# Fluorinated nano-diamond reflectors, Recent results:

1. Directional extraction and sources of Very Cold Neutrons (VCN),

2. Optimized quasi-specular reflection of cold neutrons (CN).

References to the respective **publications** (partly or totally done in the framework of the present project) are given below in the text

# The most recent publications:

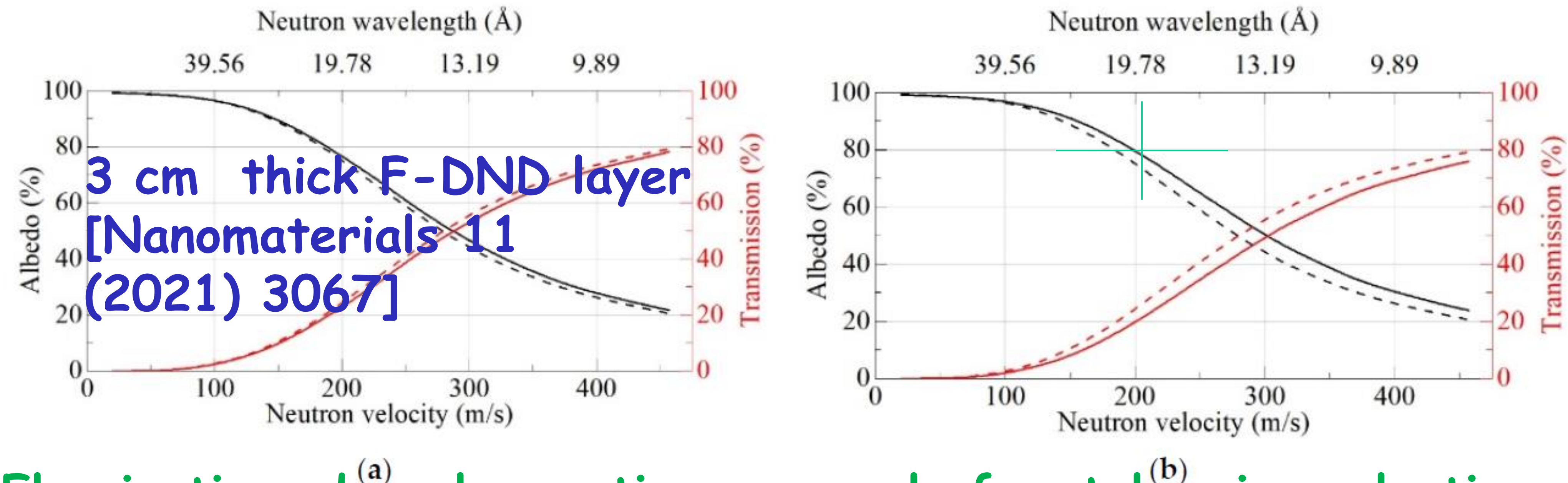
- S.M. Chernyavsky, M. Dubois, E. Korobkina, E.V. Lychagin, A.Yu. Muzychka, G.V. Nekhaev, V.V. Nesvizhevsky, A.Yu. Nezvanov, A.V. Strelkov, K.N. Zhernenkov, *Enhanced directional extraction of very cold neutrons using a diamond nanoparticle powder reflector*, **Rev. Sci. Instr. 93 (2022) 123302 (editor's highlight)**
- V.V. Nesvizhevsky, *Why very cold neutrons could be useful for neutron antineutron oscillation searches*, **J. Neutron Res. 24 (2022) 223 (proceedings of ESS/VCN/UCN workshop)**
- A. Bosak, M. Dubois, E. Korobkina, E. Lychagin, A. Muzychka, G. Nekhaev, V. Nesvizhevsky, A. Nezvanov, T. Saerbeck, R. Schweins, A. Strelkov, K. Turlybekuly, K. Zhernenkov, *Effect of nanodiamond sizes on the efficiency of the quasi-specular reflection of cold neutrons*, **Materials 16 (2023) 703 (invited article)**

# Plan of this presentation

- Diffusive reflectivity of Very Cold Neutrons (VCNs) from Fluorinated Detonation NanoDiamond (F-DND) powders,
- Experimental demonstration of the directional extraction of VCNs from the cavity in a F-DND reflector,
- A possible implementation of the VCN source at the European Spallation Source (ESS), Lund, Sweden,
- Effect of particle sizes on the efficiency of quasi-specular reflection of cold neutrons.

# Diffusive reflectivity of VCNs from F-DND

3 cm thick F-DND layer [Nanomaterials 11 (2021) 3067]

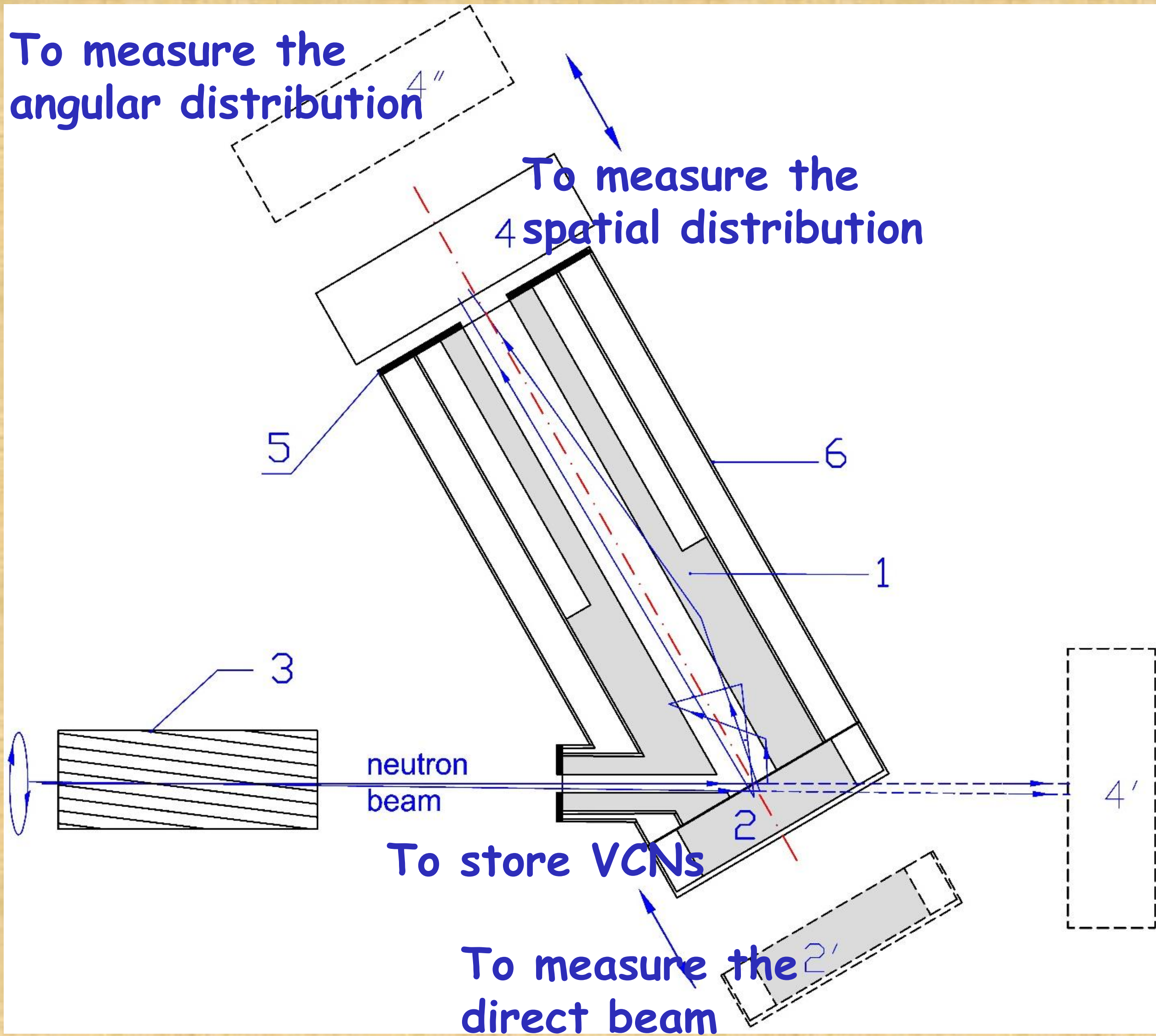



Fluorination, deagglomeration, removal of metals, size selection

**Figure 8.** Neutron albedo (black lines) and transmission (red lines) for a flat layer of DF-DNDs (dashed lines) and S-DNDs (solid lines) versus neutron velocity [m/s]. (**a**) The layer thickness is 3 cm and the powder density is 0.56 g/cm$^3$ for both samples; (**b**) the layer thickness is 3 cm and the powder density is 0.56 g/cm$^3$ for DF-DNDs, and it is 0.67 g/cm$^3$ for S-DNDs.

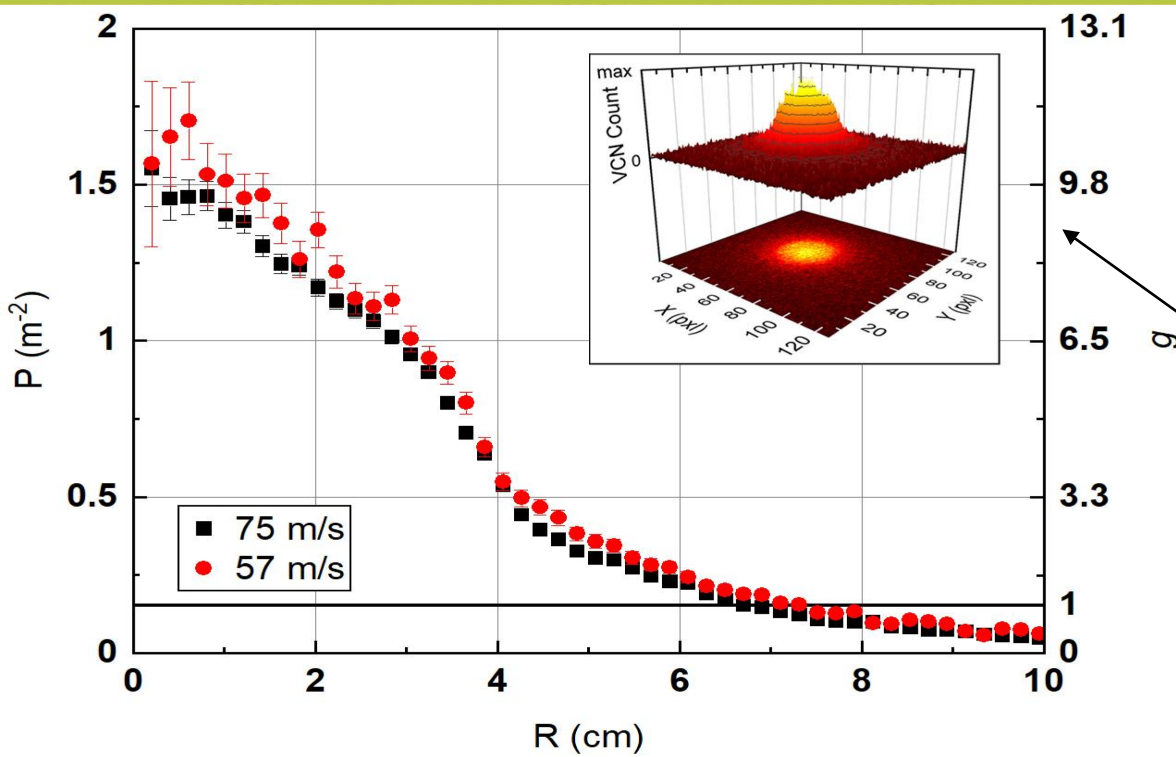
- This is a calculation based on the measurements with small samples of the optimized powder,
- The idea: to profit from the high reflectivity of VCNs with the velocities below ~200 m/s for building a VCN source

# Directional extraction of VCNs




1 - DND cylindrical reflector, 2 - DND disk reflector, 3 – VCN velocity selector, 4 – position-sensitive detector (PSD), 4' – PSD position when measuring neutron fluxes in the incident beam, 4" – PSD position when measuring the angular distribution of outgoing VCNs, 5 – Cd diaphragm, 6 – vacuum volume

# Directional extraction of VCNs

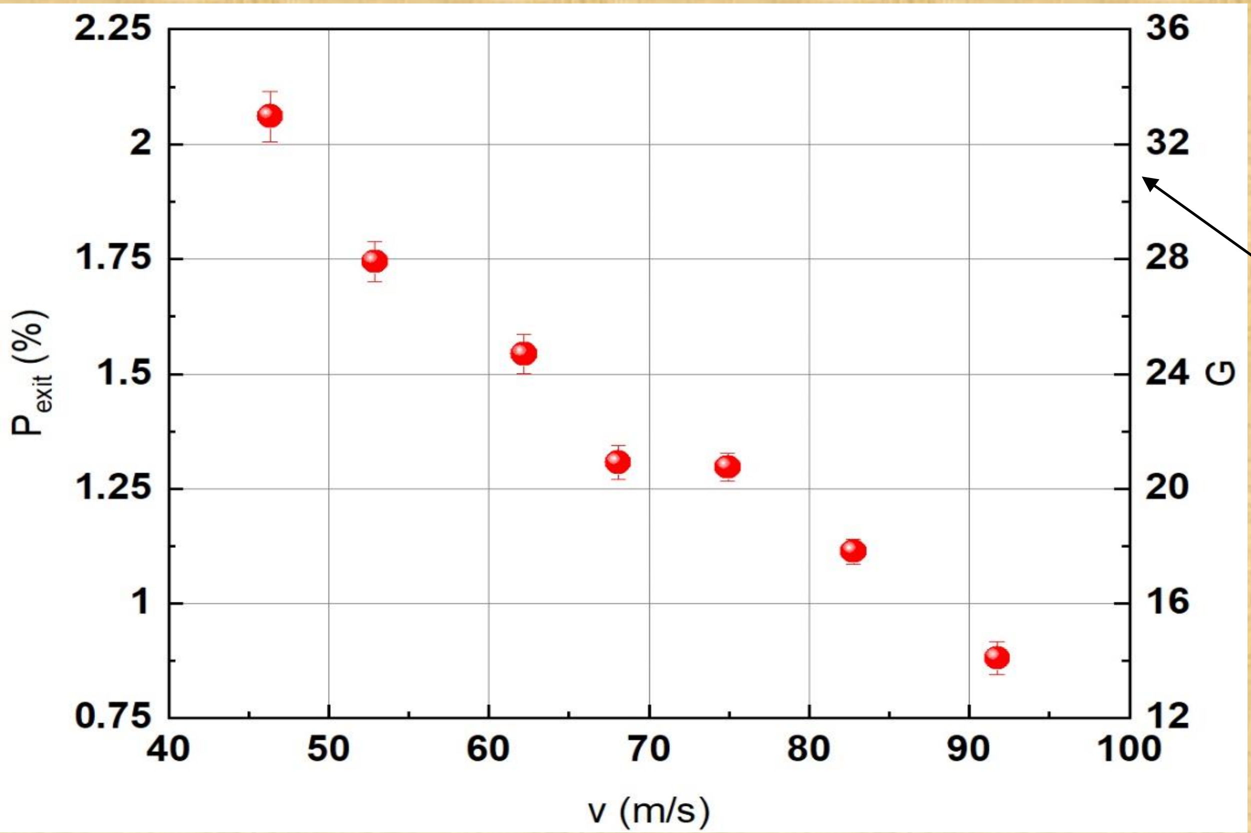



[Rev. Sci. Instr. 93 (2022) 123302]

Gain in the directional extraction

Dependence of VCN flux density recorded by a PSD located at a distance of ~42cm from the cavity exit, on the distance to the axis of the cylindrical cavity (left axis). Round dots correspond to the neutron velocity of ~57 m/s, square dots to ~75 m/s. The right axis is the gain factor g in the flux density with respect to the flux density from a homogeneous isotropic source located at the bottom of the cavity. The inset shows a map of the PSD's count intensity by pixels in measurements for the VCN velocity of ~75 m/s

# Directional extraction of VCNs




[Rev. Sci. Instr. 93 (2022) 123302]

Gain in the total extraction

Left axis: a percentage of the VCN flux exiting through the diaphragm compared to the VCN flux incoming to the cavity, as a function of VCN velocity. Right axis: gain factor G in the outgoing flux relative to the flux that would pass through the diaphragm from a homogeneous isotropic source with the intensity of the incident beam located at the bottom of the cavity

# Directional extraction of VCNs

Results of the analysis of this experiment:

- The first experimental **demonstration** of the enhanced directional extraction of VCNs using a reflector made of nanodiamond powder (F-DND),
- With respect to the flux from an isotropic source located at the bottom of the reflector cavity, the **gain** in the VCN flux density along the beam axis is **~10** for 57 m/s and 75 m/s,
- The **gain** in the total flux at the exit from the reflectivity cavity is **~14** for the fastest VCNs from the velocity range of 46-92 m/s and increases with decreasing VCN velocity reaching **~33** for the slowest VCNs,
- The use of such a reflector in VCN sources will significantly **increase the VCN flux** in experimental setups and will expand the use of VCNs.

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# A VCNs source for ESS


## Workshop on Very Cold and Ultra Cold Neutron Sources for ESS
## 2-4 February 2022

# A VCNs source for ESS

The current design is kindly provided by Luca Zanini

A concrete proposal **[J. Neutr. Res. 24 (2022) 223]** based on F-DND reflectors:

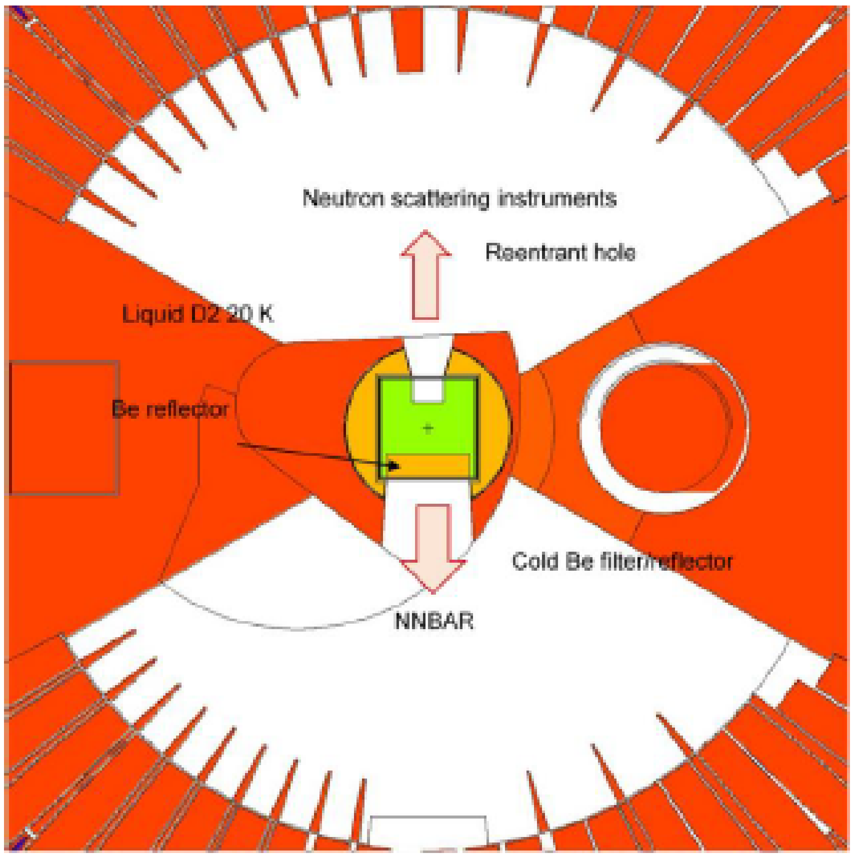
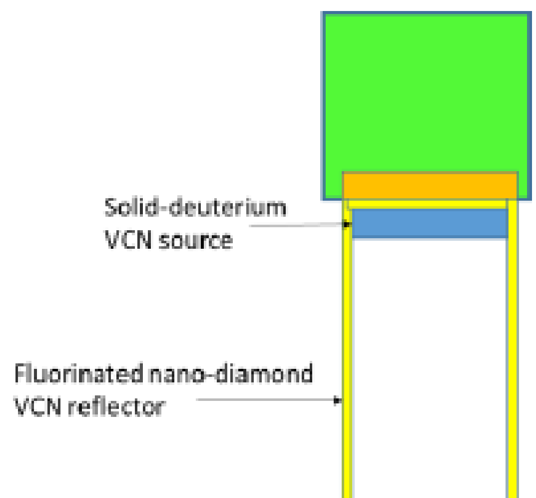



*Figure 1. On the left, a current design of the implementation of a large-volume liquid-deuterium source of CNs (the temperature of 20 K, green color). The arrow on bottom illustrates CNs passing through a Be filter (brown color) and feeding a $n-\bar{n}$ experiment. A dedicated solid-deuterium VCN converter with a F-DND reflector could be added to this design as shown below.*



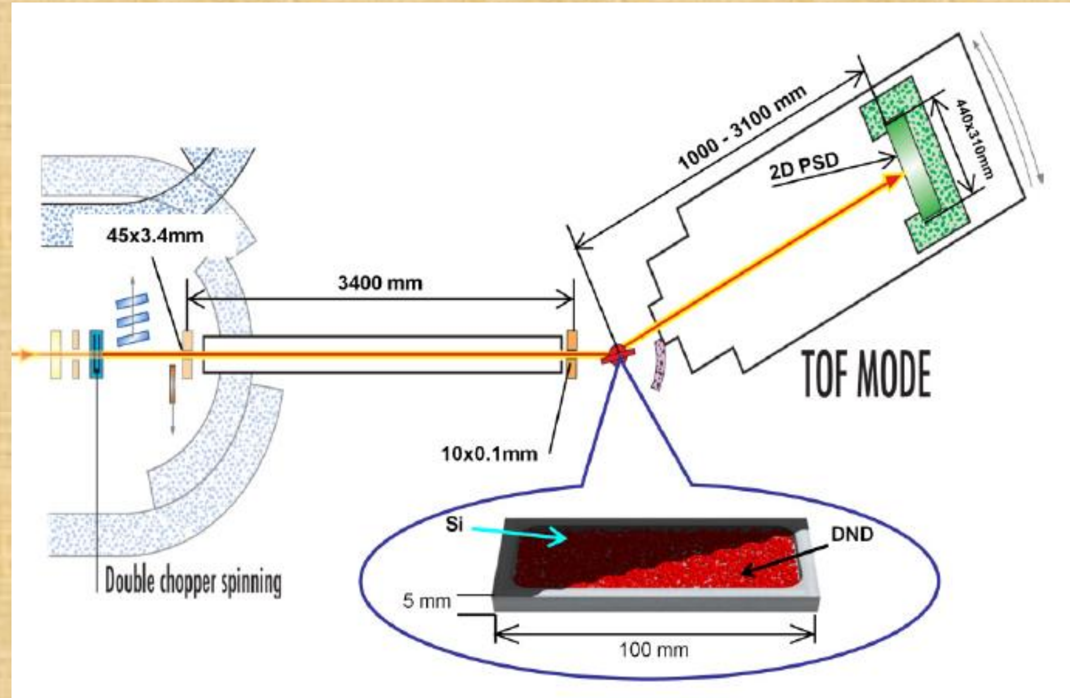
# A VCNs source for ESS

- An **optimum position** (close to the maximum flux of CN),
- An **optimum incident neutron velocity** (for VCN production),
- A very **large cross-section** – thus a very large **total VCN flux**, delivers VCNs to **many beam positions**,
- The thickness (**say, 1-5 cm**) is a compromise between the heat load to solid deuterium and the VCN extraction depth,
- No problems with neutron scattering on the **density inhomogeneity** (an important problem for UCNs but virtually absent for VCNs),
- Profits from the **pulsed structure** of the ESS neutron source,
- Could be also used to **produce UCNs [J. Neutr. Res. 24 (2022) 193]**

[A. Bosak, M. Dubois, E. Korobkina, E. Lychagin, A. Muzychka, G. Nekhaev, V. Nesvizhevsky, A. Nezvanov, T. Saerbeck, R. Schweins, A. Strelkov, K. Turlybekuly, K. Zhernenkov, *Effect of nanodiamond sizes on the efficiency of the quasi-specular reflection of cold neutrons*, **Materials 16 (2023) 703**]

$$\Delta\theta_1 \sim \lambda_{CN}/2\pi d_{ND}$$

Therefore, we expected a narrower angular distribution of the reflected neutrons and a higher reflection probability



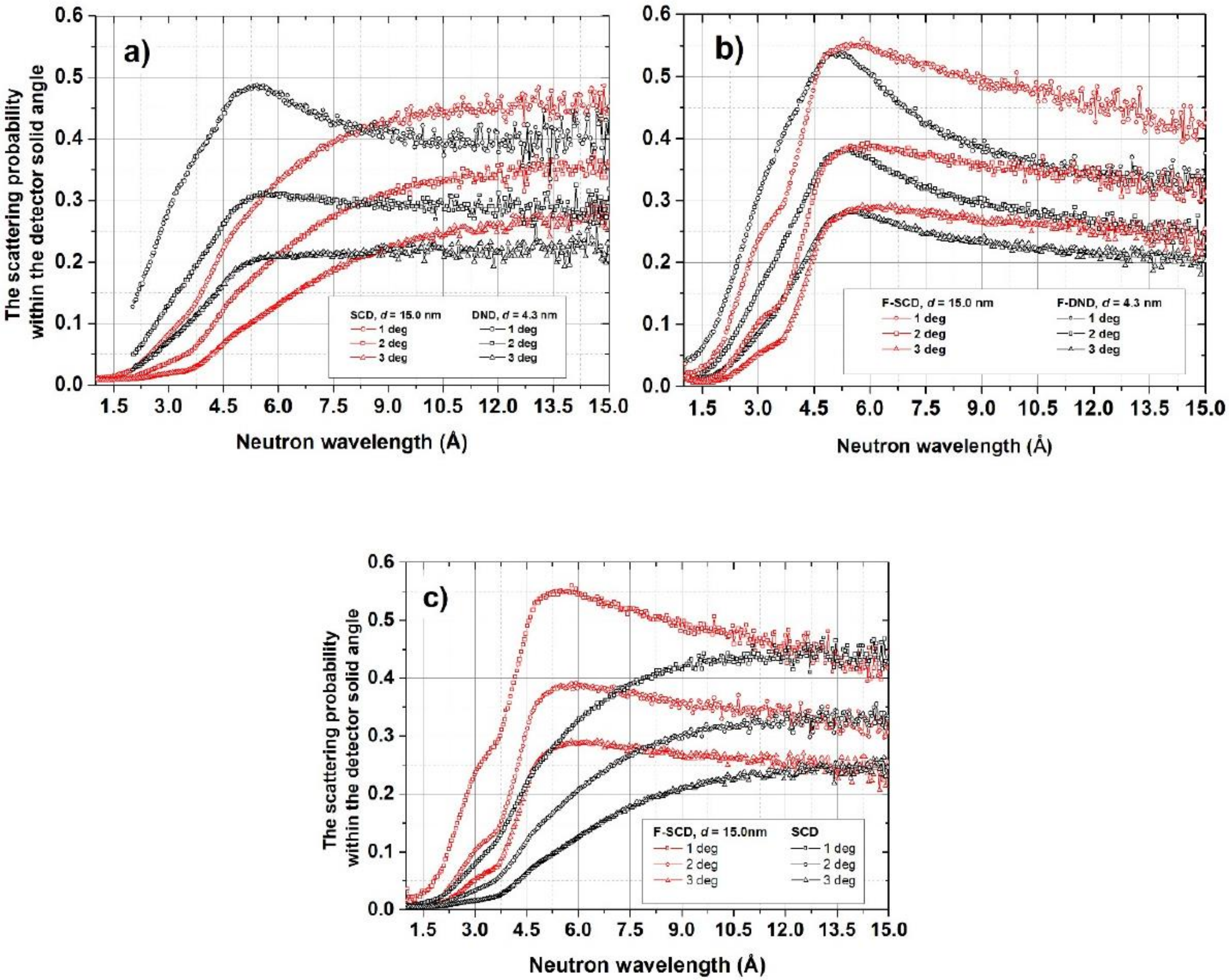



**Figure 8.** Neutron scattering probability as a function of neutron wavelength (horizontal axis) within the D17 detector acceptance. (**a**) DND and SCD samples; (**b**) F-DND and F-SCD samples; (**c**) SCD and F-SCD samples. Incident angles 1°, 2° and 3°.

SCD - nanodiamonds produced with the **shock compression method**;

**F-SC**D - fluorinated SCD

ND mean size is **15 nm**

A much narrower angular distribution for **F-SCD** than that for F-DND. This effect is due to ND sizes.

An optimum size of ND for quasi-specular reflection depends on the reflector geometry and neutron spectrum but is around **10 nm**.

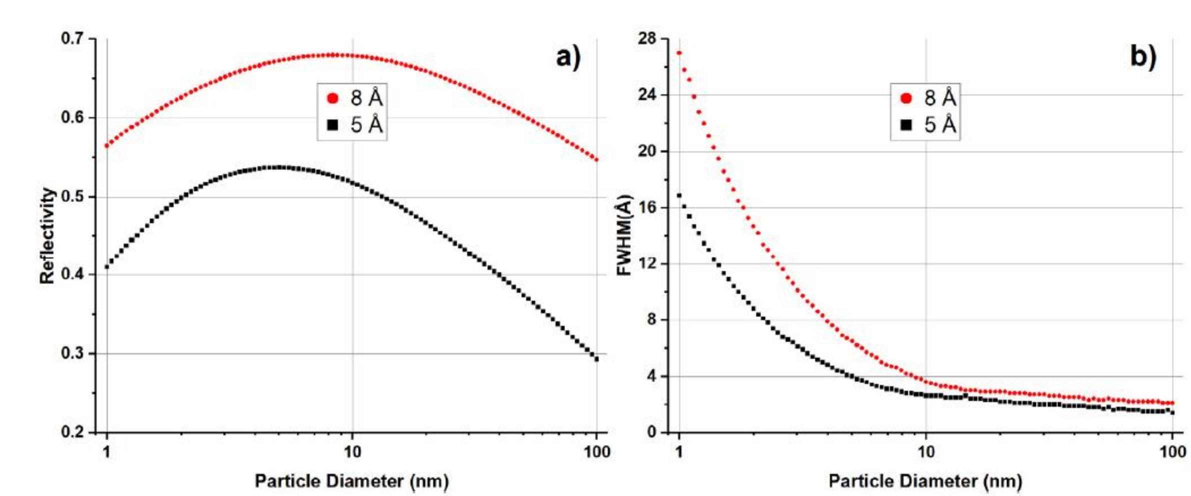



**Figure 11.** (**a**) Simulated reflectivity and (**b**) angular distribution width as a function of ND diameter. Black squares correspond to calculations for neutrons with wavelengths of 5 Å, and red circles correspond to 8 Å. The angle of incidence was set to 1° in the simulations.

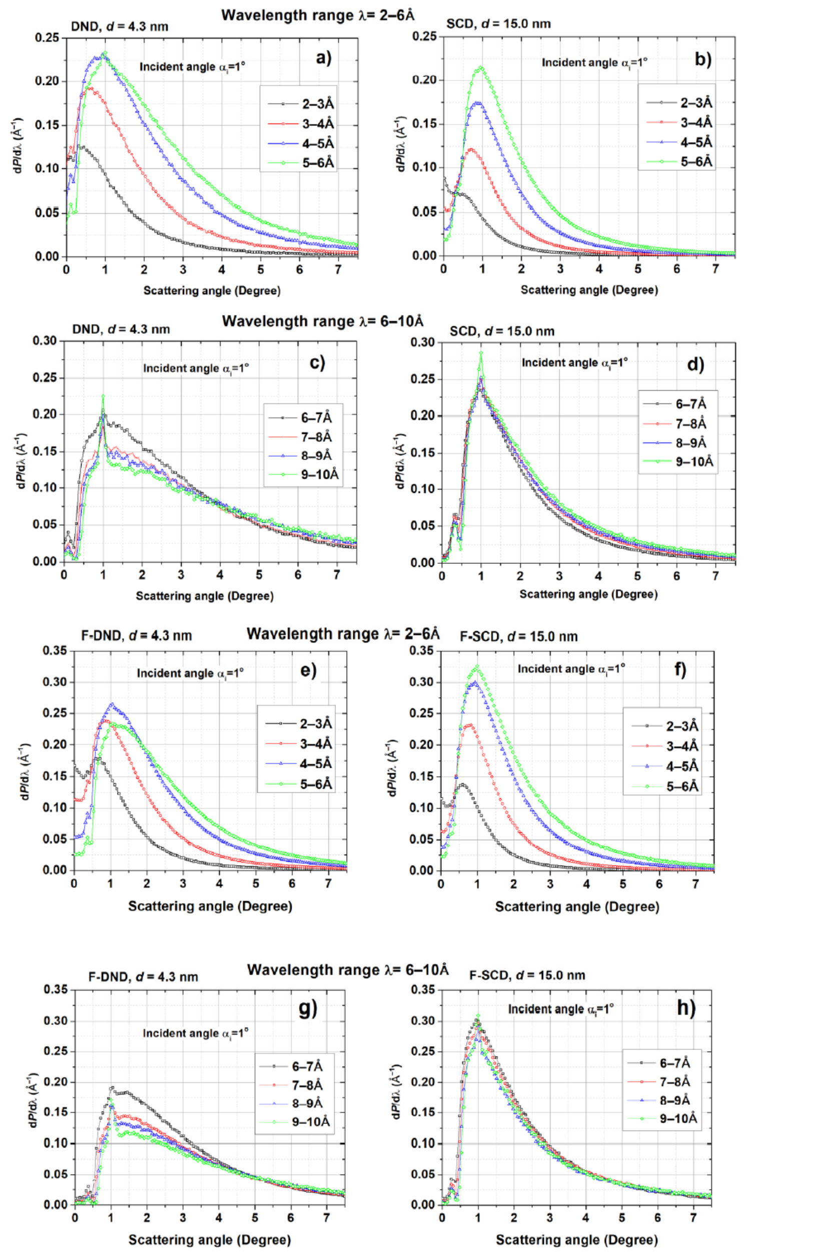



**Figure 9.** Differential probability of neutron scattering (vertical axis) as a function of the reflection angle (horizontal axis) within the angular acceptance of the D17 detector. Samples and wavelength ranges: (**a**) DND, 2–6 Å; (**b**) SCD, 2–6 Å; (**c**) DND, 6–10 Å; (**d**) SCD, 6–10 Å; (**e**) F-DND, 2–6 Å; (**f**) F-SCD, 2–6 Å; (**g**) F-DND, 6–10 Å; (**h**) F-SCD, 6–10 Å. For all cases, the angle of incidence was 1°.

# Outlook

- We are interested to simulate such a **VCN source at ESS**, together with Luca Zanini, Nicola Rizzi and colleagues,
- We are interested to simulate the performance of a **neutron-antineutron oscillations experiment at ESS** using VCNs, together with Luca Zanini, Nicola Rizzi, David Milstead, Valentina Santoro and colleagues,
- We are close to propose an optimum design for the **quasi-specular reflector of cold neutrons at ESS**,
- A few more **publications** are expected