0.5 s long frames)

record time of flight spectrum in each frame after the start of proton beam pulse



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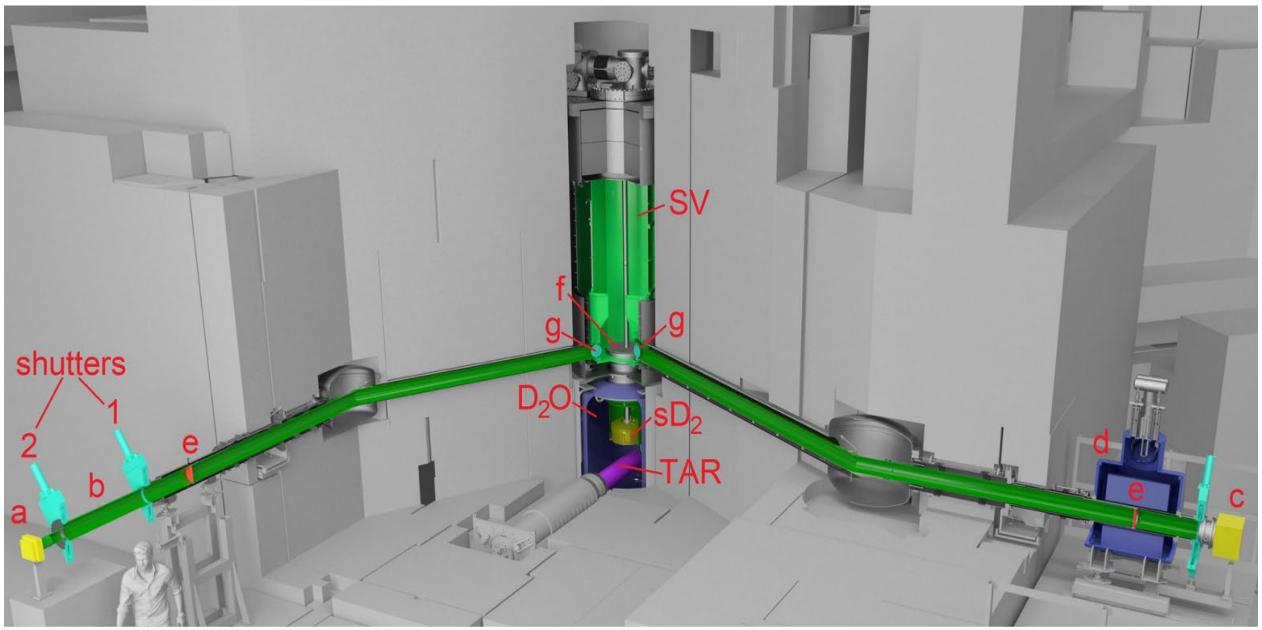
- *UCN source calibration*
  - *UCN transport*
  - *neutron production*
  - *UCN production*

UCN transport efficiency

UCN transmission spectra calibrated by

- "ping-pong" transmission measurements
- storage time and time of arrival spectra
- UCN density measurements in storage bottles at different heights
- time of flight spectroscopy



MCUCN simulation parameters scanned in wide range

Talk by Geza Zsigmond

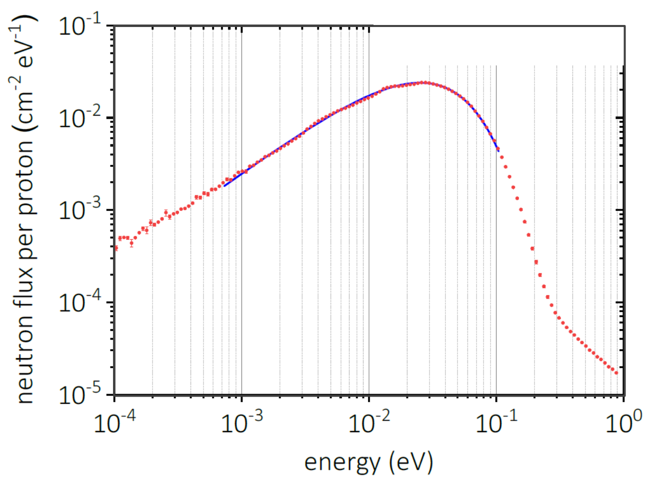
G. Bison et. al., Eur. Phys. J. A 56, 33 (2020)
G. Bison et. al., Eur. Phys. J. A. 58 ,103 (2022)
G. Bison et. al., EPJ A 59, 215 (2023)

Neutron production

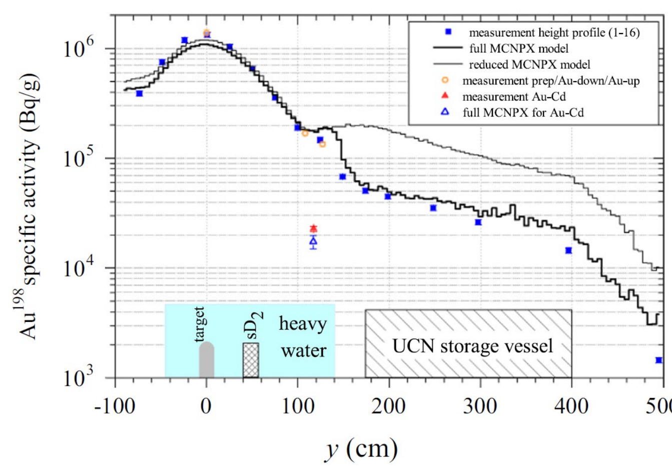
H. Becker et. al., NIM A 777 (2015)

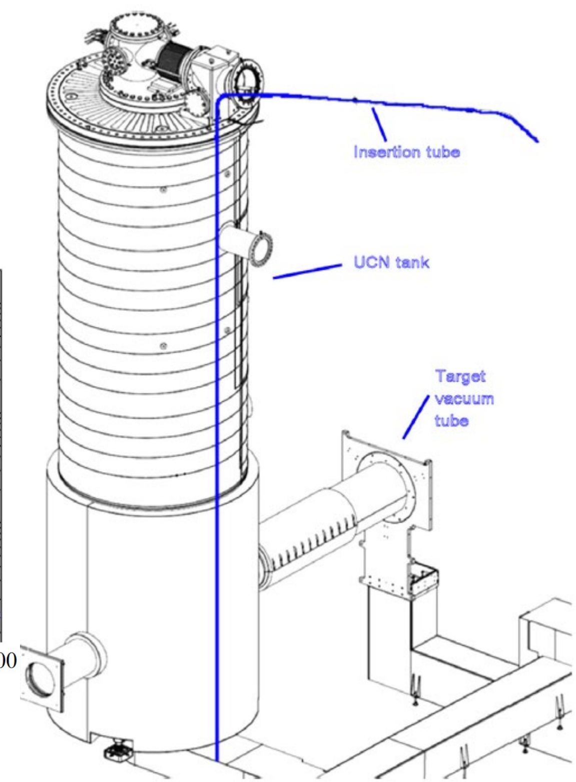
use thermal neutron spectrum from heavy water moderator

MCNP simulation of thermal flux …



… confirmed by gold foil activation





UCN losses in sD_2 -> thin films

measured isomeric and isotopic purity of D_2 by Raman spectroscopy

- C_{para} < 2.7 %
- C_{HD} < 0.2 %

compute UCN lifetime in sD_2 at 5 K

corresponding MFP = 9 cm

during operation < 1 % due to radiation induced para-to-ortho conversion

$$\tau = \frac{1}{v}\left[c_{\mathrm{para}}\ \Sigma_{\mathrm{para}} + \Sigma_{\mathrm{phonon}} + \Sigma_{\mathrm{abs,D_2}} + c_{\mathrm{HD}}\ \Sigma_{\mathrm{abs,HD}}\right]^{-1}$$

$$= \left[\frac{1}{56\,\mathrm{ms}} + \frac{1}{168\,\mathrm{ms}} + \frac{1}{146\,\mathrm{ms}} + \frac{1}{269\,\mathrm{ms}}\right]^{-1}$$

$$= 29\,\mathrm{ms}$$

$\Rightarrow \epsilon_{\mathrm{ext}}(E) \approx 1$

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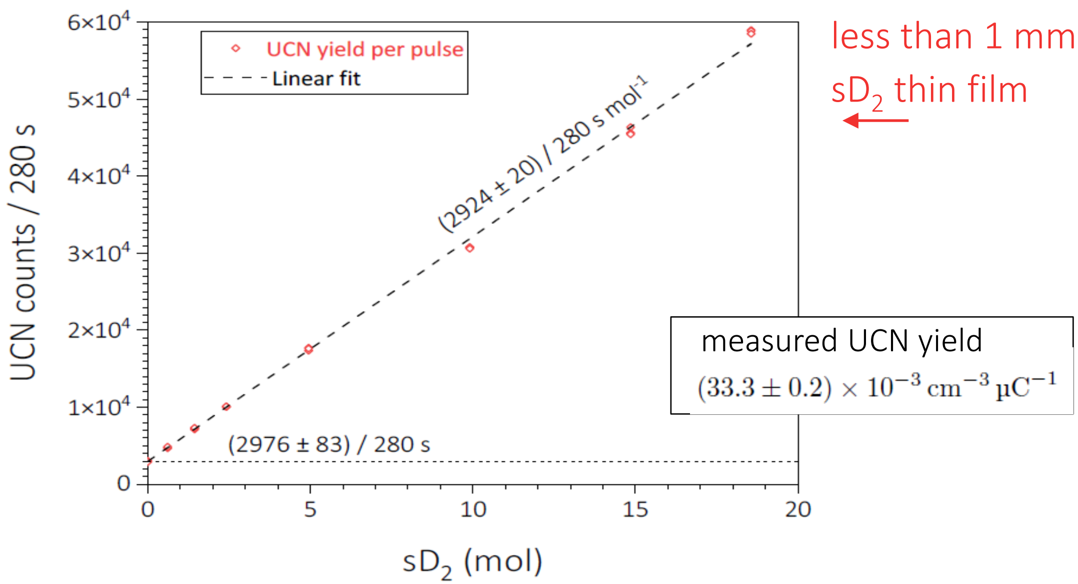
sD_2 thin film measurement

start with empty sD_2 vessel (< 0.01 mol D_2)

fill with known amount of D_2 vapor (± 0.1 mol) by monitoring condensation vessel pressure and measure UCN output

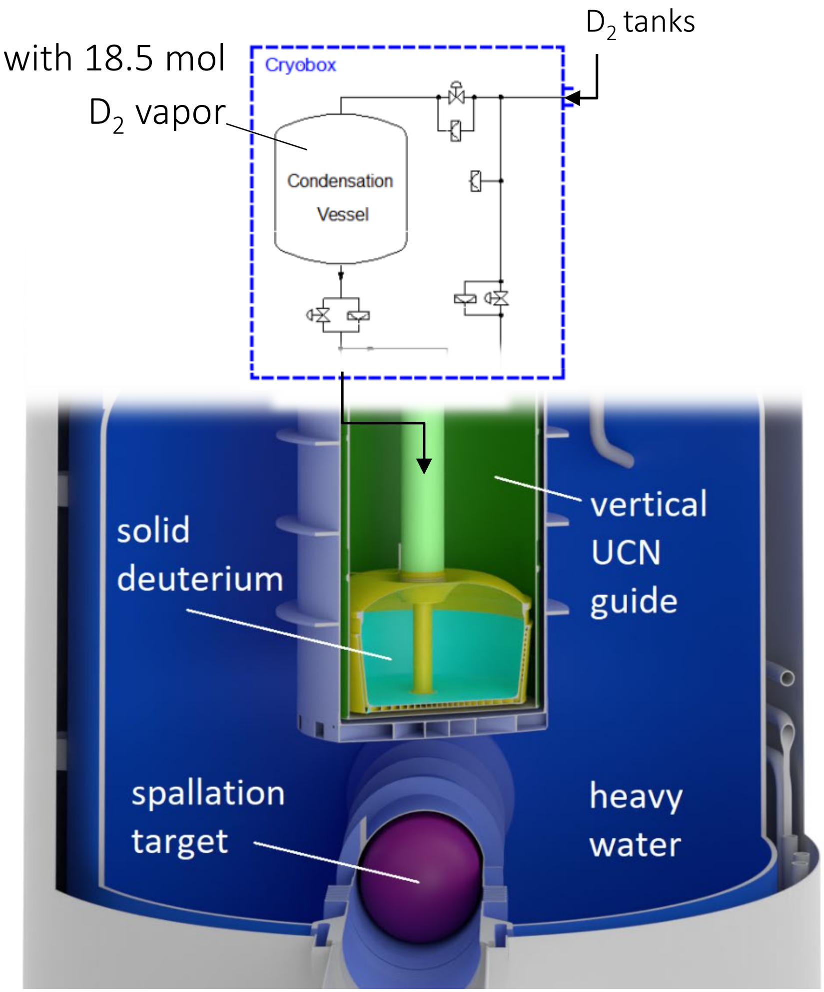


less than 1 mm sD_2 thin film

Simulated UCN yield ($10^{-3}\,cm^{-3}\,\mu C^{-1}$)	diffuse boost A	diffuse boost B	diffuse boost C	perpendicular D	perpendicular E
from base	36.3	34.6	29.8	48.3	-
from side walls	32.5	32.4	33.3	-	30.3
combined	34.1	33.3	31.9	37.7	

G.Bison et al., Phys.Rev.C 107 (2023) 035701

filled with 18.5 mol D_2 vapor



I. Rienäcker DISS. ETH NO. 28498

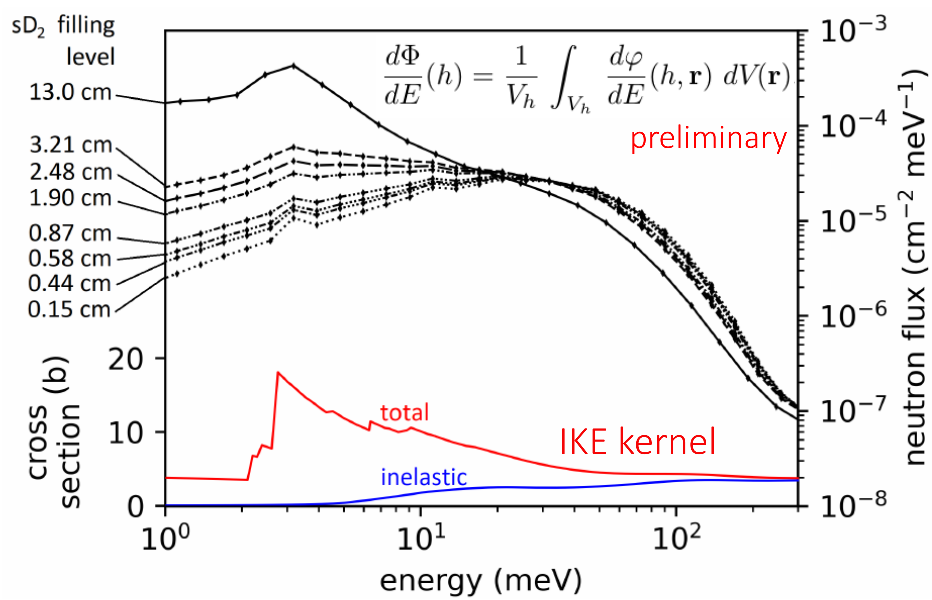
- Cold moderation
- UCN extraction from sD2

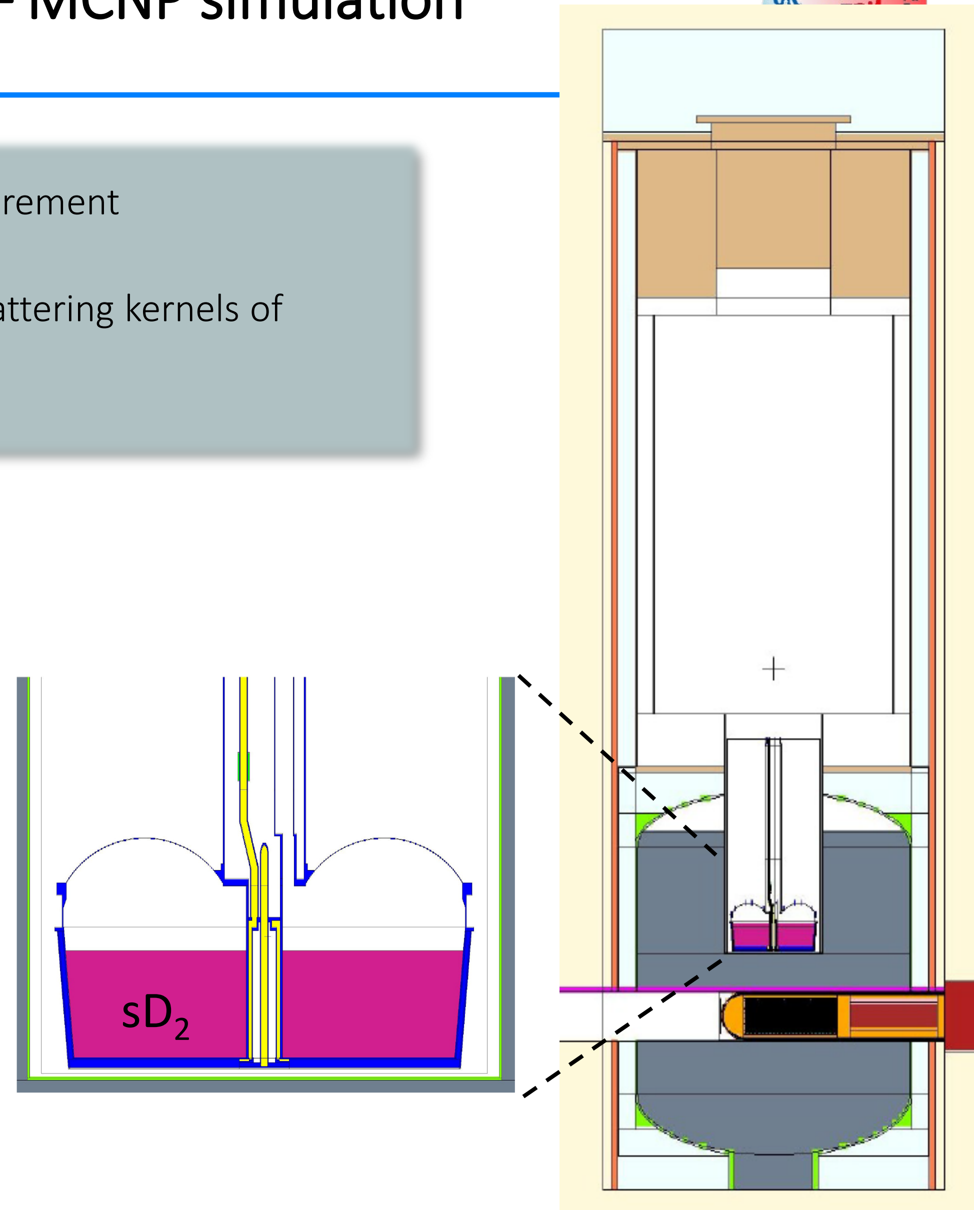
I. Rienäcker DISS. ETH NO. 28498

Cold neutron flux – MCNP simulation

same MCNP model as verified by gold foil activation measurement

added various amounts (filling levels) of sD_2 at 5 K using scattering kernels of W. Bernnat et. al., J. Nuc. Sci. Tech. 39, 124-127 corresponding to D2 masses of up to 5kg





Cold neutron flux – spatial distribution

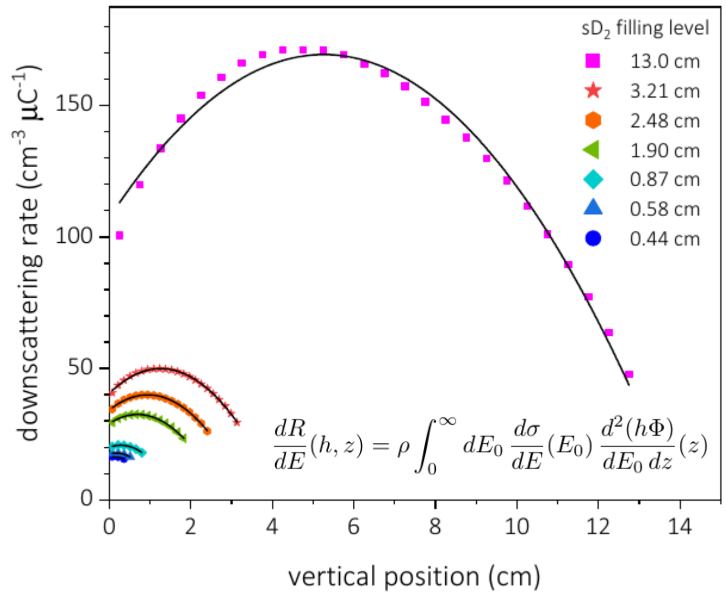
downscattering cross section based on

- incoherent approximation
- Debye model
- thermal neutron flux from heavy water moderator

similar results within uncertainties (≈20%) with coherent scattering model (C.-Y. Liu et. al., arXiv:1005.1016 (2010))

from MCNP cylindrical mesh tally compute vertical gradient of cold neutron flux

weighted by down scattering cross section to obtain UCN production rate at vertical position from surface



- integrated UCN energy range 0 – 250 neV
- typically 18000 µC per 8 s proton beam pulse
- 22000 cm^3 nominal sD_2 volume

Measure extraction efficiency

increase sD2 filling level by deposition of D_2 vapor into cooled moderator vessel

after deposition, remelt and freeze entire amount of D_2 to avoid surface frost

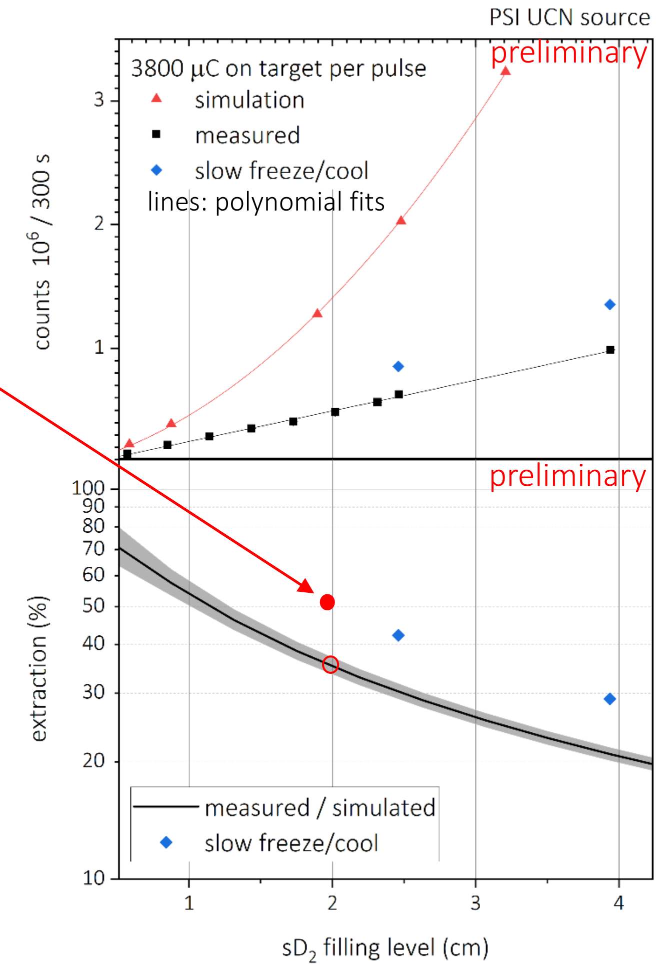
two freezing / cooling methods:

- fast (full cooling power)
- slow (0.25 K / hour)

compare to simulated UCN yield based on thin film calibration measurement

50 % extraction from 2 cm sD_2 converter is achievable …

… but requires slow freezing / cooling



Extracted UCN

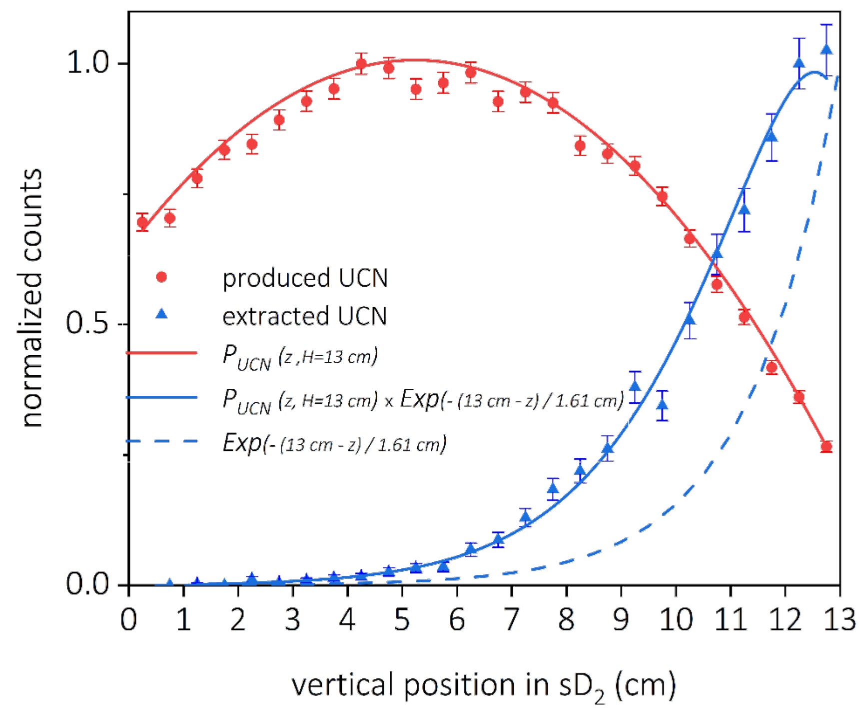
tally starting position of extracted UCN

can be approximated by product of
exponential distribution and
cold neutron flux vertical gradient

extraction depth
(mean of exponential distribution)
1.6 cm from sD_2 surface

mean of total distribution
2.3 cm from sD_2 surface

preliminary



isotropic scattering σ = 63 barn

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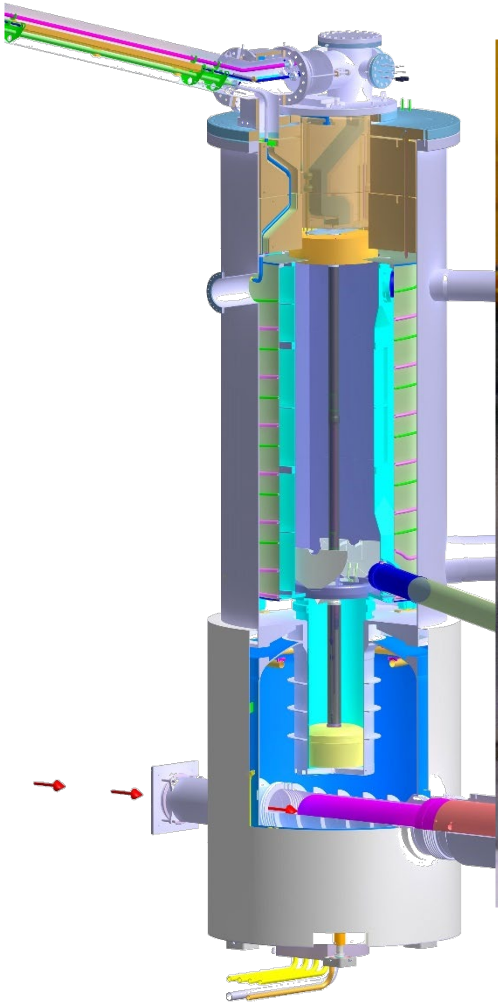
- Project EZE UCN

(EZE - Replacement of central deuterium unit)

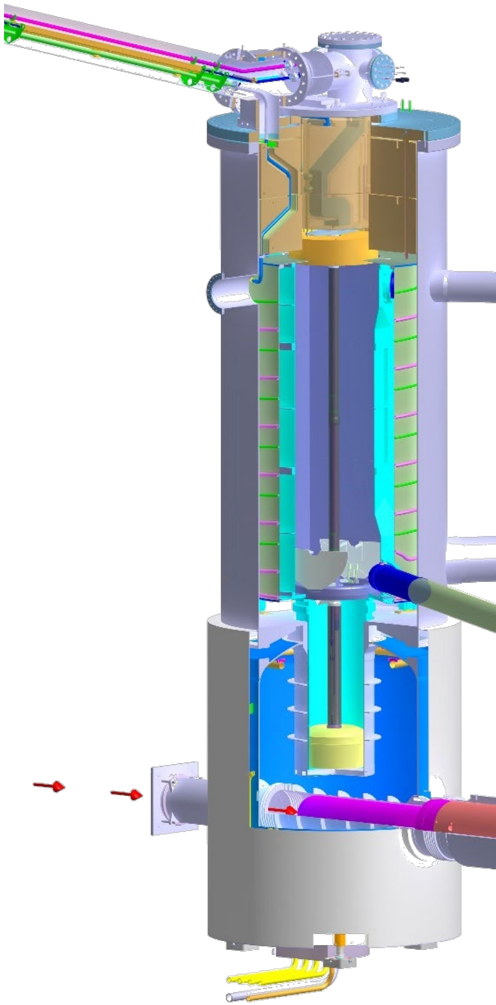
EZE Project
(Ersatz Zentraleinschub)

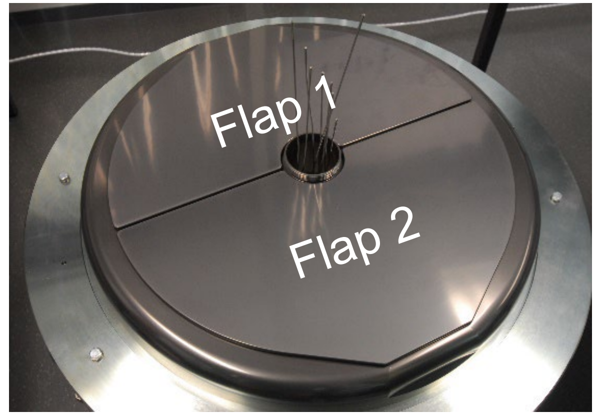
PSI / NUM department project 2023 - 2027

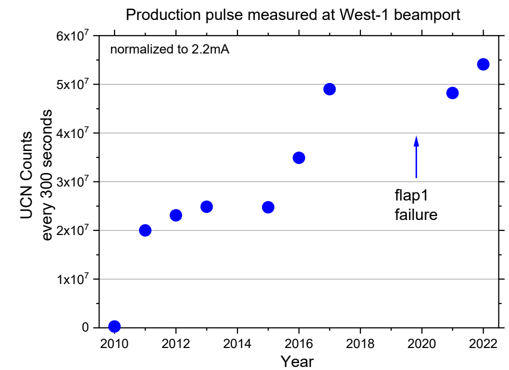


we have to solve 2 ongoing problems

EZE Project
(Ersatz Zentraleinschub)





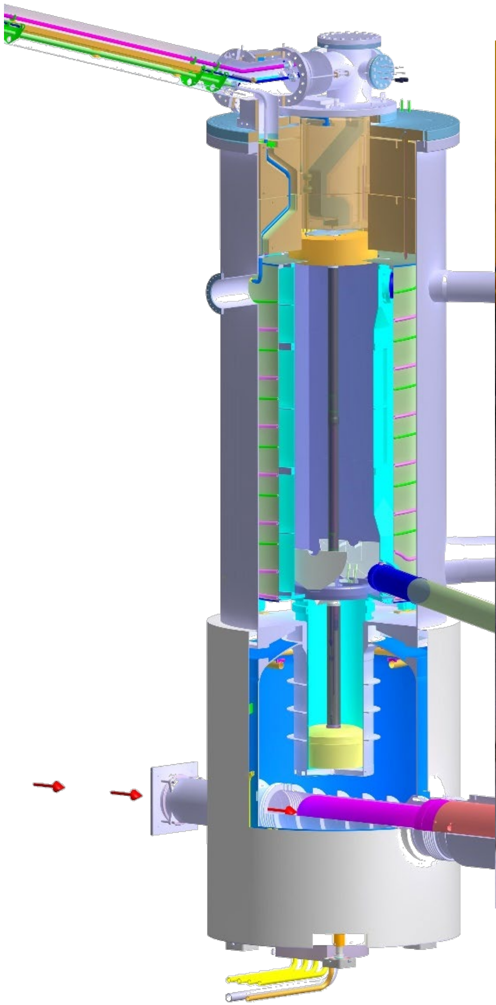


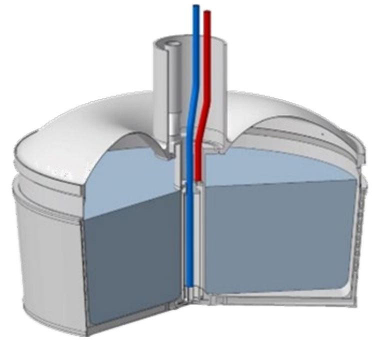
Flap 1 has a vacuum leak
→not operable anymore

Operation Mode (of remaining flap)	UCN output reduction
8s pulse (flap closed after pulse)	25%
2s benchmark pulse (flap permanently open)	7%

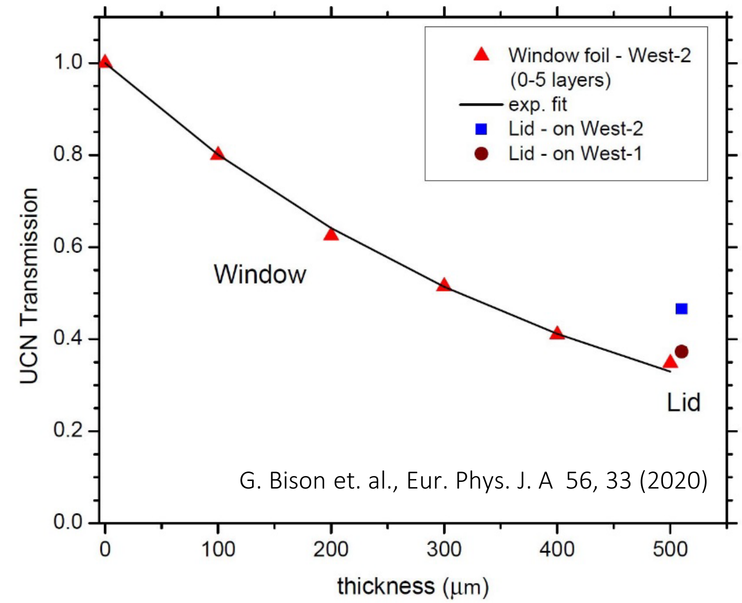
cite paper

EZE Project
(Ersatz Zentraleinschub)





small cold leak
→
new sD2 vessel
with different lid



Summary & Outlook

- Operation with n2EDM baseline setup up to end of 2026

- Replacement of Central unit 2027

- PSI accelerator shutdown due to upgrade within the IMPACT project, currently planned to end in mid 2028

- HIPA proton beam current regularly (already approved) at 2.4mA and upgrade to 3mA in discussion

- Restart of UCN with improved UCN output serving an upgraded n2EDM experiment in the 'Magic field phase' towards ~5×10^{-28} $e{\cdot}cm$ sensitivity.

- Thanks for your attention

- Thanks for many slides go to Ingo Rienäcker - PhD 2023