Investigating the Solid Deuterium in the PSI UCN Source Moderator

PhD Seminar 2018, Zurich

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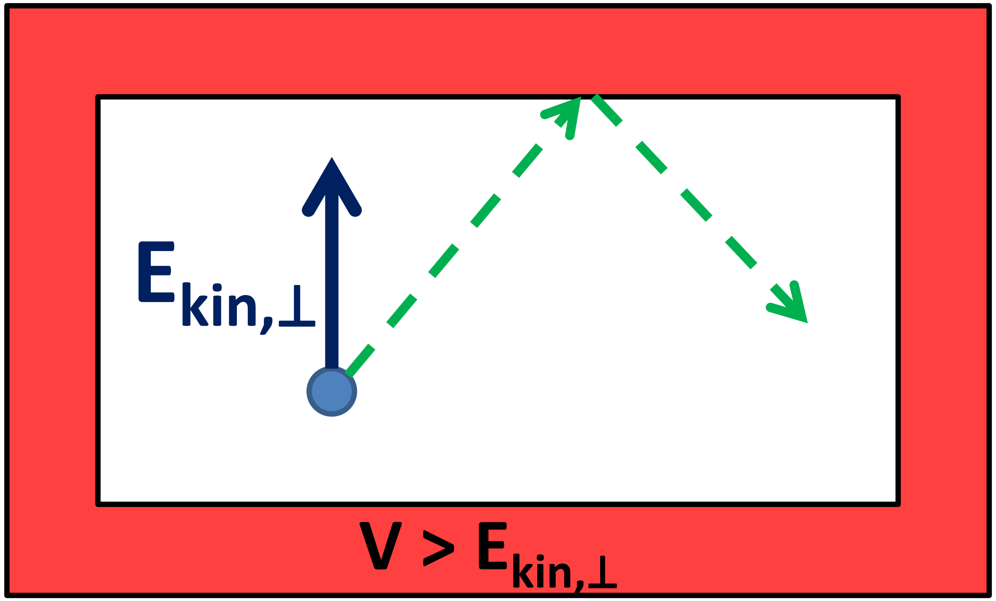
- What are UCN and their uses?
- Working principle of the PSI UCN source
- Investigation and characterization of the behavior of the D_2 used in the PSI UCN source

What Are UCN?

- **Ultracold Neutrons (UCN):** very slow neutrons, typically with a kinetic energy of ≤ 335 neV (8 m s^{-1} , 3 mK)
- **Can be totally reflected on neutron optical potential, storage possible** in vessels made of appropriate materials for a timespan of several minutes limited by their β-decay lifetime
- **Magnetic and gravitational confinement also possible**

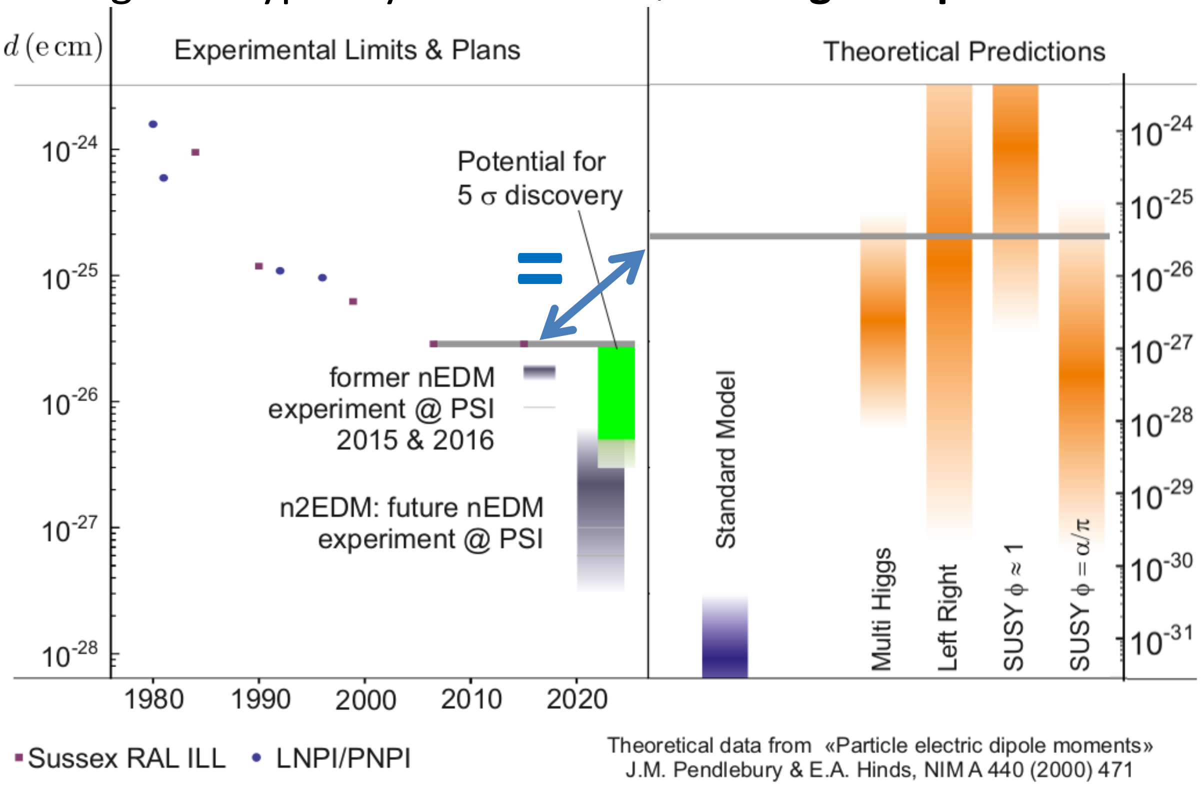


Material	V [neV]
^{58}Ni	335
Fe	210
Cu	168
Al	54
Ti	-48

Research with UCN

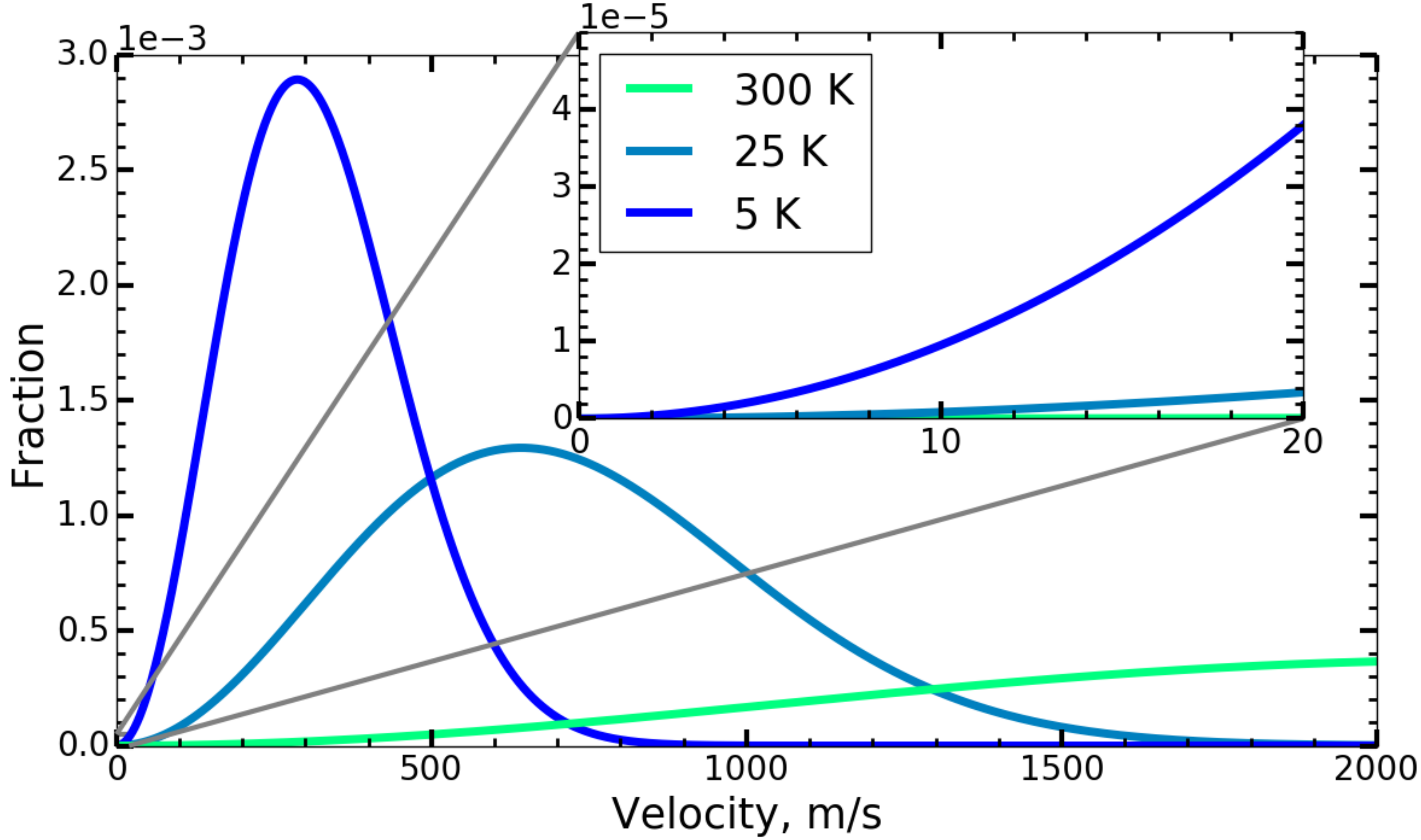
- **Valuable tools in high precision physics experiments,** e.g. measurements of free neutron lifetime and neutron electric dipole moment (nedm), for example the **nEDM (dismantled in Oct 2017) and future n2EDM experiments at PSI**
- **Precision** in experiments using UCN typically **scales with $\sqrt{N}$ → high output desired**

Evolution of the nedm limit



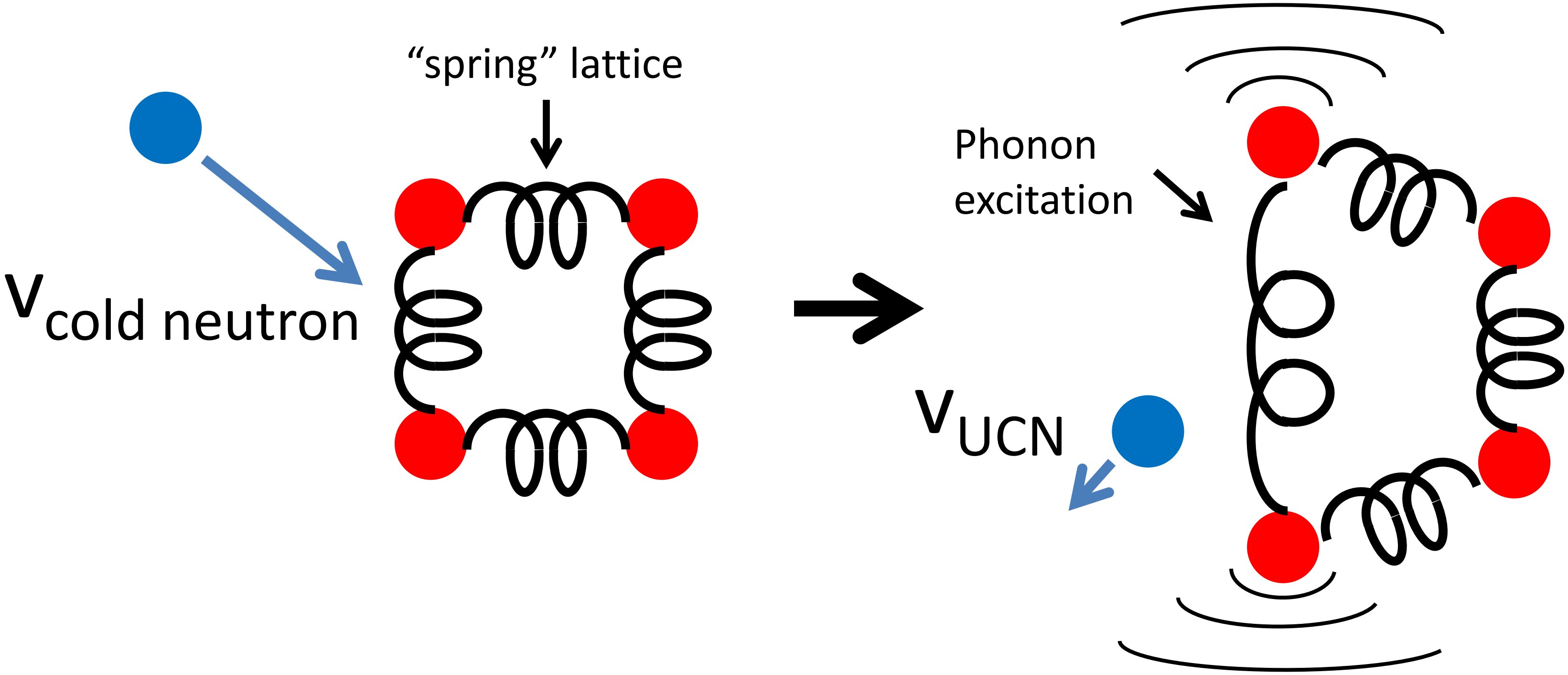
Production of UCN

- **Extract the low-energy tail of a distribution of neutrons in thermal equilibrium with a medium (moderator)**, e.g. D_2O close to a nuclear reactor

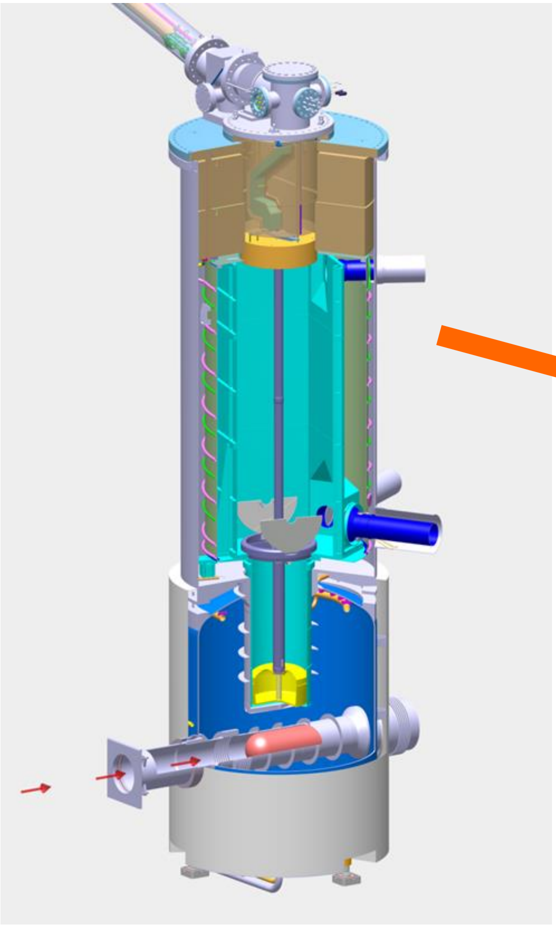


Production of UCN

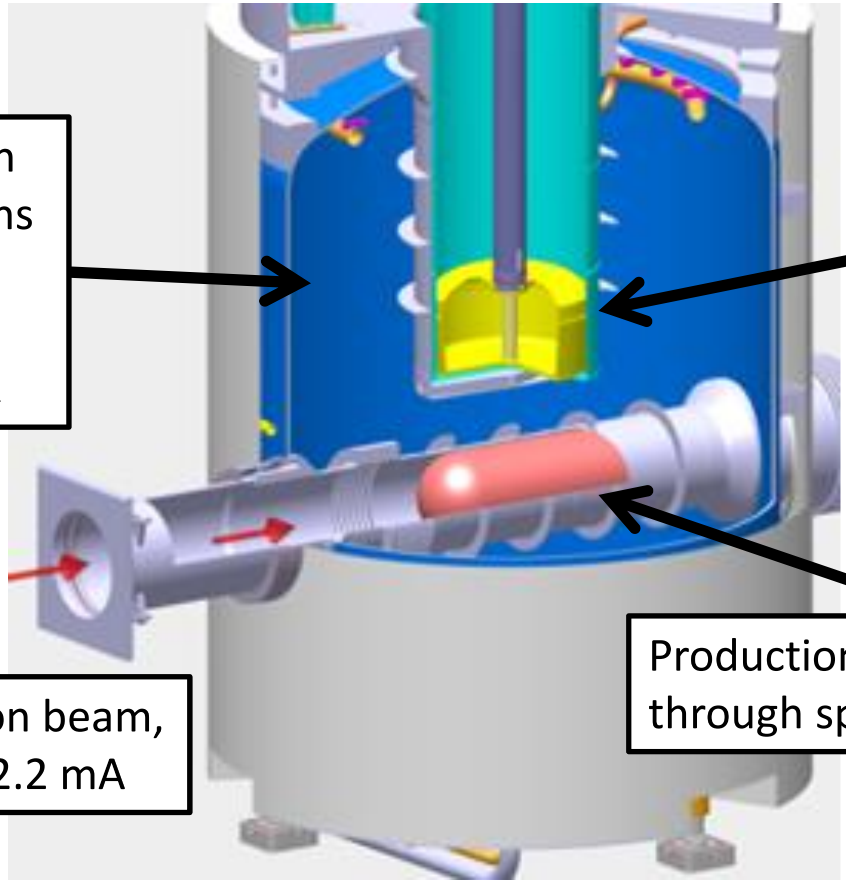
- Other possibility: **inelastic scattering of cold or thermal neutrons to transfer nearly all of their kinetic energy to an excitation of the scattering medium**, e.g. through phonon excitation in solid deuterium (D_2) or superfluid He
- **Higher UCN densities than the actual thermal equilibrium distribution** at the temperature of the scattering medium would be → **"superthermal" production**



PSI UCN Source: Working Principle



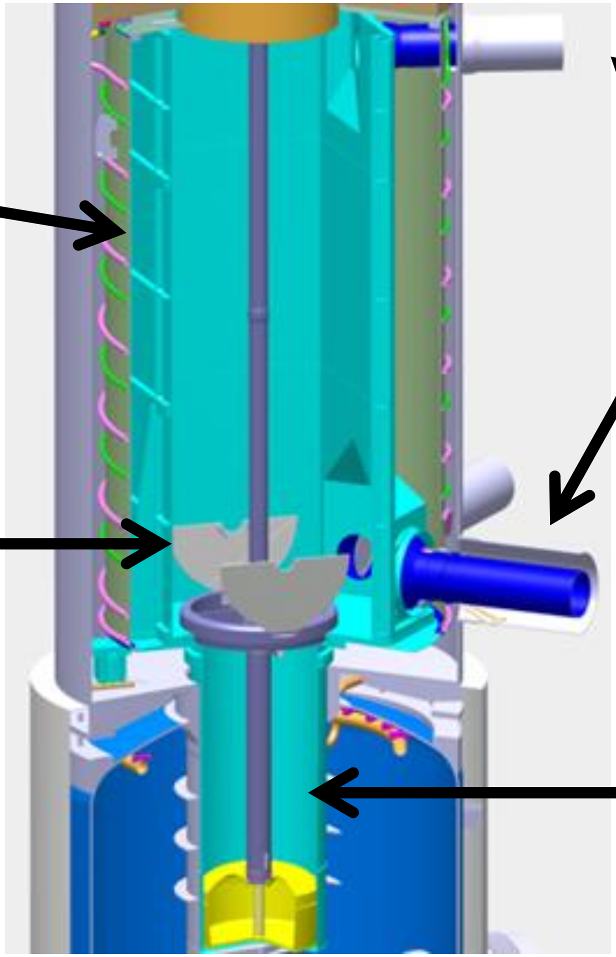
First Step: Moderation



Second Step: Storage and Extraction

Intermediate DLC-coated storage volume, 2.3 m^3

Flaps to close off storage tank at end of UCN production, i.e. proton pulse

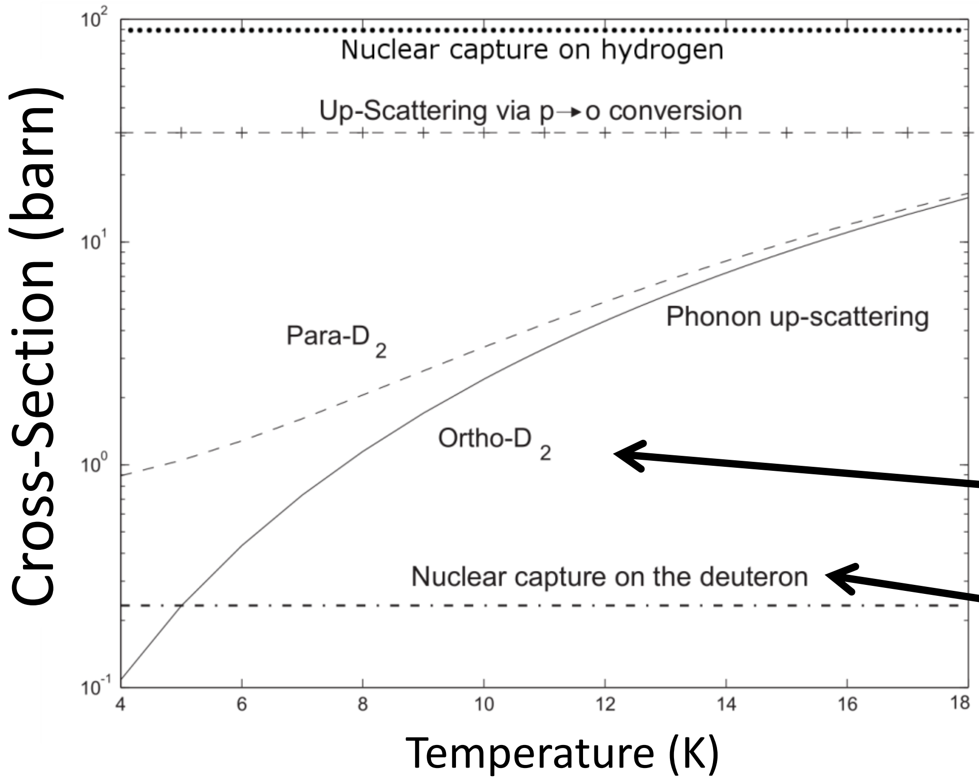


Neutron guides towards experiments

Collection of UCN flying upwards in storage volume

Loss of UCN in D_2

- Life time of UCN in D_2 : $1/\tau = 1/\tau(process\ 1) + 1/\tau(process\ 2) + \ldots$
  → large τ desired
- $\tau(process) = 1/(N_{scatterers} * \sigma_{process} * v_{UCN})$ → decrease $N_{scatterers}$ or $\sigma_{process}$

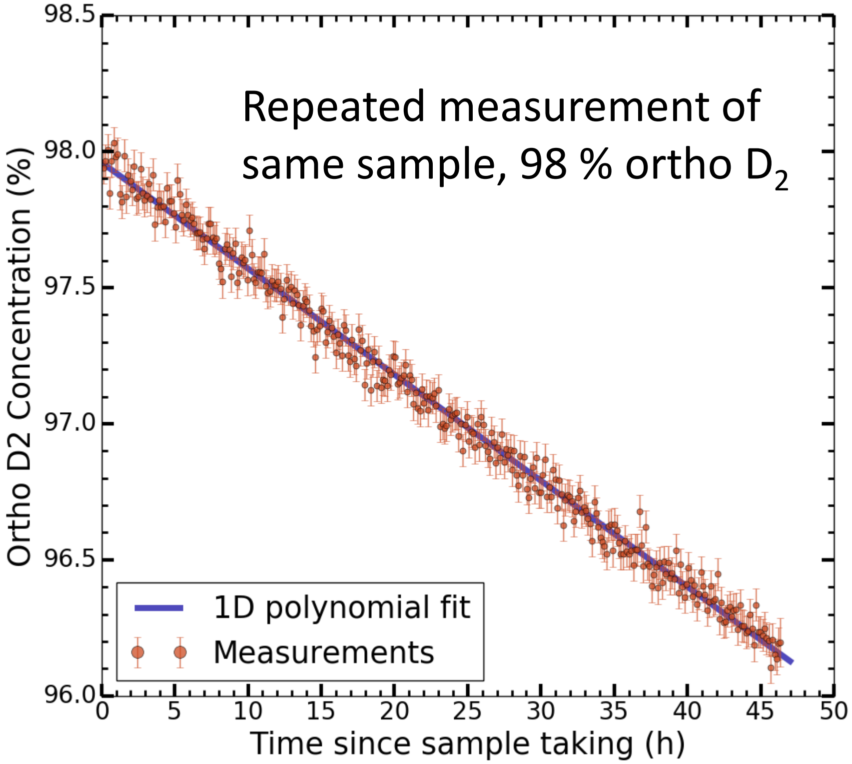


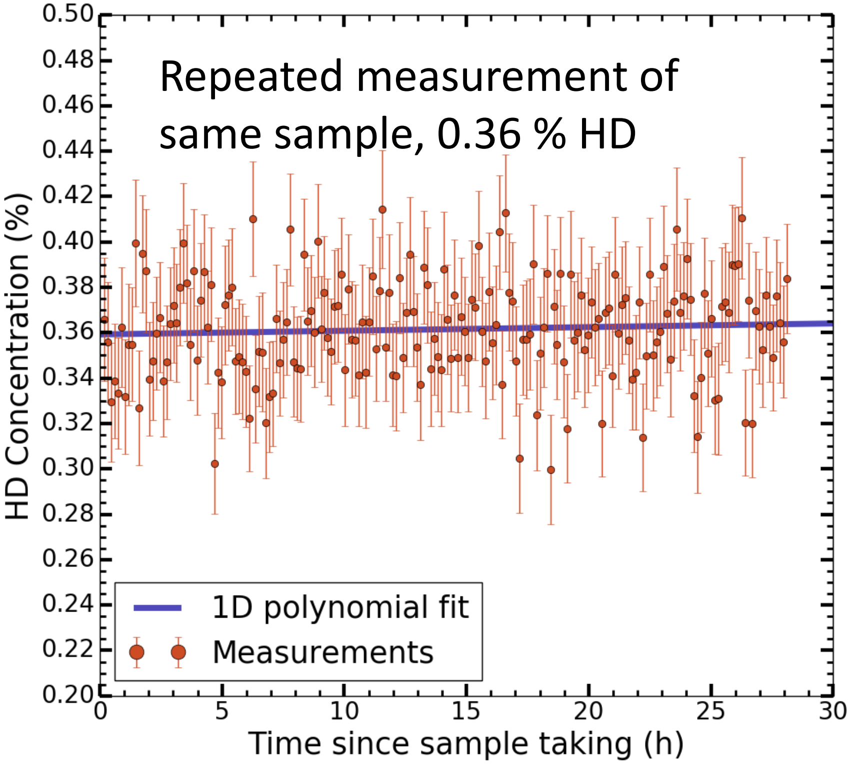
D_2 has two spin isomers (like H_2) called ortho and para caused by the spin addition of the two D and Bose-Einstein statistics with $E_0(\text{ortho}) < E_0(\text{para})$

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

Monitoring Para-D_2 and HD Concentrations

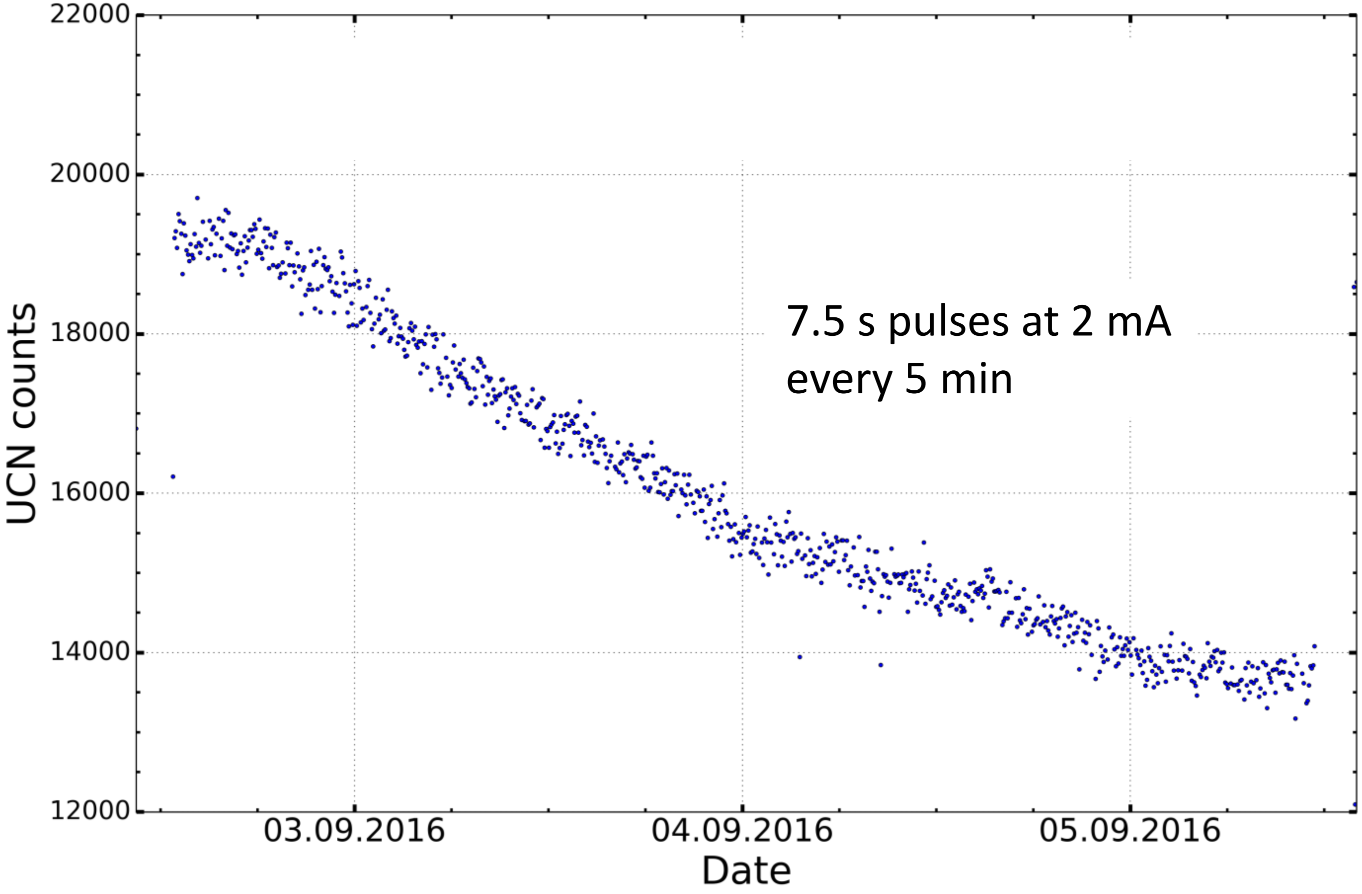
- The para-D_2 and HD concentrations are monitored using Raman spectroscopy
- Both are within acceptable limits





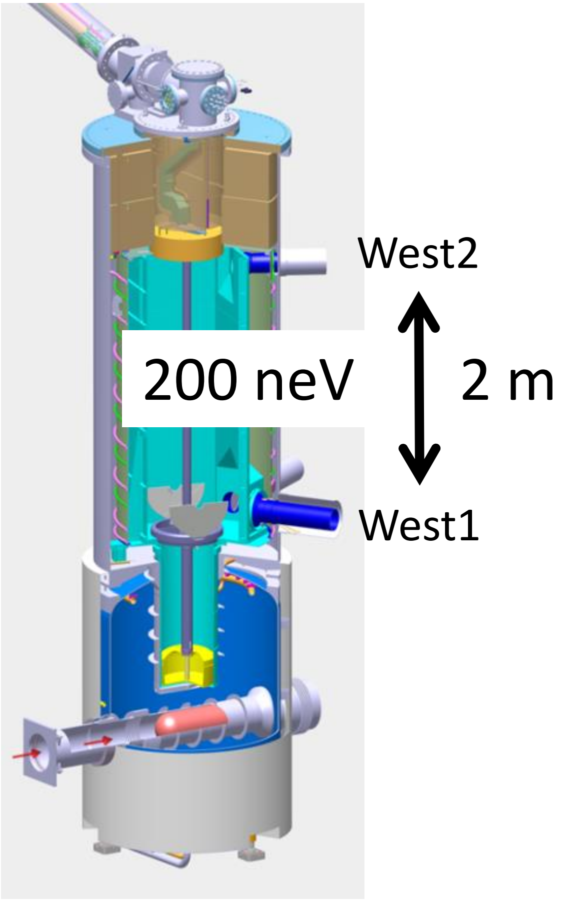
Short-Term Decrease

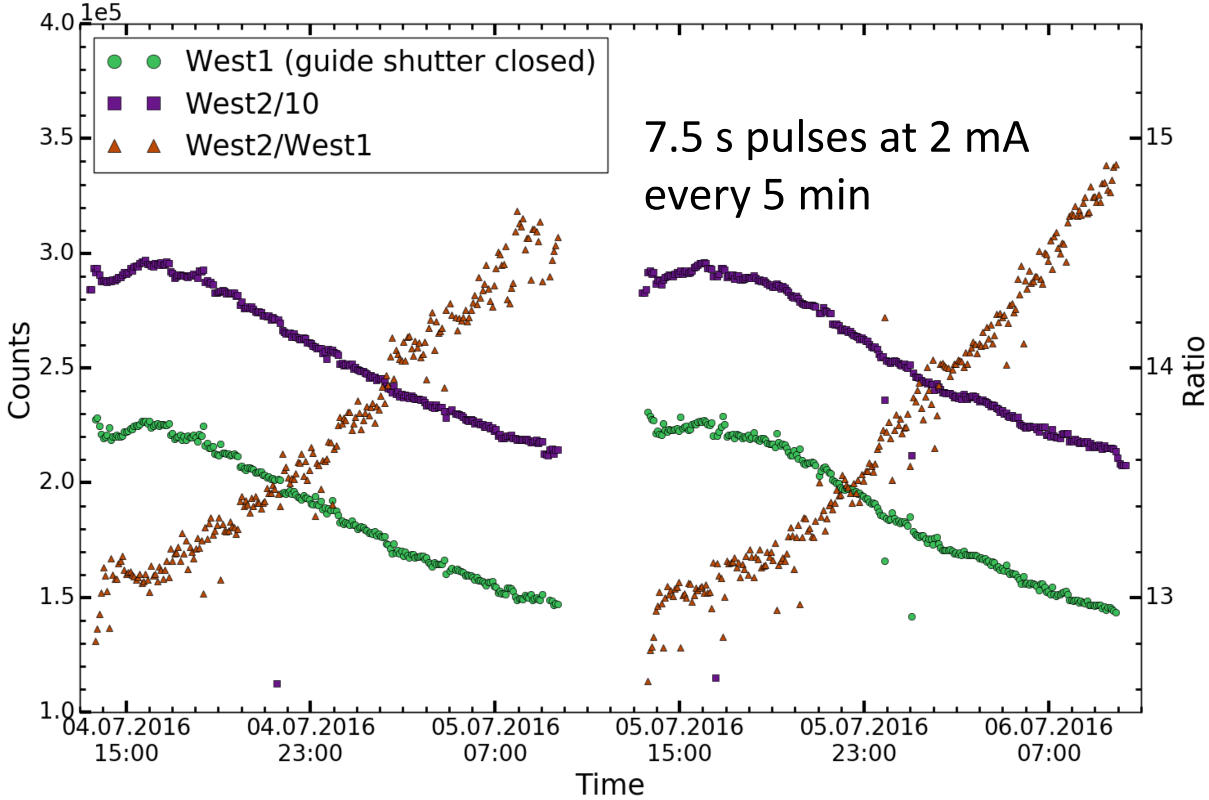
- After 24 h of pulsing, decreases of about 15 % are observed



UCN Counts at Different Heights

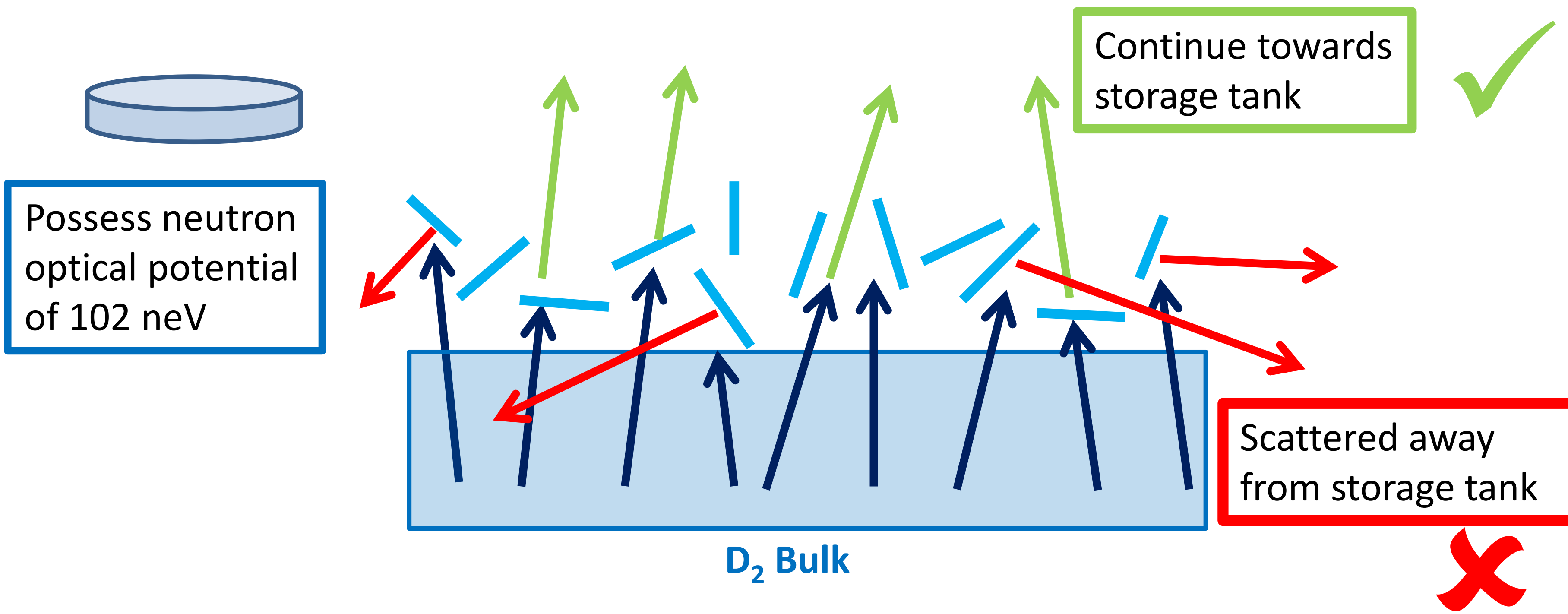
- Ratio West2/West1 increases → **slow UCN output decreases more rapidly than fast UCN output**





Frost Model

- Most attractive idea to **explain the energy-dependent decrease**: **frost hypothesis**
- **Degeneration of the D_2 surface** because of the heat input during the proton pulses
- Simplified picture : **small D_2 flakes** start to form on the bulk surface that act as mirrors and **increase the scatter of exiting neutrons** → slower UCN more prone to being scattered

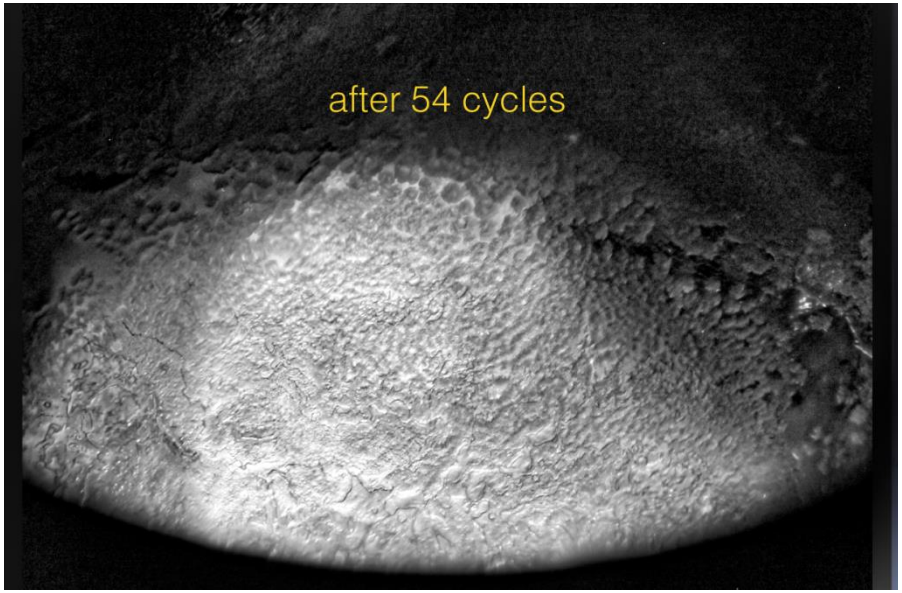


Tests of D_2 behavior at PULSTAR Reactor by E. Korobkina

- Visual inspection of solid D_2 surface degradation after heat cycling, possible because setup not yet inserted into reactor
- Further evidence towards frost model to explain UCN loss

Smooth surface

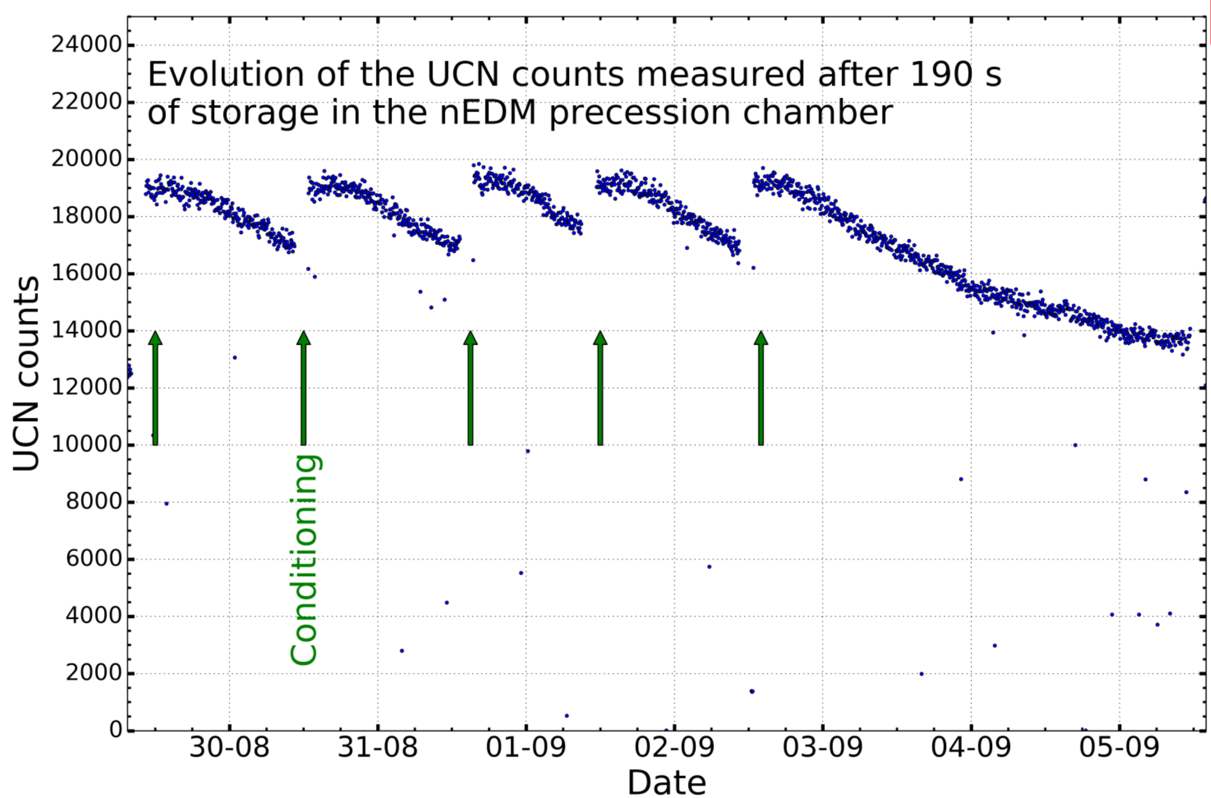
Rough surface after several heat cycles

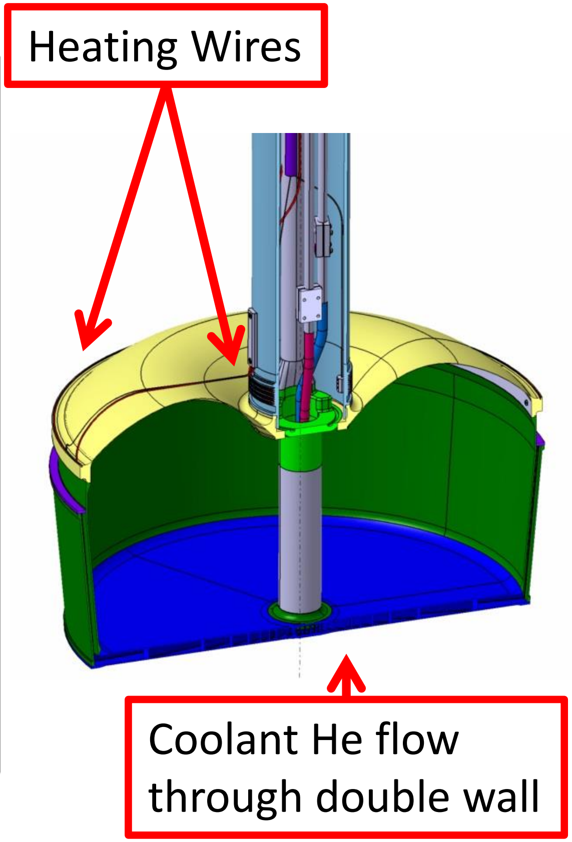


Photos by E. Korobkina and group, NC State University

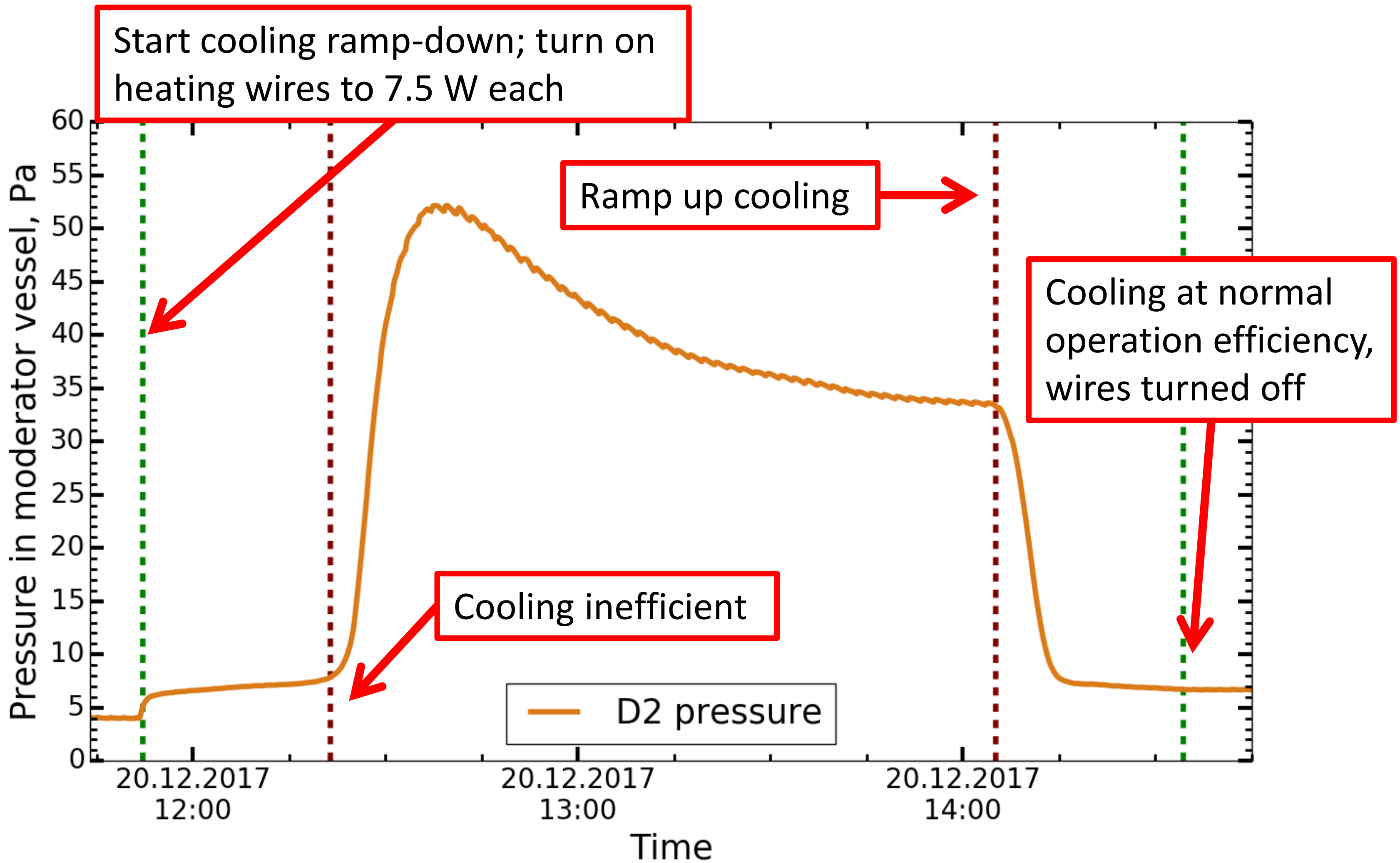
Conditioning

- Development of **surface treatment called "conditioning"** to recover output: Reduce He cooling of moderator vessel with additional heat input using heating wires
- But **conditioning interrupts operation** → **Minimize time** needed for output recovery



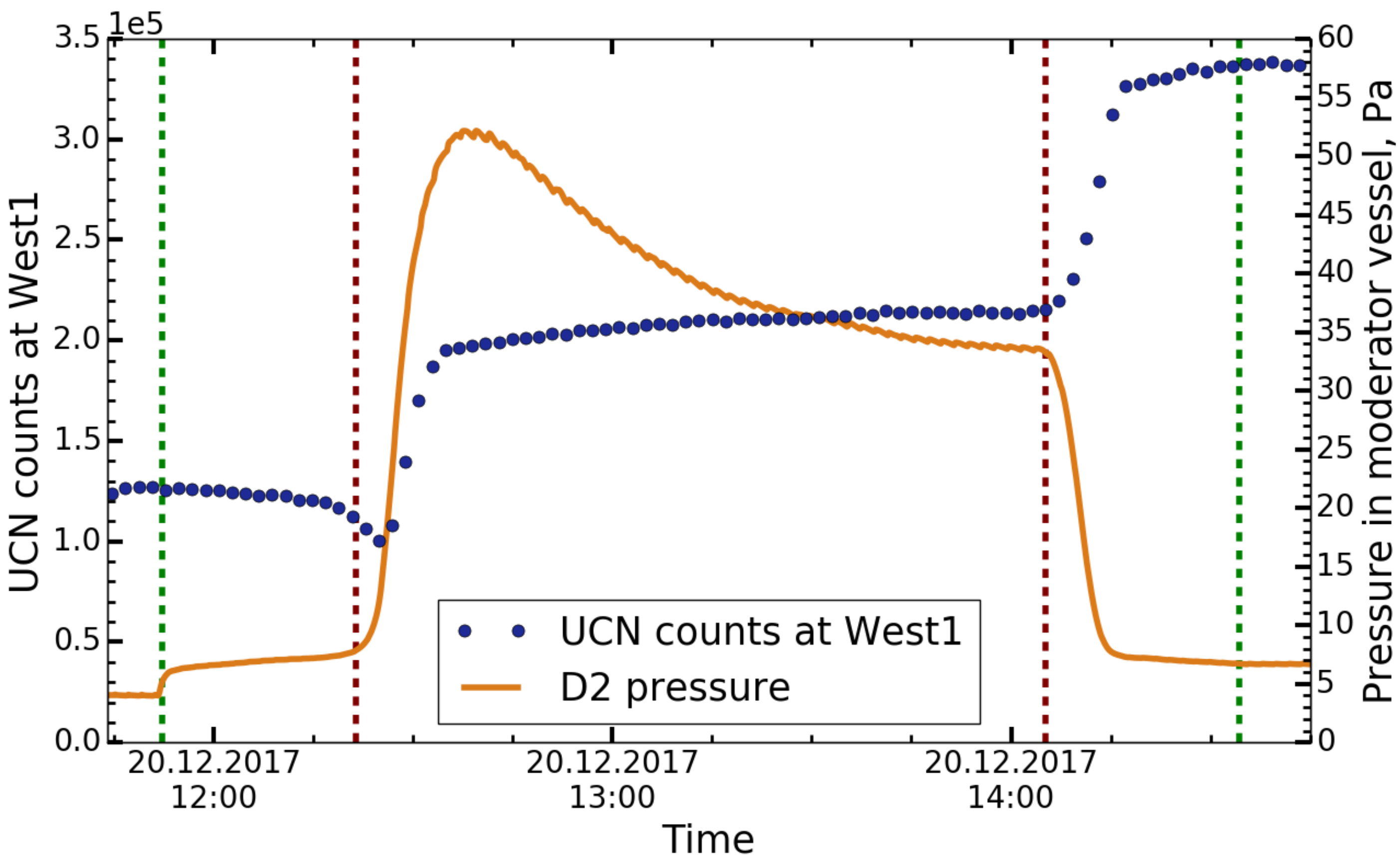


Conditioning Procedure

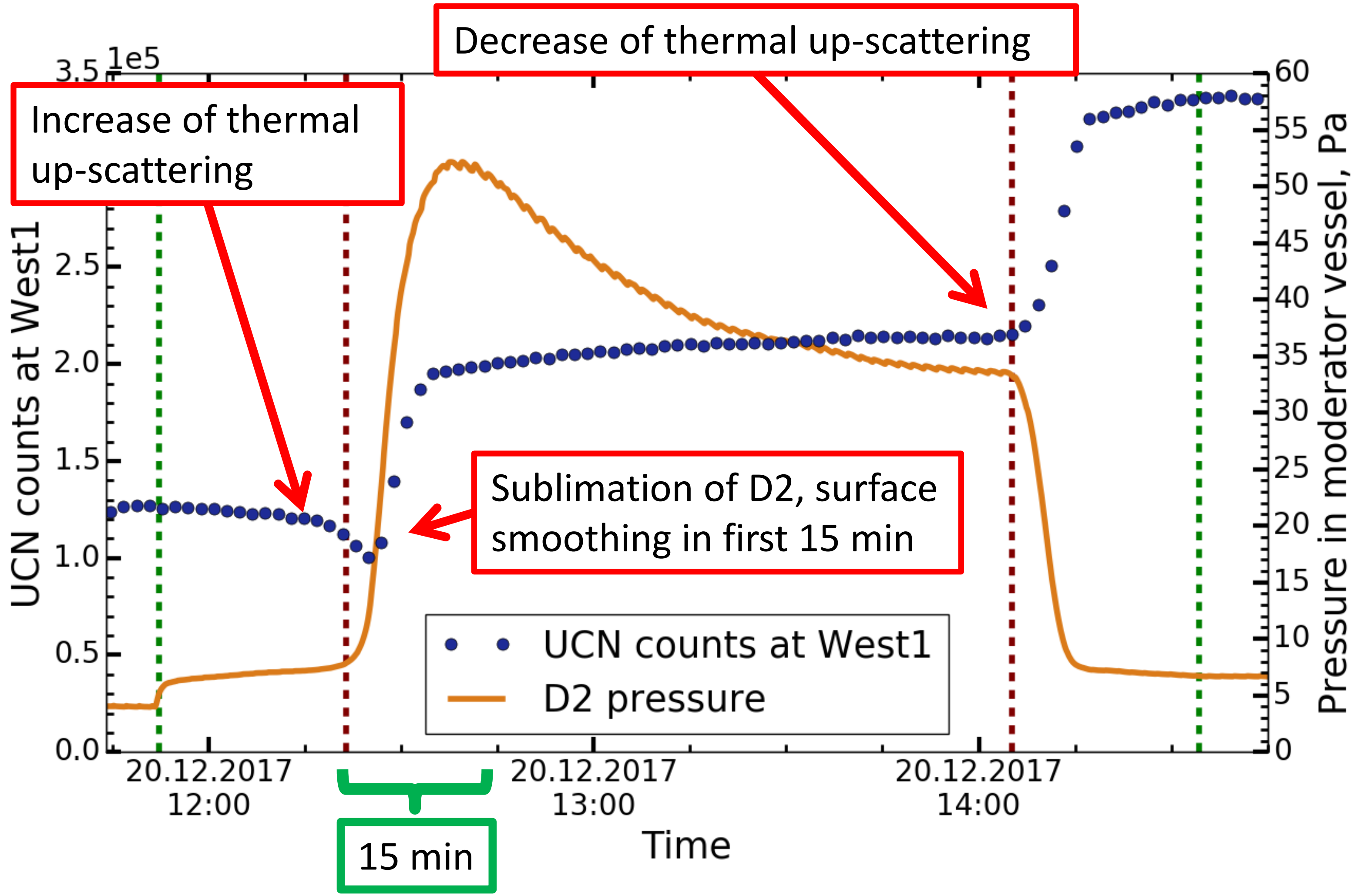


Probing UCN Output

- **Probe UCN output during conditioning** with short 0.1 s pulses at 1.4 mA in quick 2 min succession → minimal interference with conditioning process

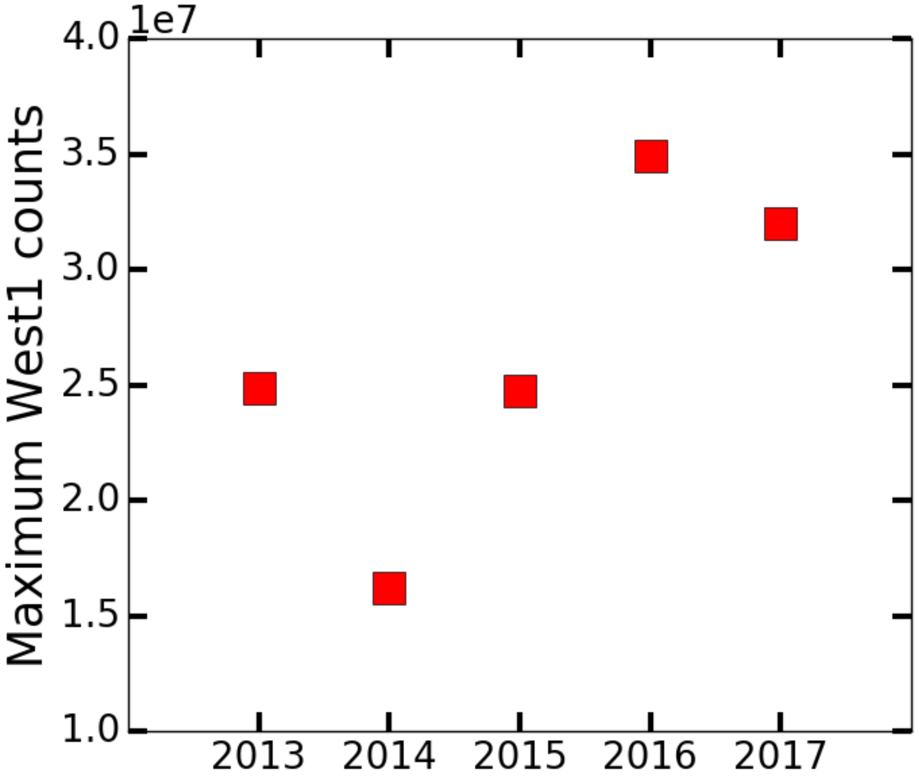


Interpretation



Resulting Output

- **Conditioning has helped reach new record UCN outputs**
- Insights will be used to **ensure high UCN output for next experiments and push the sensitivity on neutron el. dipole mom. further up**



Summary

- The **PSI UCN source shows short-term decrease** in its output, even though molecular losses are kept under control and monitored with Raman spectroscopy
- The short-term decrease can be explained with **D_2 snow forming on top of the bulk**
- **Conditionings**, short periods of reduced cooling and heat input, are applied to **counter the daily decrease**
- **Refinement of the conditioning** procedure has allowed the PSI source to keep its **average UCN output high**, helping the **nEDM and future experiments** to further **push their sensitivity up**

Thank you for your attention

Backup Slides

Ortho/Para Deuterium

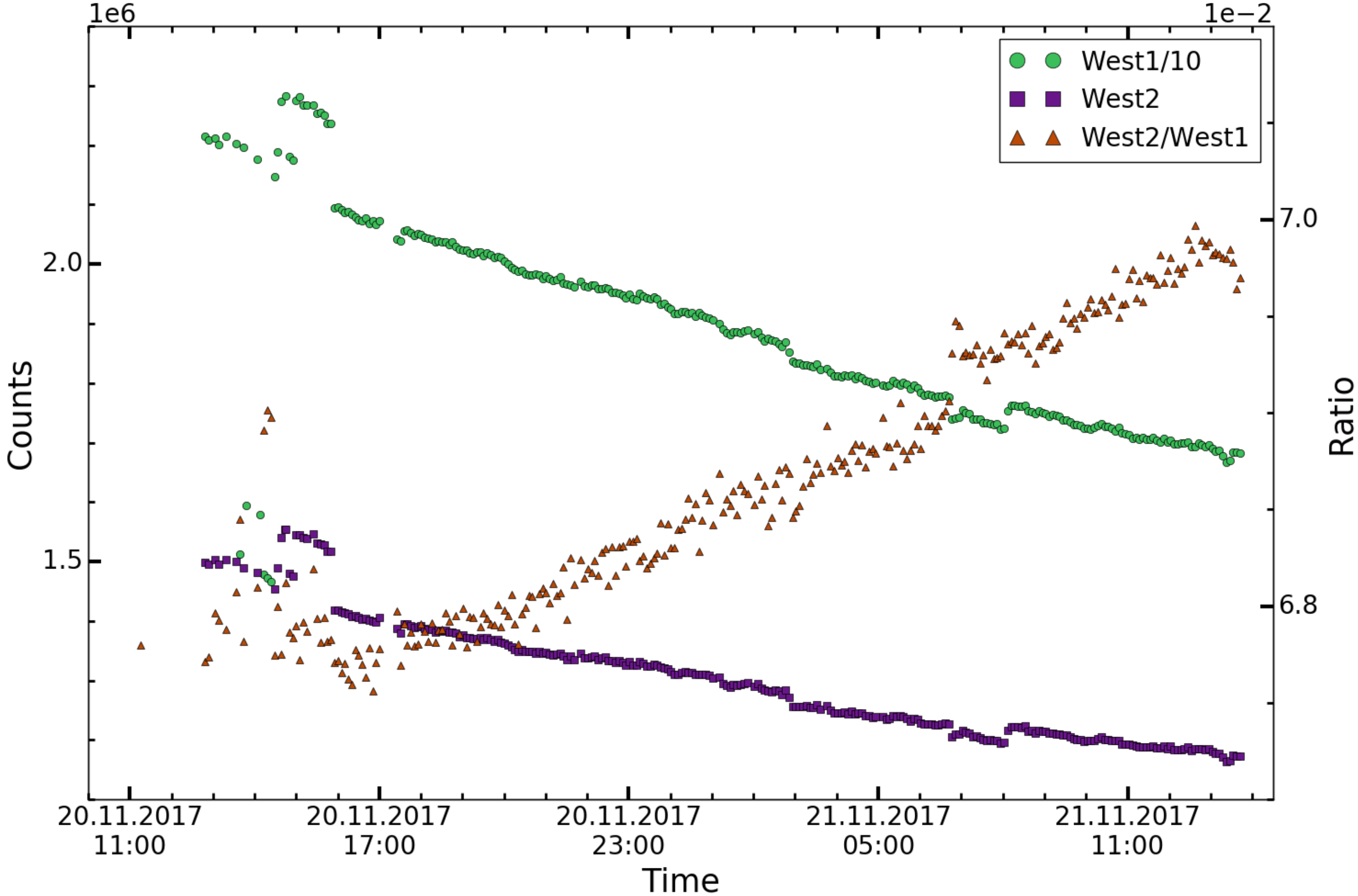
- Similar to $^{1}H_2$, D_2 has two spin isomers called ortho and para D_2
- D_2 is a homonuclear diatomic nuclear and D has integer nuclear spin (ground state S = 1) → system of two undistinguishable bosons → wave function must be symmetric under exchange of the deuterons
- $\Psi_{tot} = \Psi_{vib}\,\Psi_{rot}\,\Psi_{spin}$, where Ψ_{tot} must be symmetric and Ψ_{vib} is always symmetric
- For Ψ_{tot} to be symmetric, the following combinations result

S	Degeneracy	Ψ_{spin}	Ψ_{rot}	J	State
0	1	Symmetric	Symmetric	Even	Ortho
1	3	Antisymmetric	Antisymmetric	Odd	Para
2	5	Symmetric	Symmetric	Even	Ortho

- Ortho states more stable than para, but self-conversion very slow (τ = 80 days)
- In terms of UCN production, a high para content leads to a high number of para to ortho conversions through interaction with UCN, resulting in a high increase in kinetic energy of the neutron and effectively eliminating the UCN

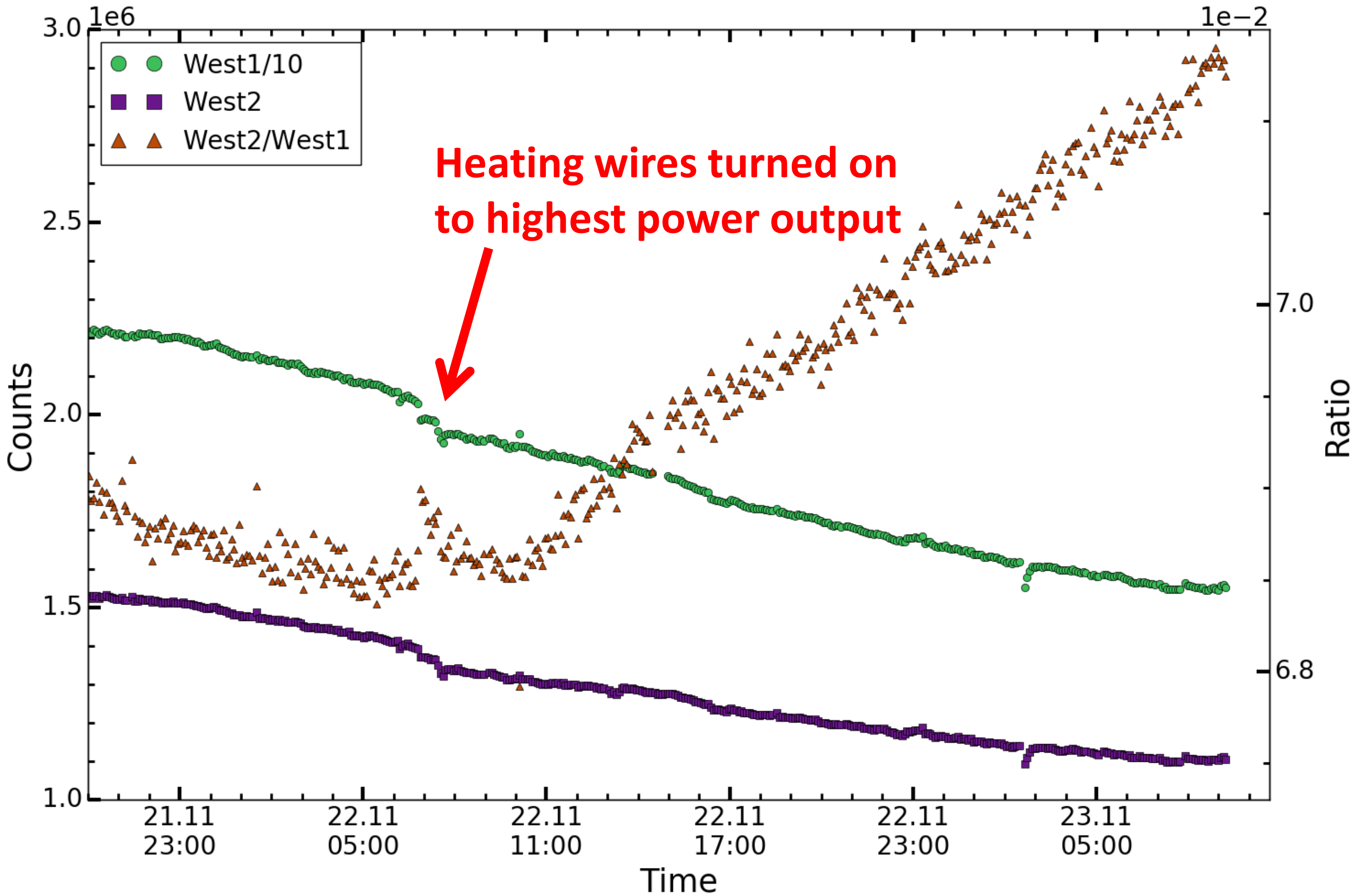
Further Examples of Ratio Change

- Example of West2/West1 ratio change with all port shutters open



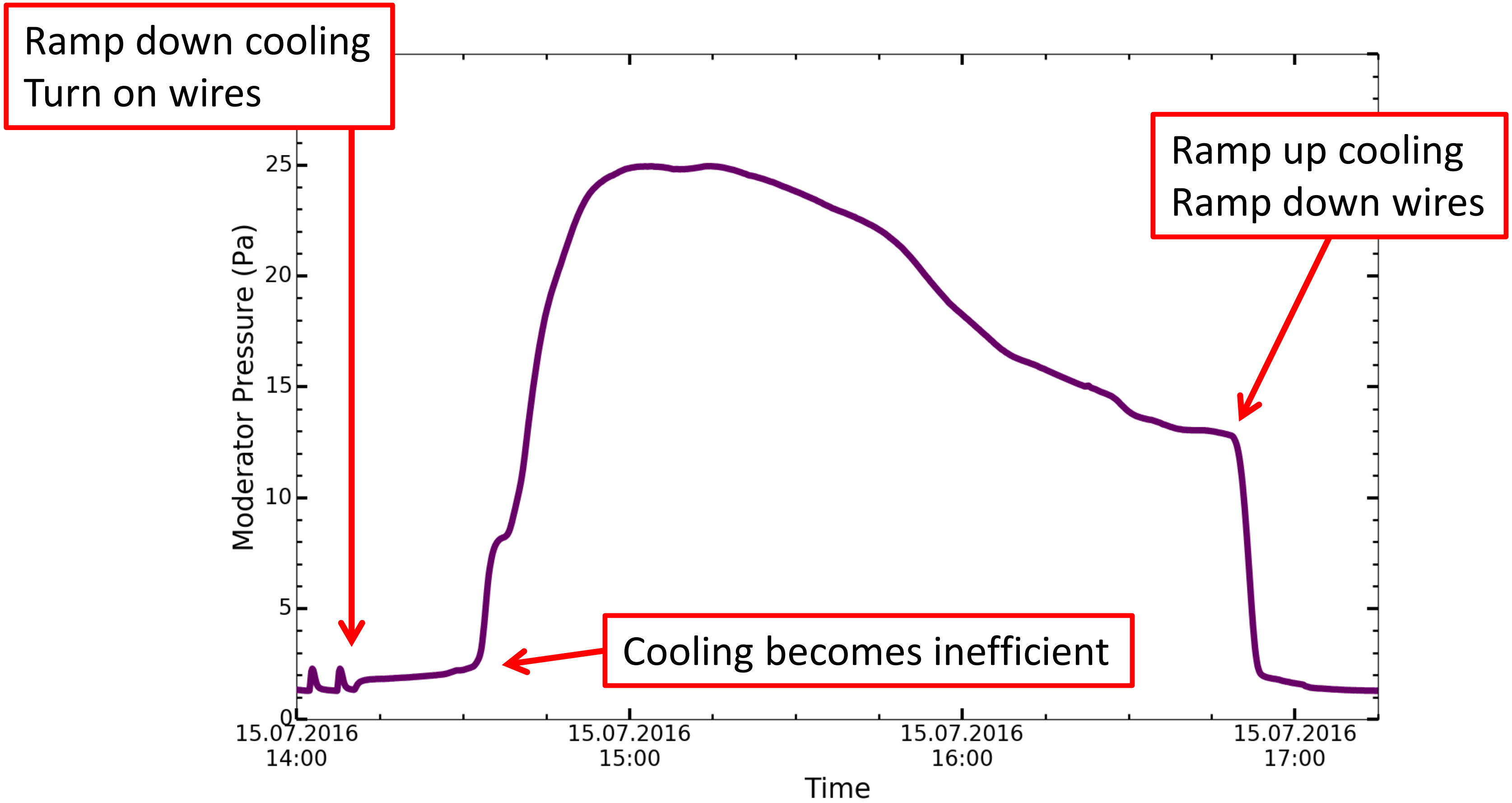
Further Examples of Ratio Change

- Lid heating during operation with high cooling power does not eliminate the frost



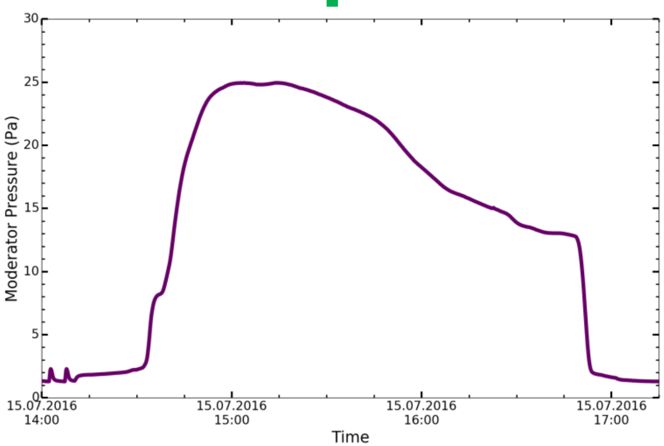
D_2 Pressure during Conditioning

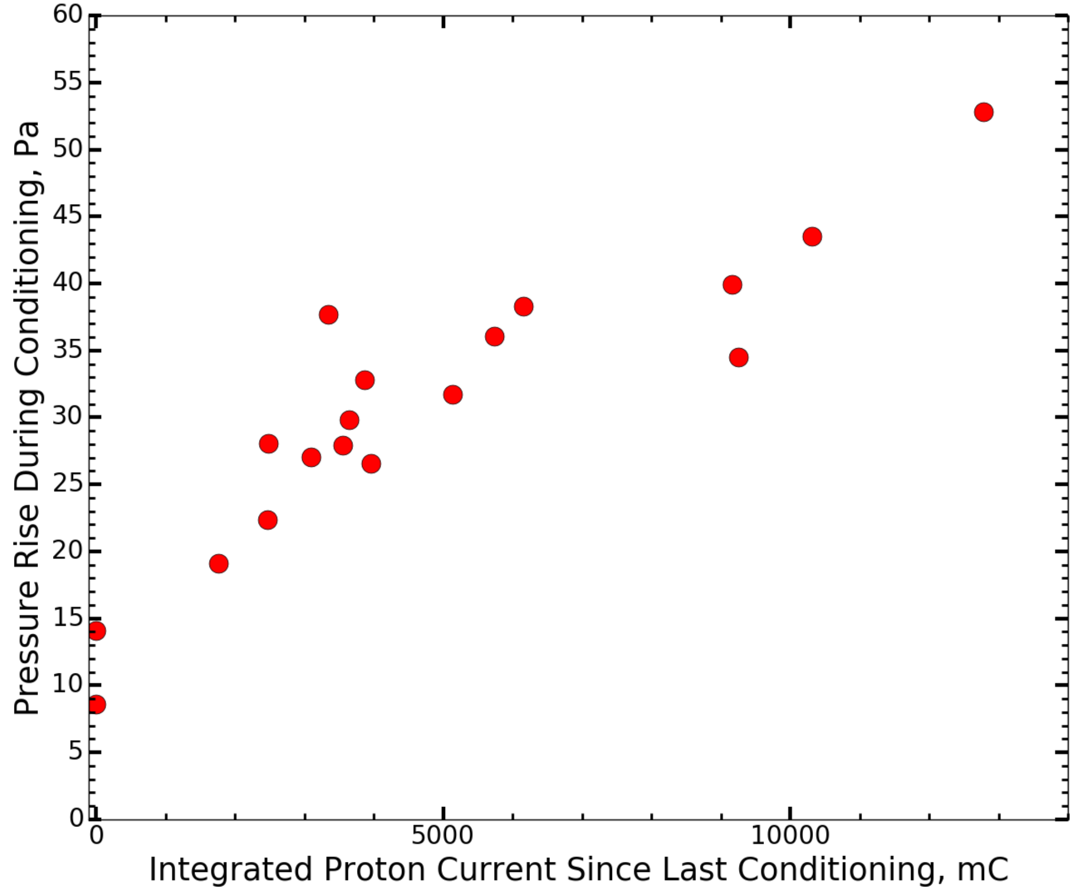
- The pressure inside the moderator vessel shows a typical evolution during conditioning



Integrated Current vs Pressure during Conditioning

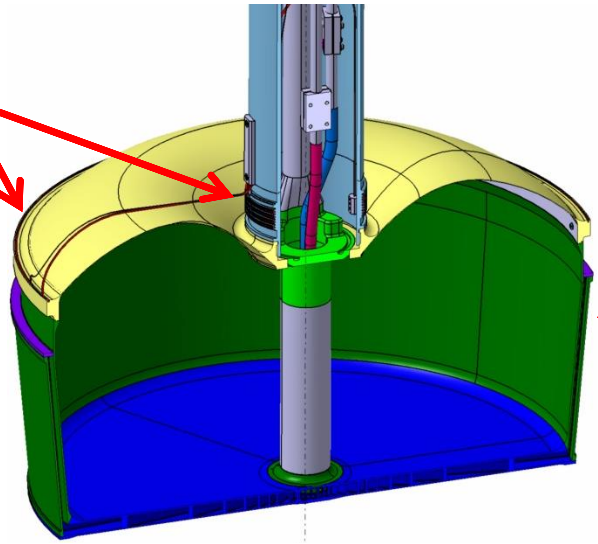
- **Further evidence for D_2 structures building up during operation**: the more we pulse until the next conditioning, the higher the D_2 pressure during conditioning



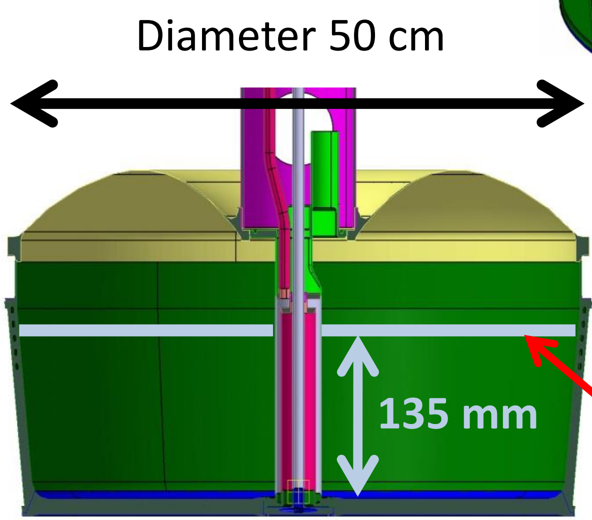


Cold Moderator Vessel

Lid Heating wires, 15 W each



Moderator vessel, $AlMg_3$, total allowed sD_2 volume of 30 L, cooled with supercritical He



Fill height for 4.7 kg, i.e. 23 L sD_2 at 5 K

Coolant He flow