Intense sources of ultra-cold neutrons at long pulse spallation sources

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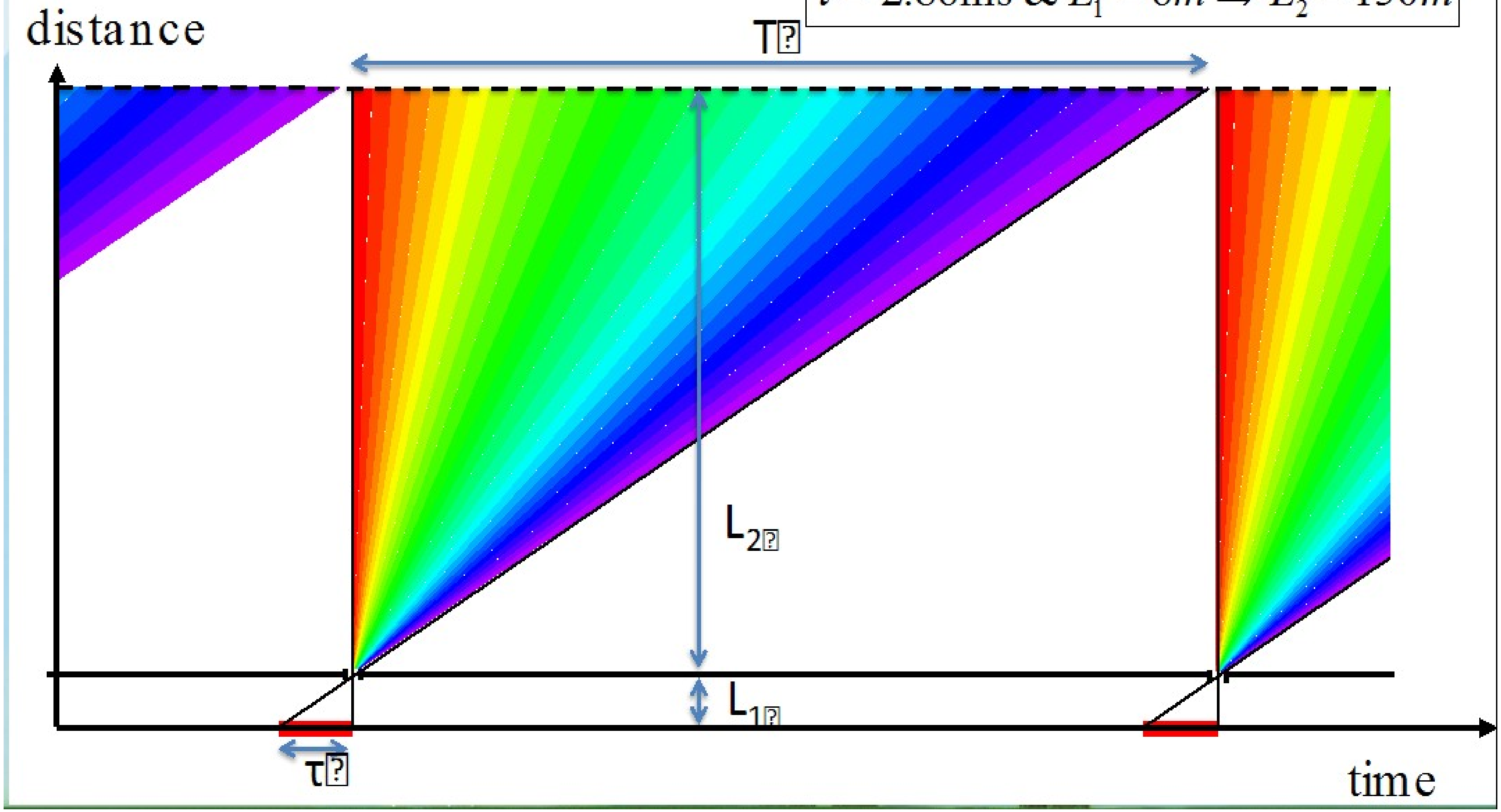
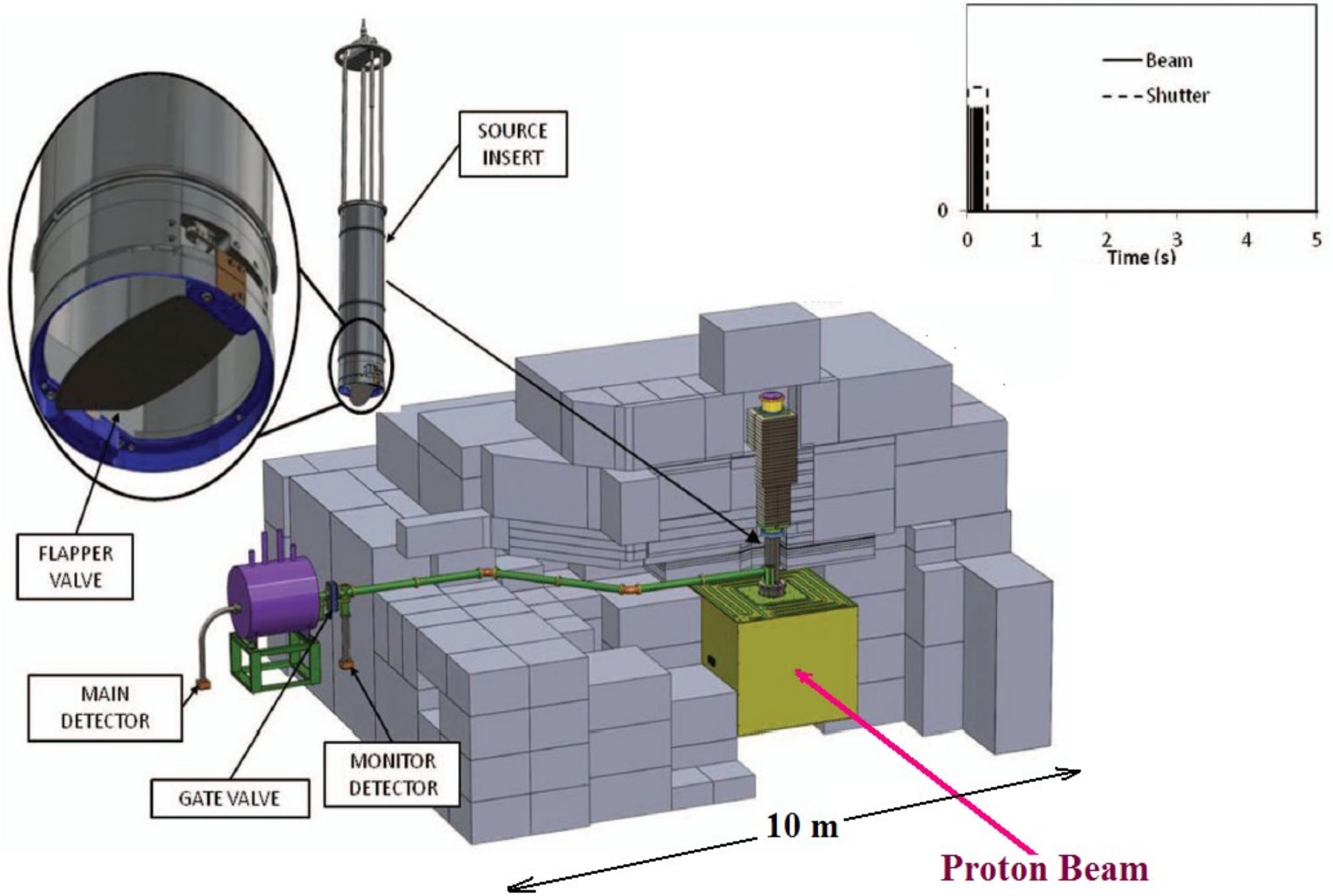
Why 150m?

$$T / \tau = 25 \Rightarrow L_2 / L_1 = 25$$

$$\tau = 2.86\text{ms} \;\&\; L_1 = 6m \Rightarrow L_2 = 150m$$



THE PIONEERING UCN SOURCE AT LANL

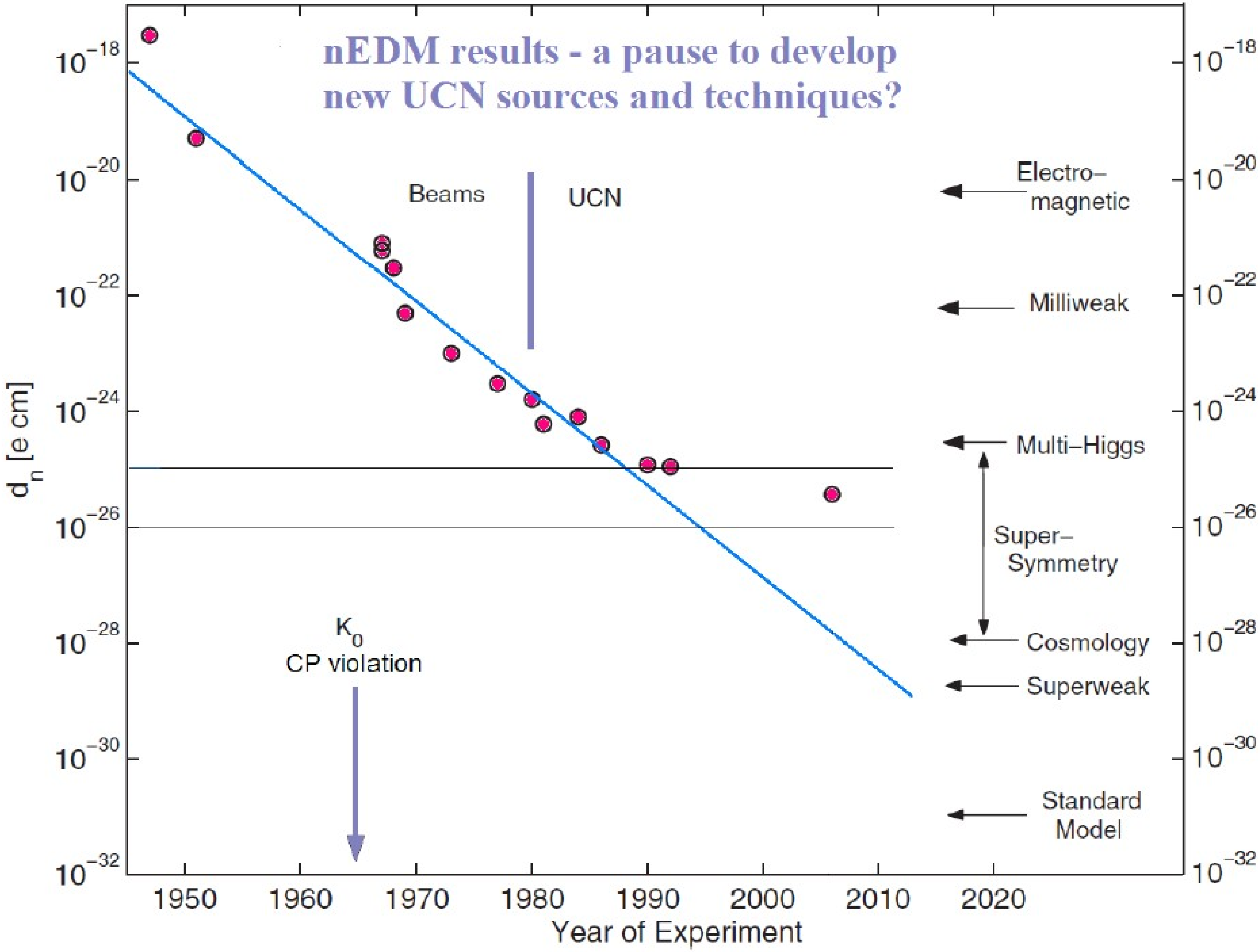


A limit to the achievable nEDM precision has always been foreseen

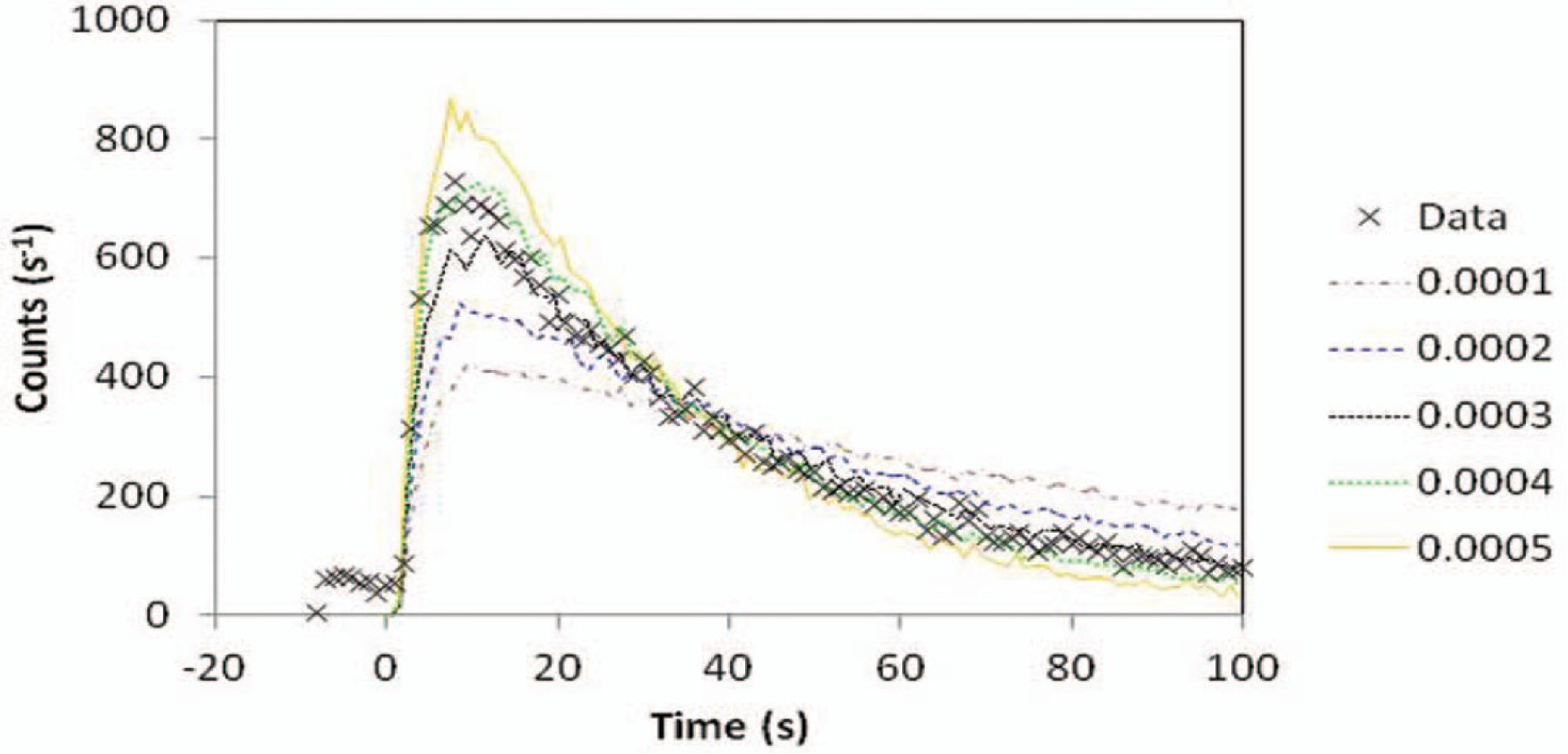
Golub and Pendlebury
Contemorary Physics 13, 519 (1972)
Revew on nEDM - a concluding remark....

" If no effort were to be spared an nEDM error of 2×10^{-27} e cm might ultimately be achieved "

nEDM results - a pause to develop new UCN sources and techniques?



UCN COUNTS AFTER ONE PULSE SET



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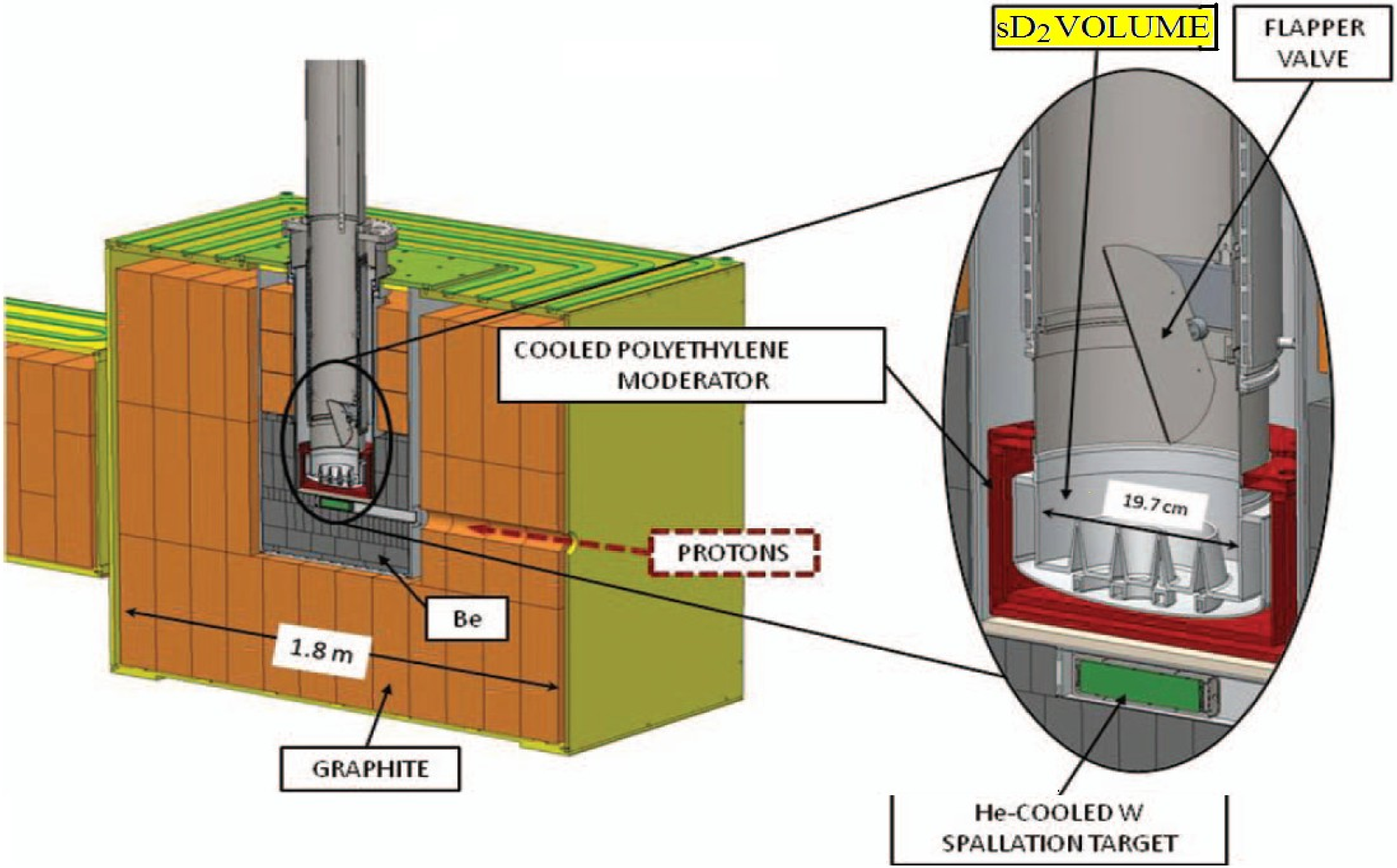
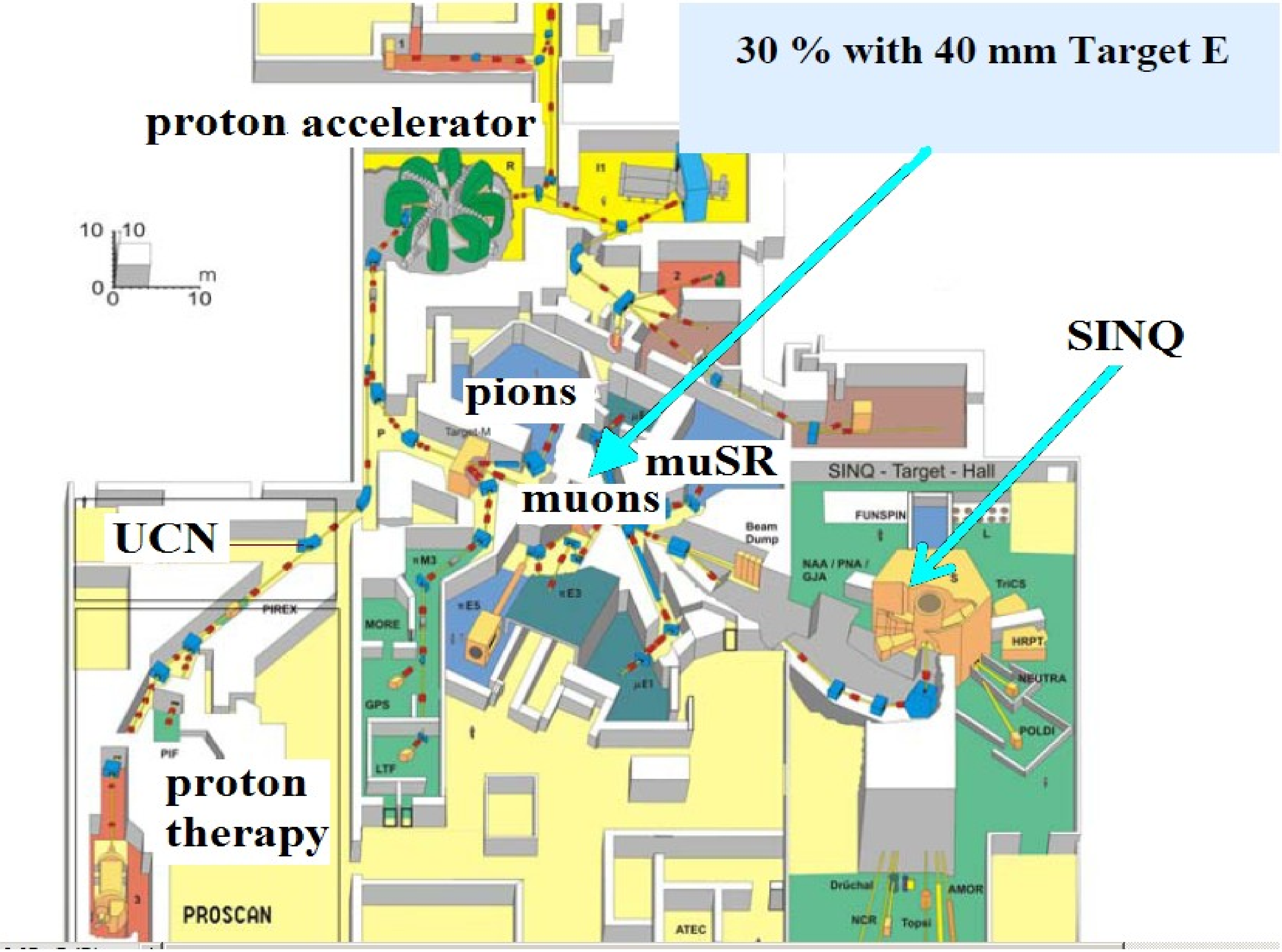
Flapper closed lifetime measurement.

THE UCN SOURCE RELATIVE TO THE SPALLATION TARGET



MULTIPLE USES AND TARGET STATIONS OF THE PSI PROTON BEAM



30 % with 40 mm Target E

proton accelerator

SINQ

pions

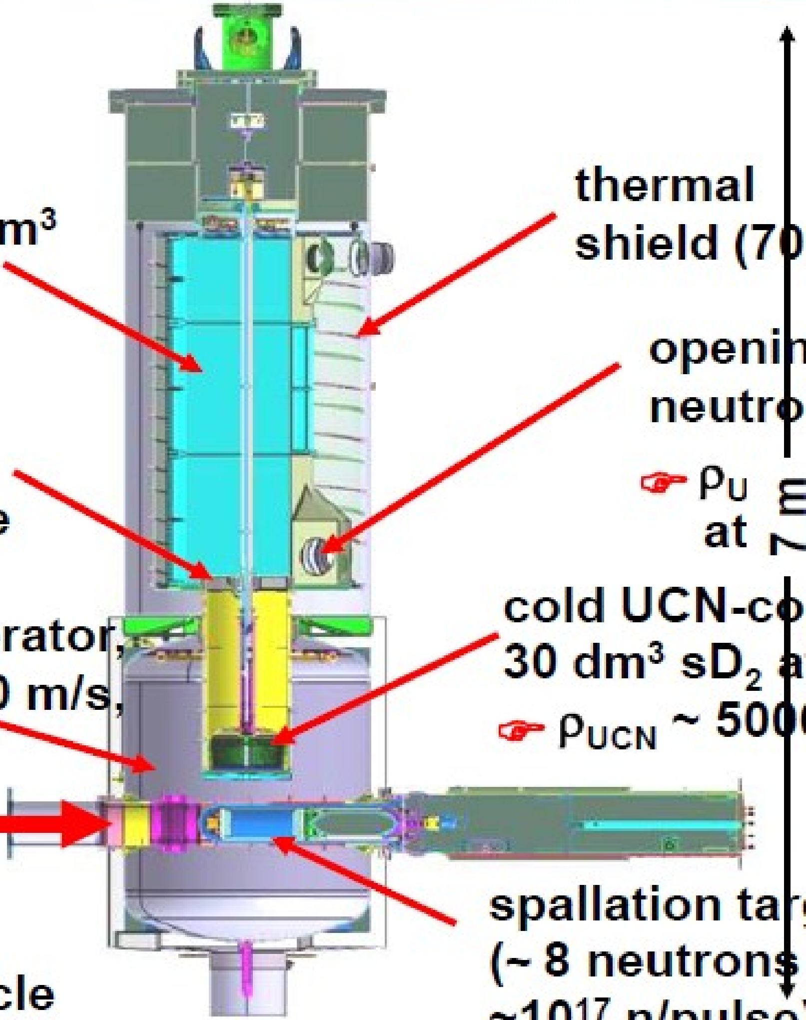
muSR

muons

UCN

proton therapy

UCN-Source



UCN storage volume,
height 2.5 m, volume 2 m^3
☞ ρ_{UCN} ~ 2000 cm^{-3}

thermal
shield (70K)

opening for
neutron guide
☞ ρ_{UCN} ~ 1000 cm^{-3}
at experiments

UCN shutter
verticle guide

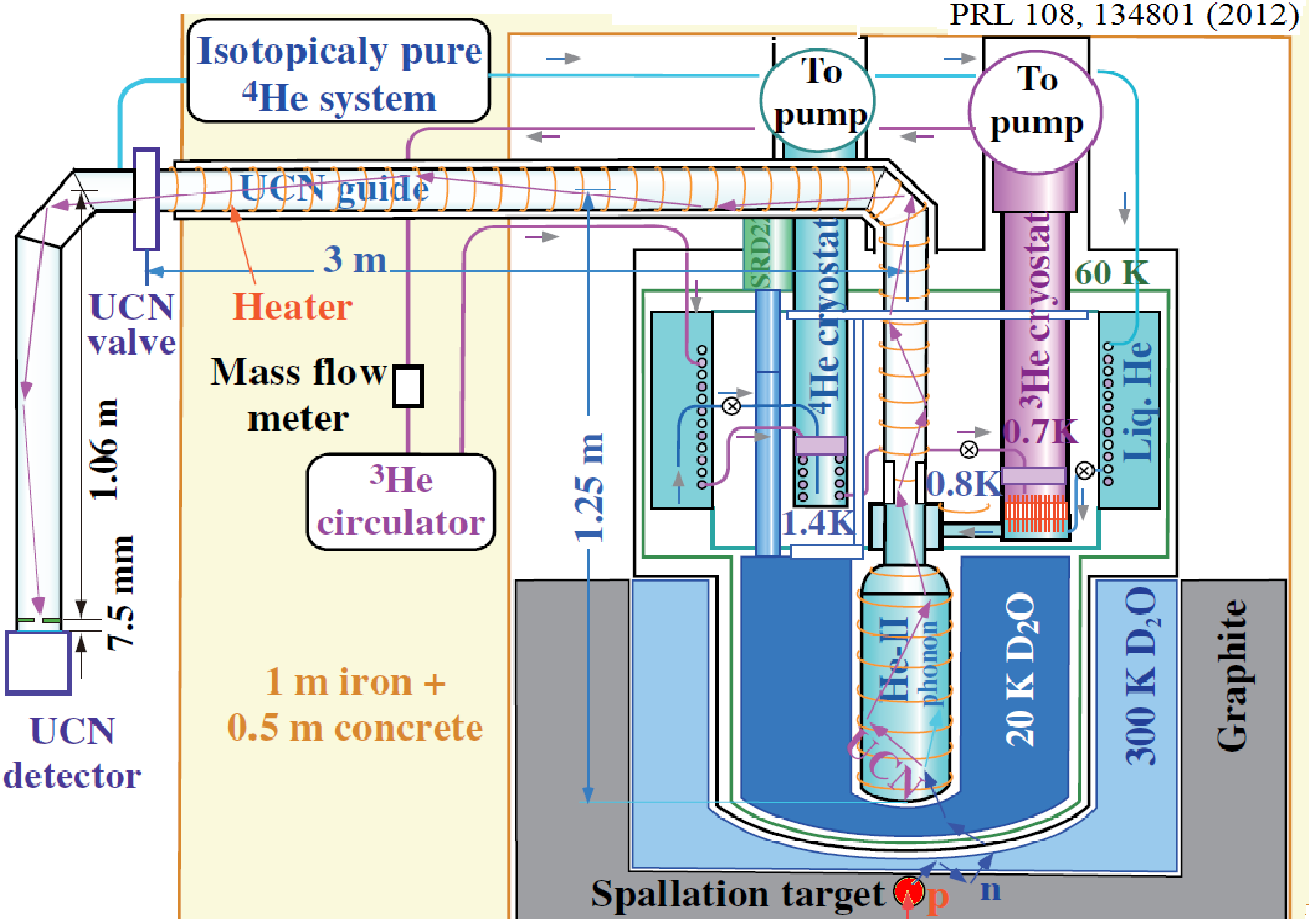
3.5 m^3 heavy water moderator,
thermal neutrons, v=2200 m/s,
neutrons travel ~10 m.

cold UCN-converter
30 dm^3 sD_2 at 5 K
☞ ρ_{UCN} ~ 5000 cm^{-3}

pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% macro duty cycle
(8 s every ~800 s)

spallation target (Pb/Zr)
(~ 8 neutrons per proton,
~10^{17} n/pulse)

THE SPALLATION UCN SOURCE IN OSAKA USING PURE SUPERFLUID HELIUM AT 0.7 K



PRL 108, 134801 (2012)

STORING UCN LIQUID HELIUM II

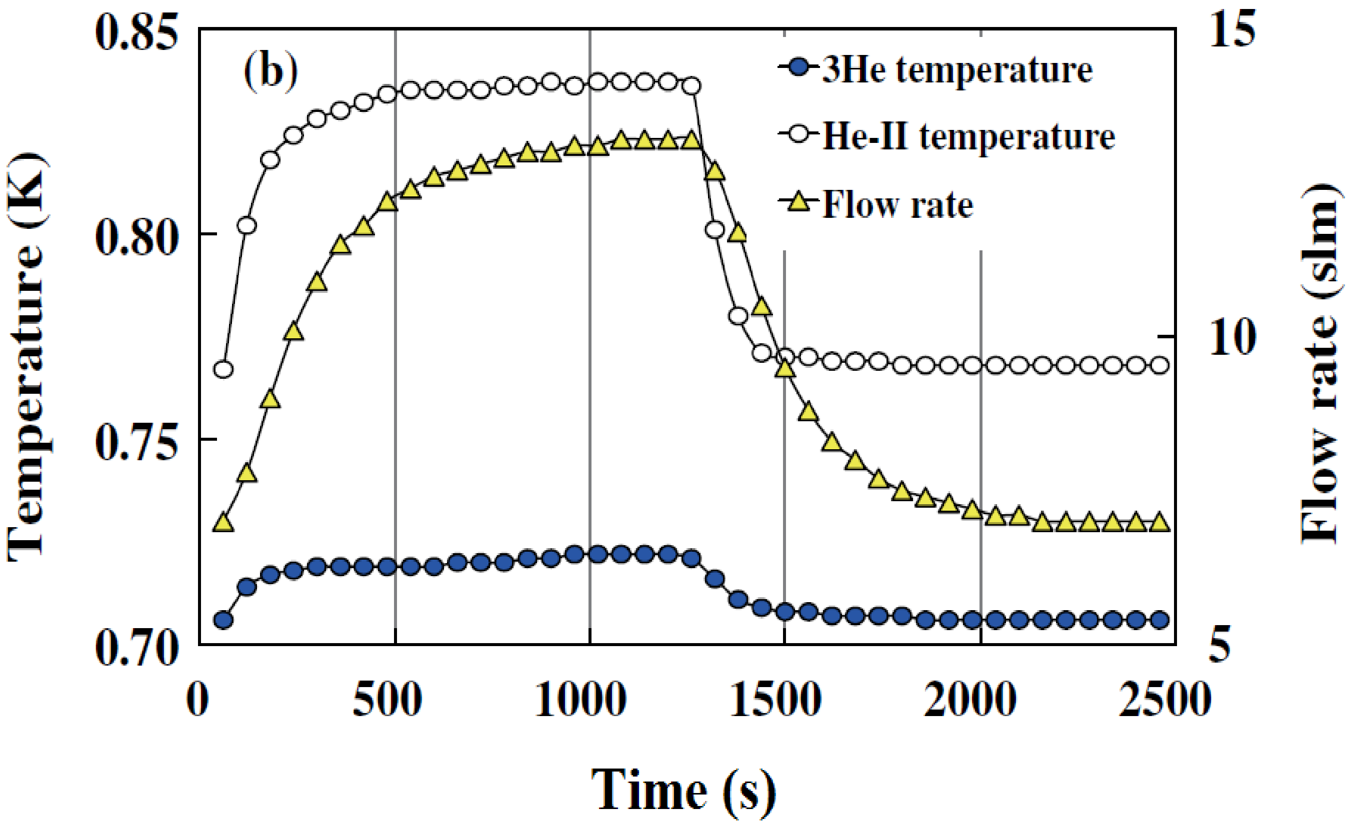
The next problem of storing UCN in liquid helium is caused by the phonon up-scattering processes, which limit the lifetimes and cause rather low temperatures to be required. The **partial lifetimes** due to phonon scattering at various helium temperatures are:

0.5 K	0.6 K	0.7 K	0.8 K	0.9 K	1.0 K	1.1k
11900 s	3817 s	1365 s	474 s	117 s	72 s	32 s

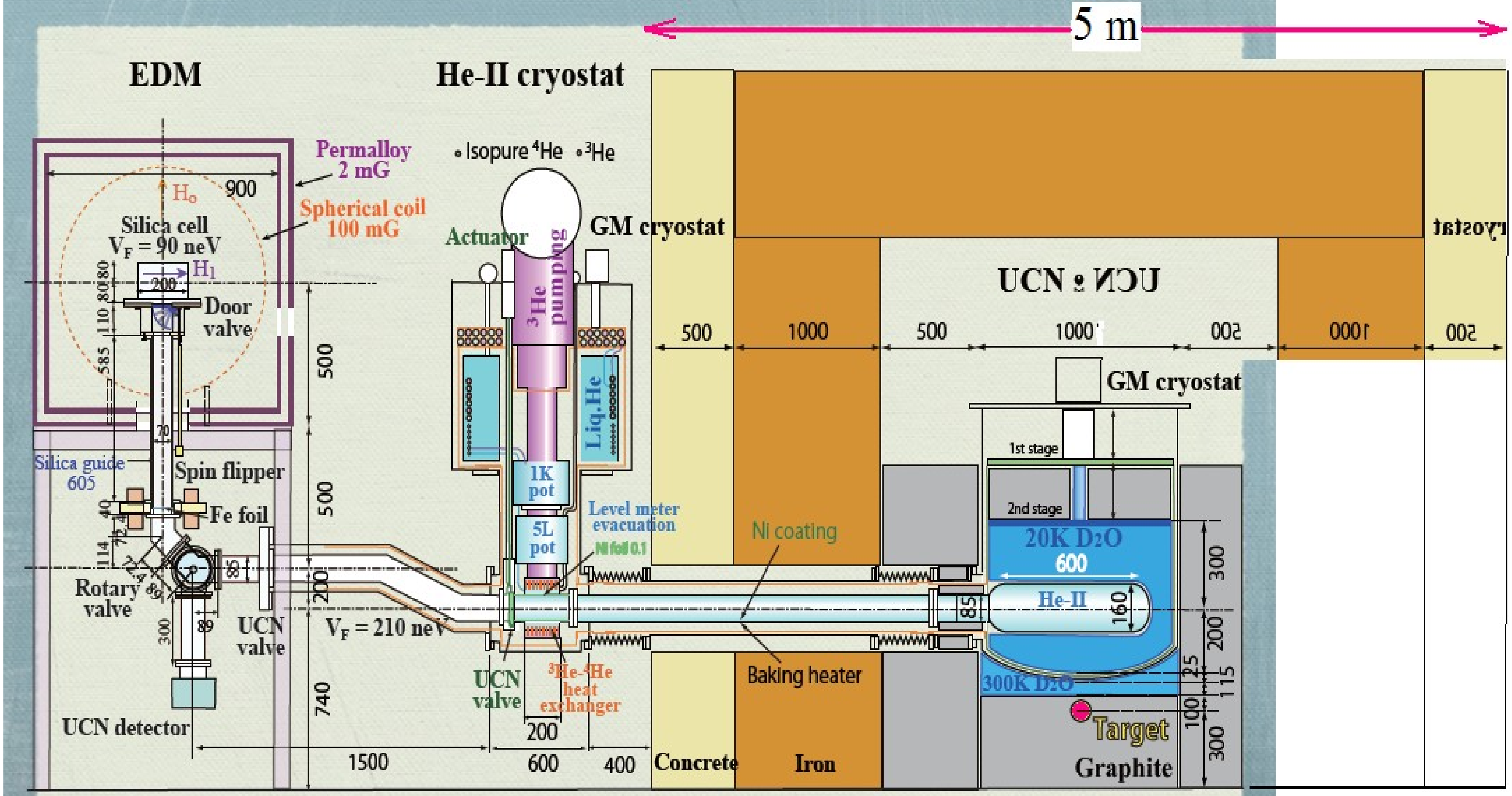
Thus one is aiming to keep the helium in the lower end of this temperature range

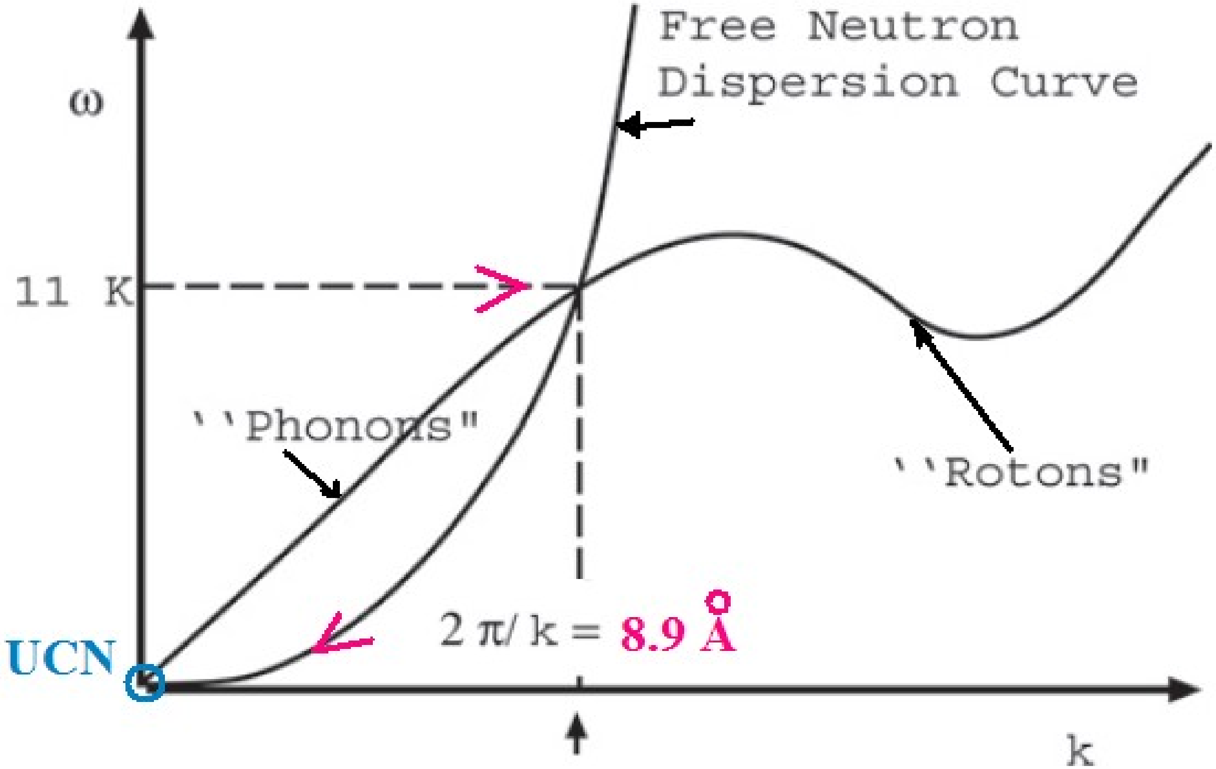
This brings a problem for production of UCN in a helium filled spallation source where the tolerance for removing the spallation heat is rather low. The OSAKA source has produced the highest countable UCN density yet at about 130 UCN per cm3 but this first version is restricted to an increase of a further factor of 2 due to the raised He temp.

Fig. 4(b). The He-II temperature gradually increased from 0.77 to 0.83 K during the proton-beam bombardment with a current of 1 μA at 400 MeV for a duration of 600 s.



We are constructing the 2nd UCN source and EDM apparatus

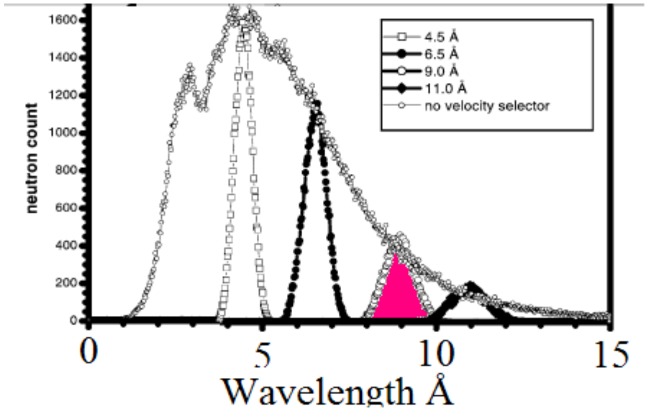




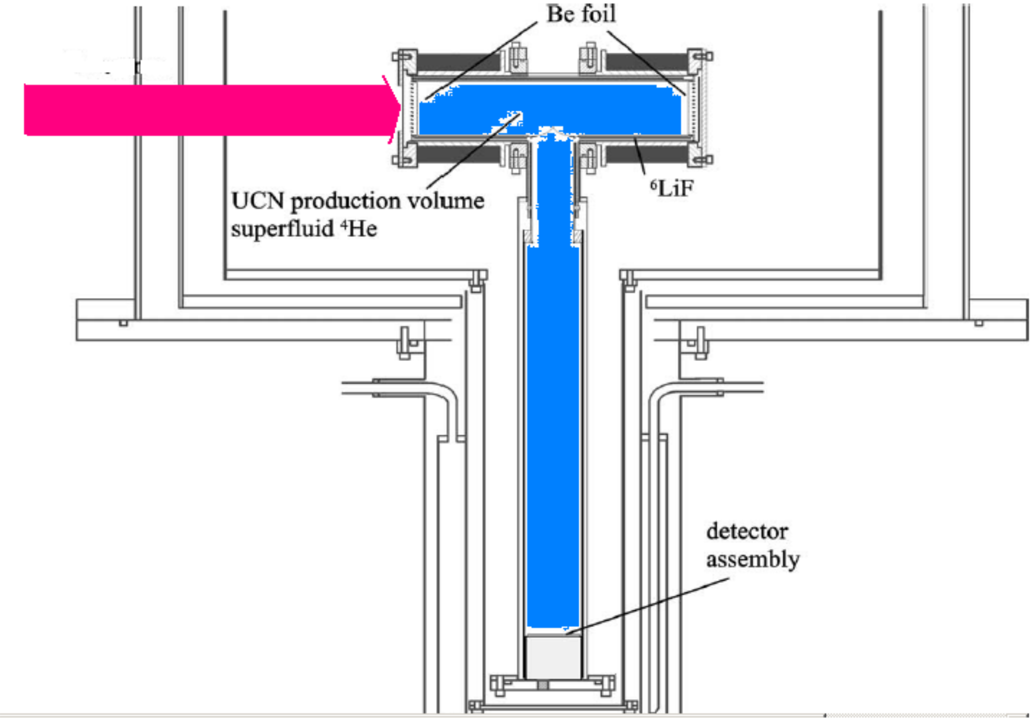
Free neutron and superfluid ^{4}He elementary dispersion curves.

Restricting the neutron input to 8.9 Å to reduce heating and background

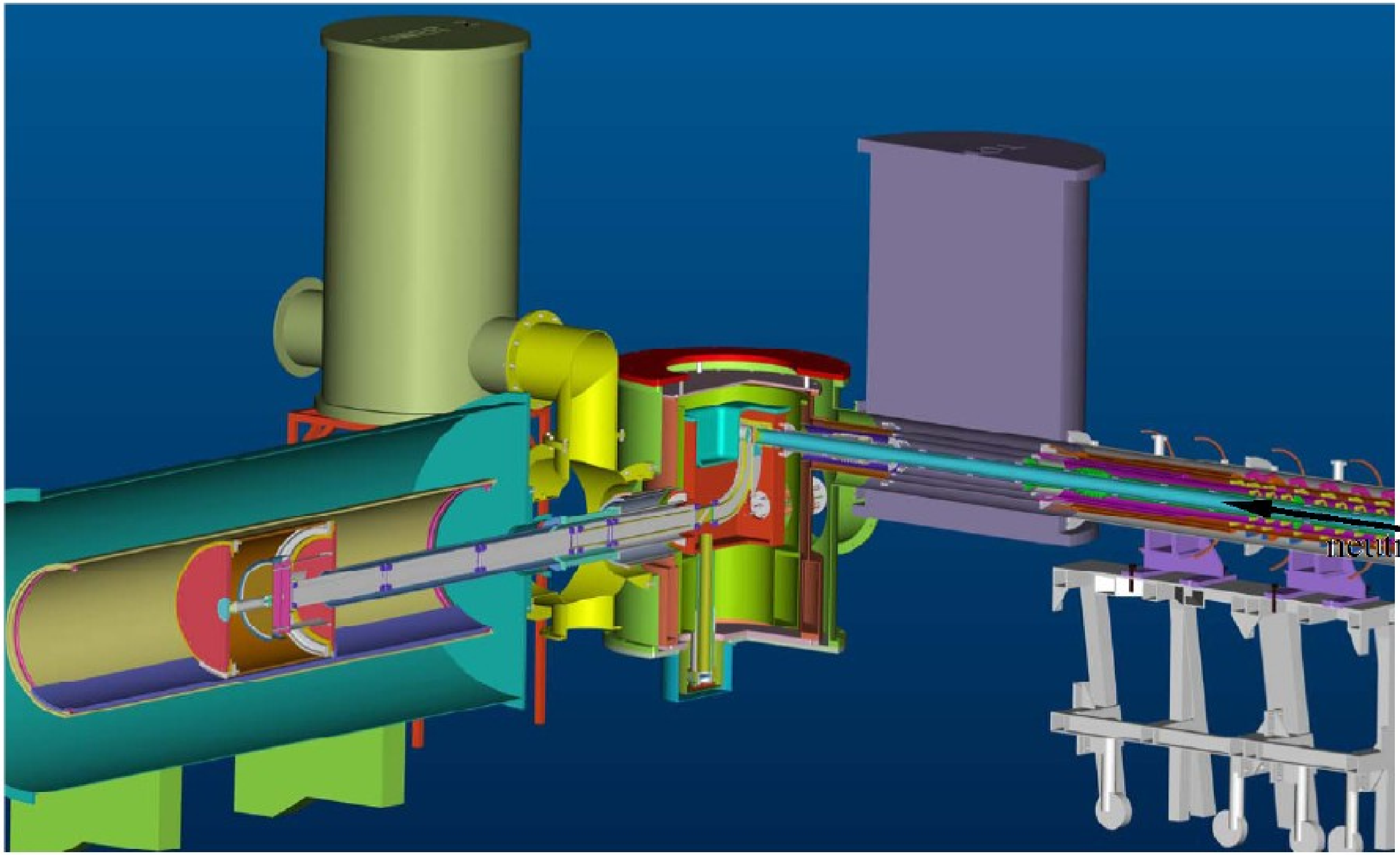
Golub and Pendlebury
Physics Letters A 1974



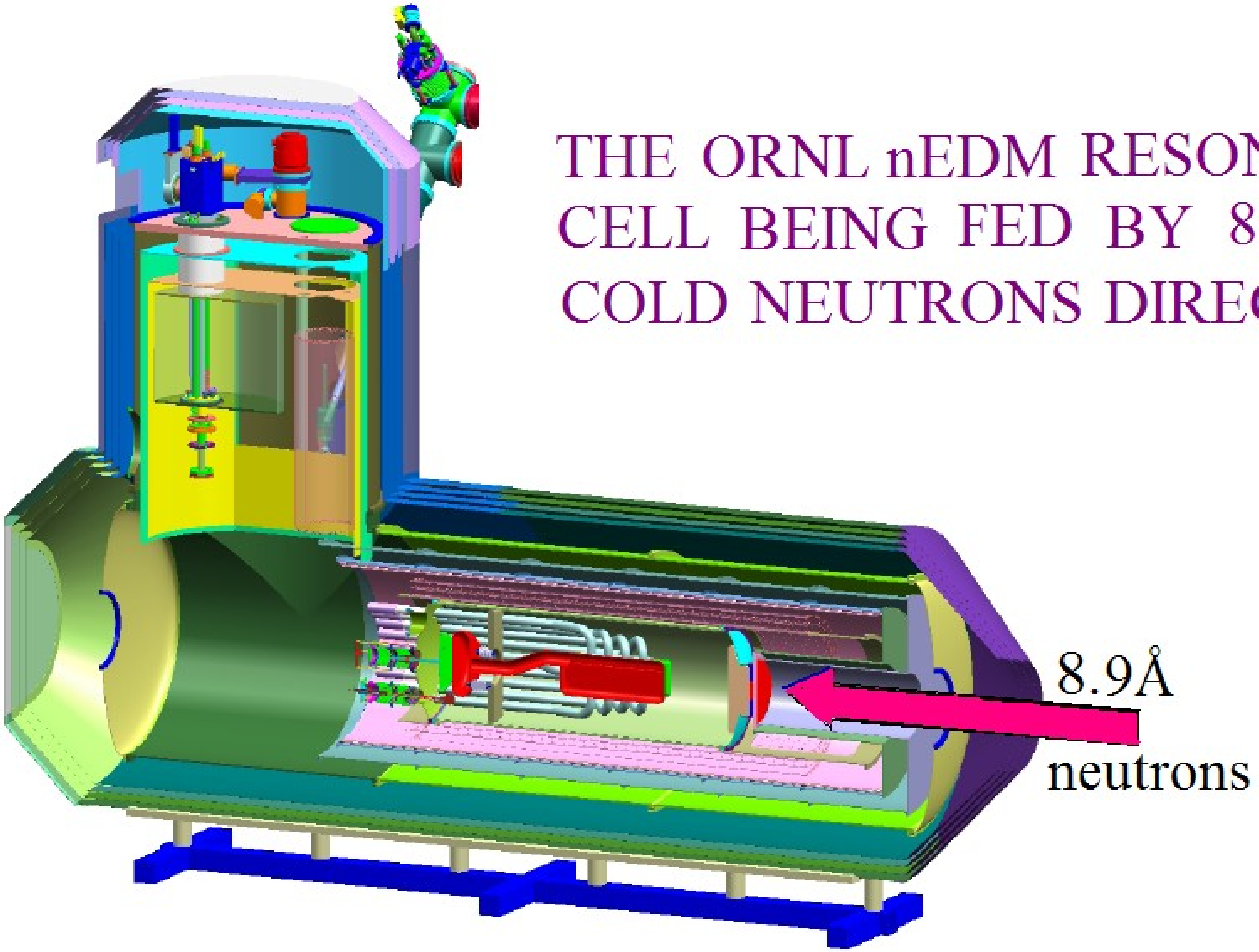
Selected spectrum entering the cryostat



CryoEDM



THE ORNL nEDM RESONANCE CELL BEING FED BY 8.9Å COLD NEUTRONS DIRECTLY



CAUSES OF UCN LOSSES WHEN STORING UCN IN He II AT 0.6 K

1. Strongly UCN energy dependent losses

(i) n-gamma reactions of UCN with hydrogen in the surface
(cross section 332 mb) **260 s**

(ii) Doppler shifted scattering of UCN from Be nanoparticles
in Brownian motion **3000 s**

2. UCN energy independent losses

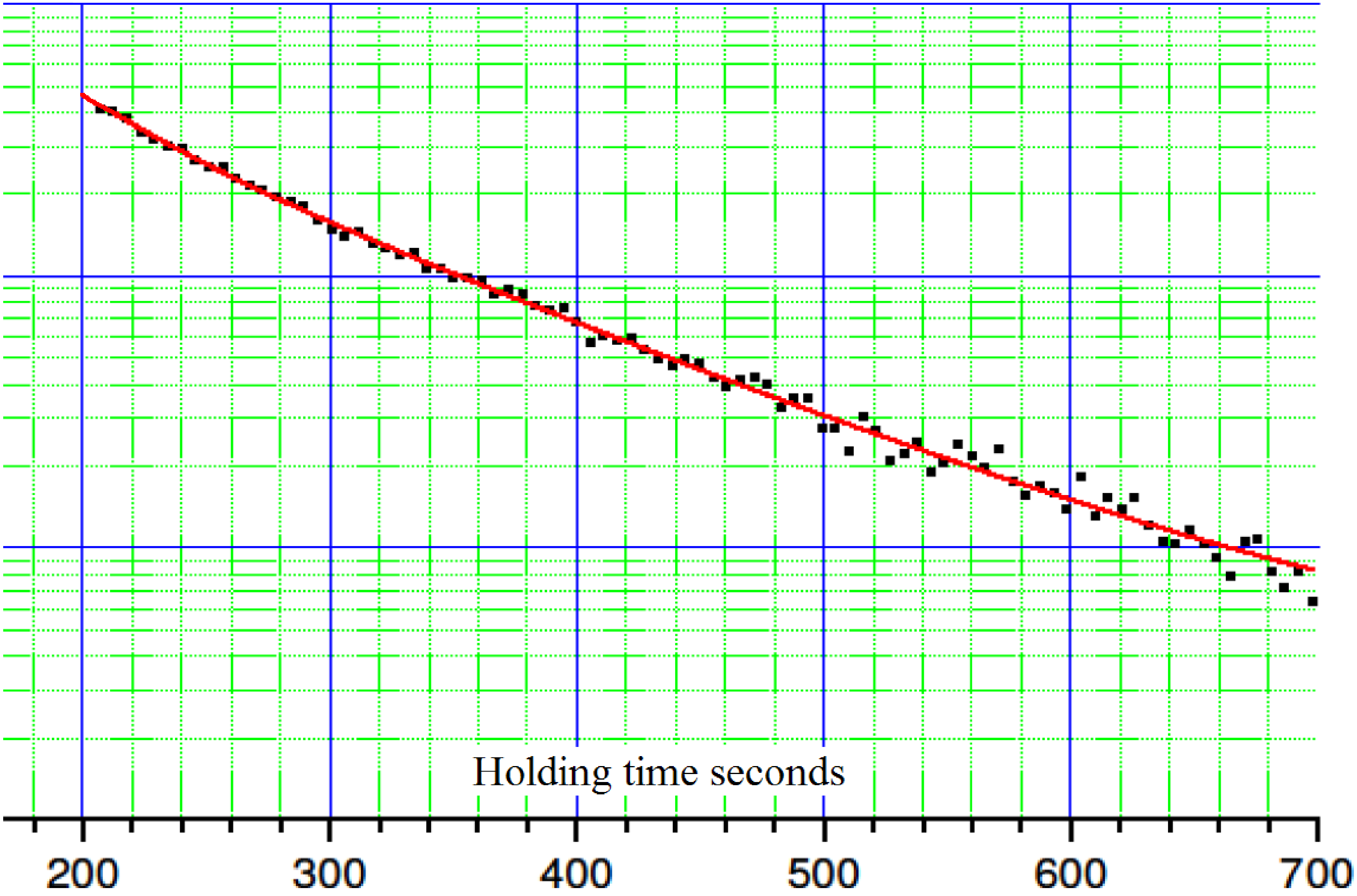
(i) Phonon up-scattering of UCN **3817s**

(ii) Leakage of UCN at joints in the vessel walls **3230 s**

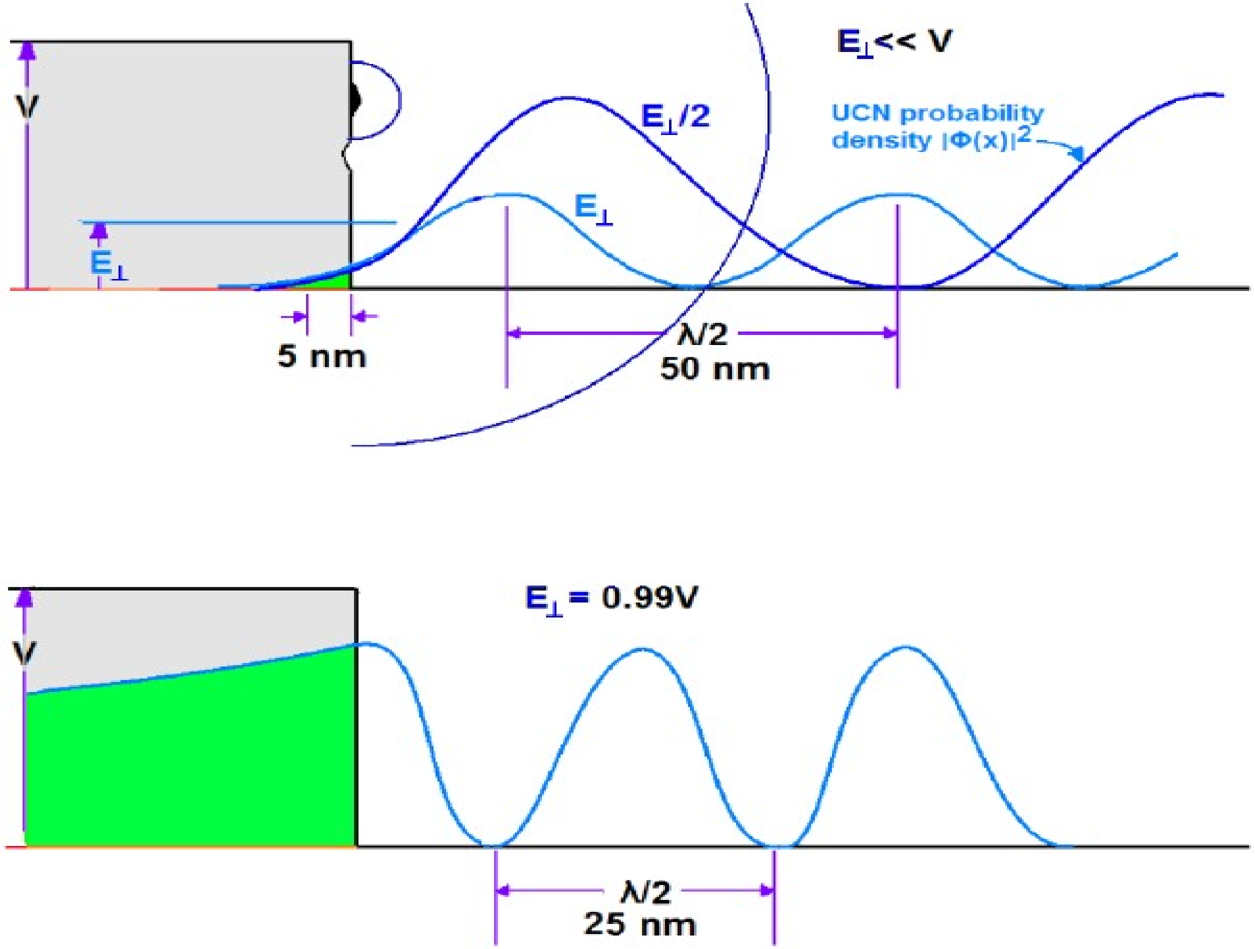
(iii) Any reactions of the UCN with 3He **1000000 s ?**

(iv) Beta decay of the UCN **882 s**

CRYOEDM - UCN COUNTS VERSUS HOLDING TIME IN SECONDS IN A LONG TUBE OF He II 6.5 CM DIAMETER



The reason why *f* reduces with UCN energy



The wave functions are known in the two regions, being

$|\Phi(x)|^2 = A^2 \sin^2[(x\sqrt{2mE_\perp} / \hbar + \phi] \quad x > 0$ i.e, in the vacuum space and

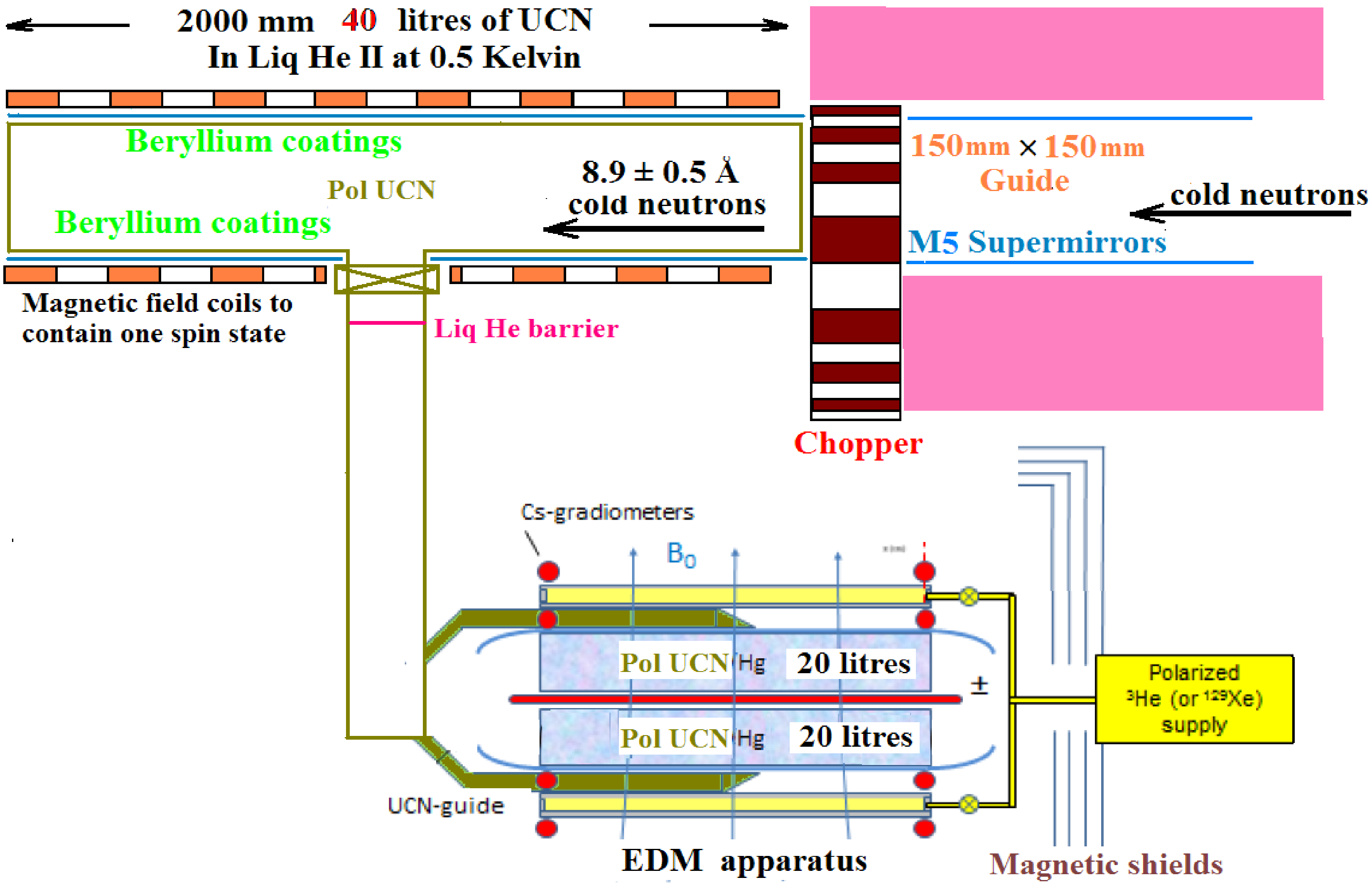
$|\Phi(x)|^2 = B^2 \exp^2[(x\sqrt{2m\{V - E_\perp\}} / \hbar] \qquad x \leq 0$ in the wall

By equating the amplitudes and their gradients at the surface x = 0 one can find ϕ and A/B. It is then possible to show that

$$|\Phi(x = 0)|^2 / |\Phi_{peak}|^2 = E_\perp / V$$

Therefore the probability that a reflection is diffuse is $\propto E_\perp / V$

AN INTENSE SOURCE OF UCN USING M5 SUPERMIRRORS



2000 mm 40 litres of UCN
In Liq He II at 0.5 Kelvin

Beryllium coatings

Pol UCN

Beryllium coatings

8.9 ± 0.5 Å
cold neutrons

Magnetic field coils to
contain one spin state

Liq He barrier

150mm × 150mm
Guide

cold neutrons

M5 Supermirrors

Chopper

Cs-gradiometers

B_0

Pol UCN Hg 20 litres

±

Pol UCN Hg 20 litres

Polarized
^{3}He (or ^{129}Xe)
supply

UCN-guide

EDM apparatus

Magnetic shields

WHAT DENSITIES OF UCN CAN BE EXPECTED USING M5 SUPERMIRRORS?

I will assume that the cold neutron brightness at 10 Å of the ILL reactor and LPSS will be similar

2001 estimates of intensity for the H112 guide with M2 supermirrors near the outer wall of the reactor dome were 3.2×10^{8} n/cm²/s/Å

Now taking M5 supermirrors and taking an additional factor of 6.2 increase of intensity for that we arrive at a flux of 2.0×10^{9} n/ cm² s/ Å

Given that the measured production rate is $(4.55\pm0.25)\times10^{-8}$ $d\varphi/d\lambda$ the predicted UCN down-scattering rate is 91 UCN/cm³/s

If the UCN can build up over 400 secs and if there is a volume sharing loss of 56% then a

final densities of 1.4×10^{4}/cm³ and 1.4×10^{7}/litre are obtained

HOW MUCH HEATING OF THE HELIUM VESSEL MIGHT BE EXPECTED FROM NEUTRON CAPTURE REACTIONS?

The incident neutron current is 2×10^{9} n/cm /s/Å ×1Å ×200 cm^{2}

$= 4\times10^{11}$ n/s

Assigning 10^{7}eV of energy release per neutron capture locally leeds to an input power of $4\times10^{18}\times1.60\times10^{-19}$ = 0.64 watts

If half the gamma ray energy escapes from the helium vessel the CryoEDM fridge would just handle this amount of heating

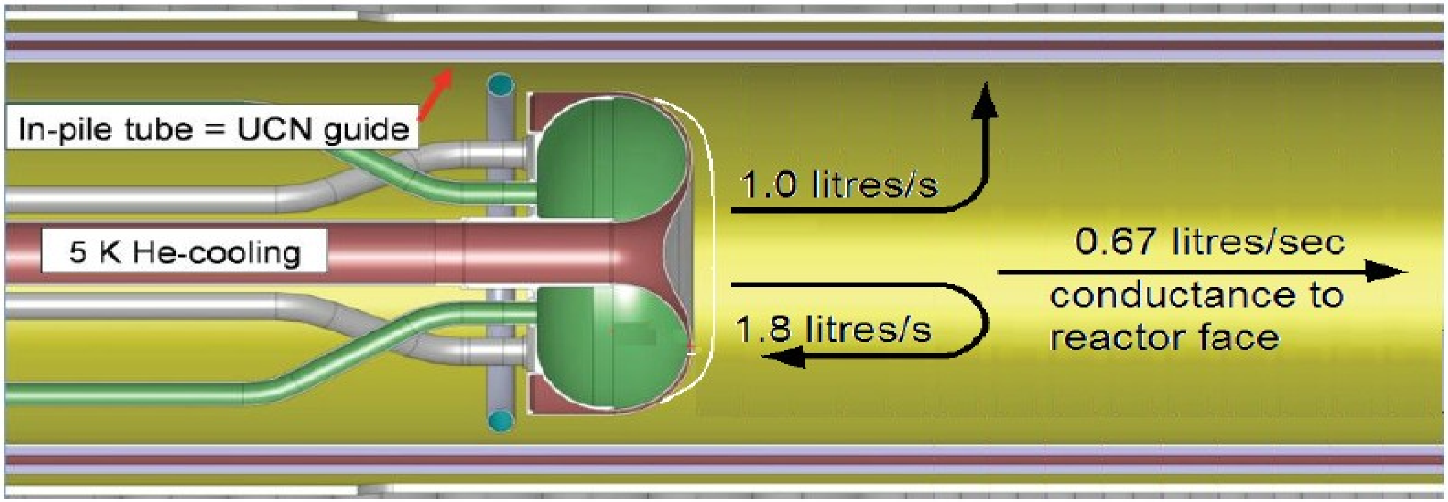
DIRECT CONVERSION OF THERMAL NEUTRONS TO UCN IN A THROUGH TUBE BELOW THE SPALLATION TARGET

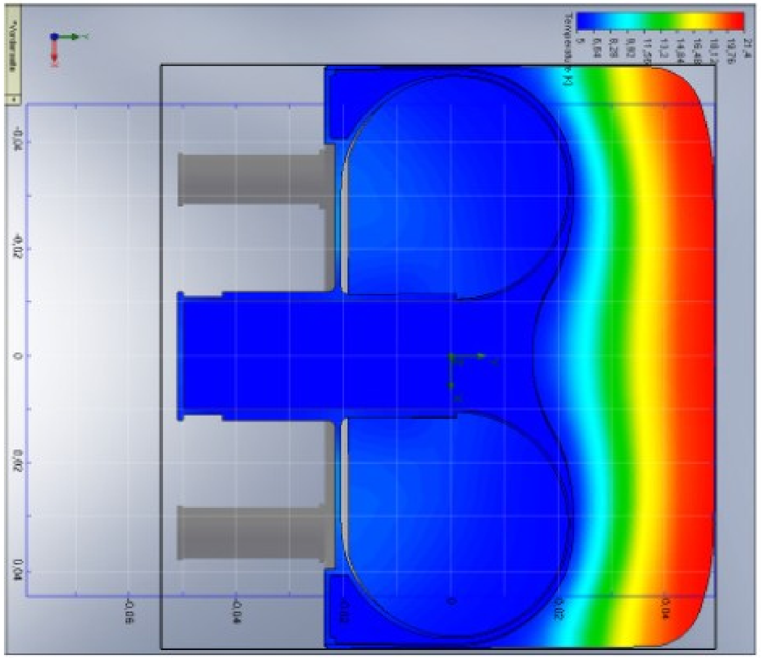
A design of this type has been produced for the FRM-II reactor in Garching, Muenchen, but has not yet been operated

The converter for the FRM-II design combines a 50 gm solid hydrogen precooler and a 25 gm solid deutrium converter - diagrams to follow.

This design allows considerable flexibility for the positioning of the UCN experiments since (a) the angle of the through tube in the horizintal plane may be chosen and (b) the UCN may travel though 20 m of guides in variable directions in the horizontal plane to the UCN experiments.

	UCN source FRMII Exit of beam port	**Experiment hall** PENeLOPE
Flux density [UCN · cm^{-2} · s^{-1}]	$7.0 \cdot 10^4$	$6.2 \cdot 10^4$
Flux [UCN · s^{-1}]	$8.0 \cdot 10^6$ /s	$7.0 \cdot 10^6$
Max. UCN density [UCN · cm^{-3}]	$1.2 \cdot 10^4$ /cm^3 (V = 100 dm^3)	$3.0 \cdot 10^3$ (V = 700 dm^3)





Extreme case with 3 cm thick D_2 and 100% increased heating

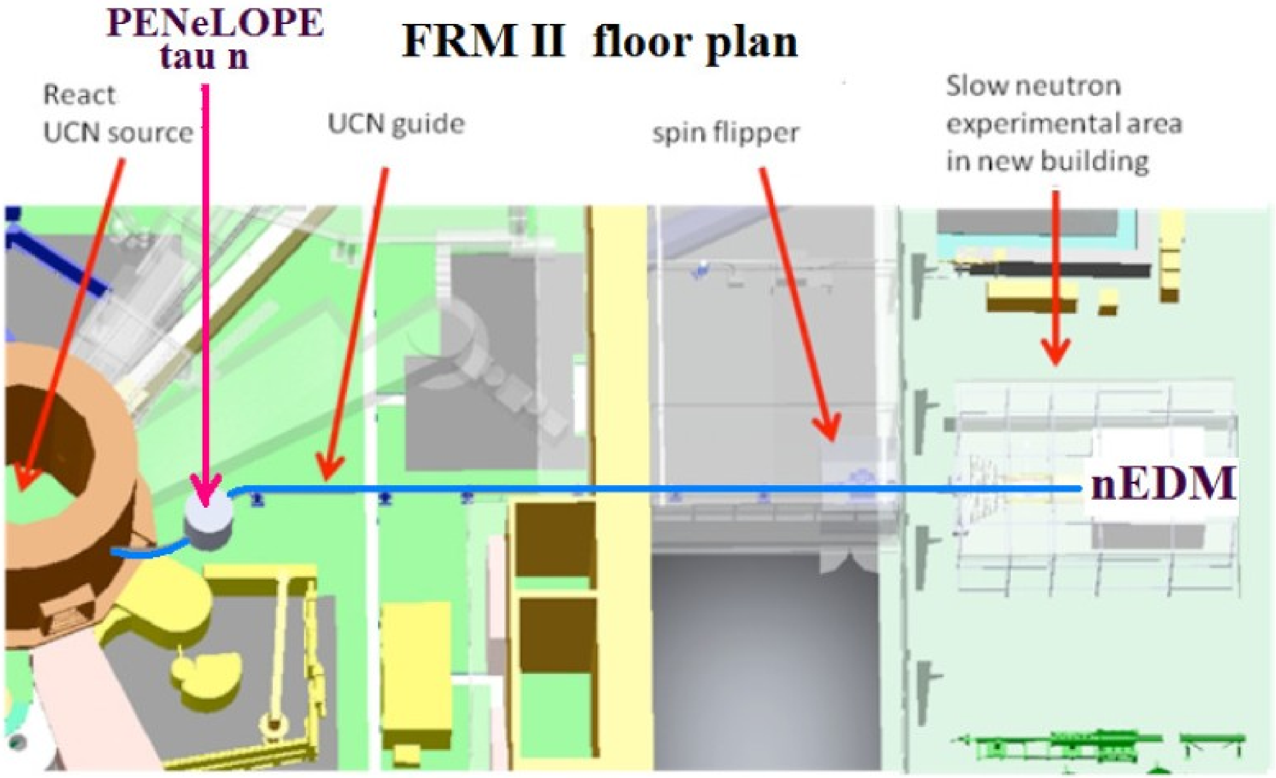
Solid D_2 temperature profile

~1 cm of o-D_2
are feasible to have vapor pressure at the level of 10^{-3} mbar

Thin sources are not so good for providing high UCN current flows.
Fortunately, nEDM experiments need high UCN densities but can be designed to use quite small UCN flows.

UCN Guide tubes

The importance of UCN guide tubes varies greatly among the projects from very great in the case of FRM-II at Munic where UCN transmission over 40 m is required, to very low in the case of SNS where only the distribution of UCN over 0.5 m is of any concern.



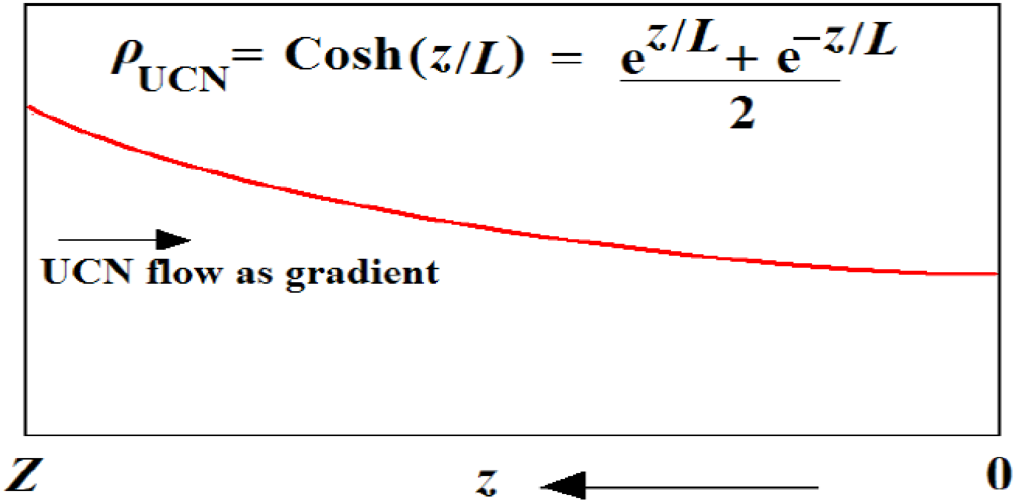
FRM II floor plan

The final stages of filling are important where there is rather little net UCN current and UCN density gradients are small. Thus, guide tube performance for filling an apparatus can be very well described by standard molecular flow diffusion theory, Golub & Pendlebury Rep. Prog. Phys, 1979 **42** 439-501 pages 486-491.

The density at the end z is

$$\rho_{UCN}(z) = \rho_{UCN}(0)/Cosh(z/L)$$

where ***L* is the diffusion length** in the guide



Where L is the diffusion length

$$L = \sqrt{\frac{2R\,\upsilon\,\tau\,(2-f)}{3f}}$$

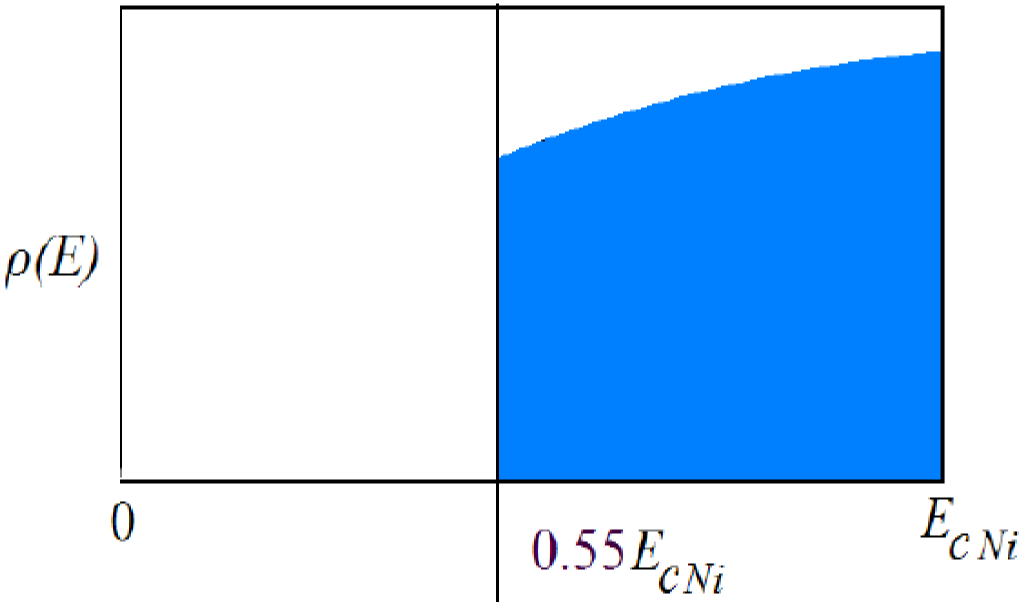
and f is the fraction of reflections that are diffuse. Approximately,

$$f = (\upsilon/\upsilon_c)^2 f_c \quad \& \quad (2-f) \simeq 2 \quad \& \quad \tau_{unbaked} \simeq (\upsilon_c/\upsilon)^{2.5} (R/\upsilon_c)\,2700\ \mathrm{s}$$

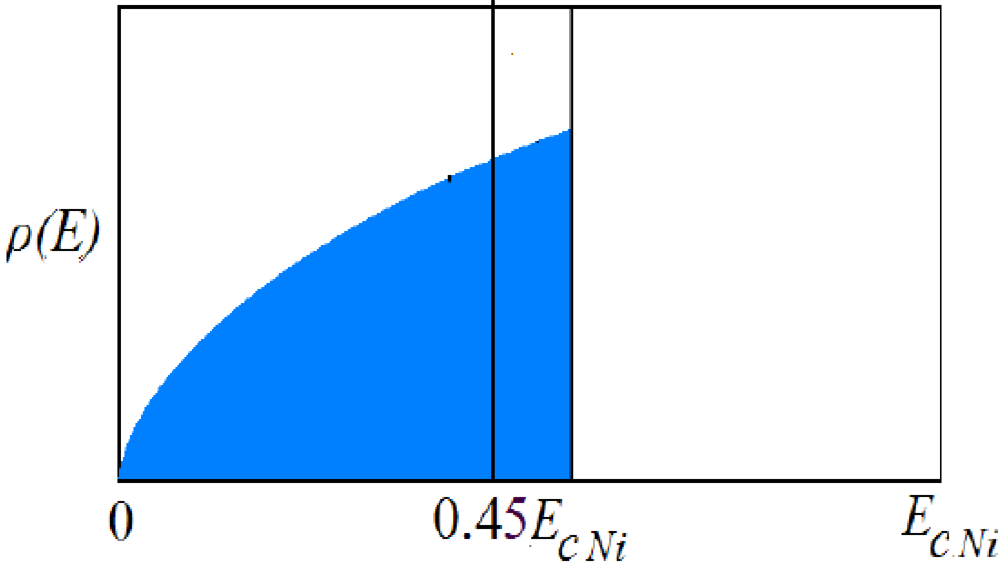
Leading to $L = 60\,R\,(E_c/E)^{7/8} \times (f_c^{-1/2} \approx 3.5)$

Using these results we find that if the FRM-II guide was continued with the same diameter as it has in the reactor (ϕ = 0.125 m) for a length of 40 m, then

E/E_{cNi} of UCN	L /m	Cosh (Z/L)	1/Cosh(Z/L) Attenuation factor	UCN lost in the guide in Litres/s
0.9	14.4	11.41	0.088	5.8
0.7	17.9	6.17	0.162	5.0
0.6	20.5	4.55	0.220	4.5
0.5	24.7	3.32	0.301	4.0
0.3	37.6	1.81	0.554	2.8
0.1	98.4	1.11	0.904	1.2



Spectra of the UCN in the reactor tube after they fall out of the solid deuterium that has a Fermi potential of approximately 0.95 m

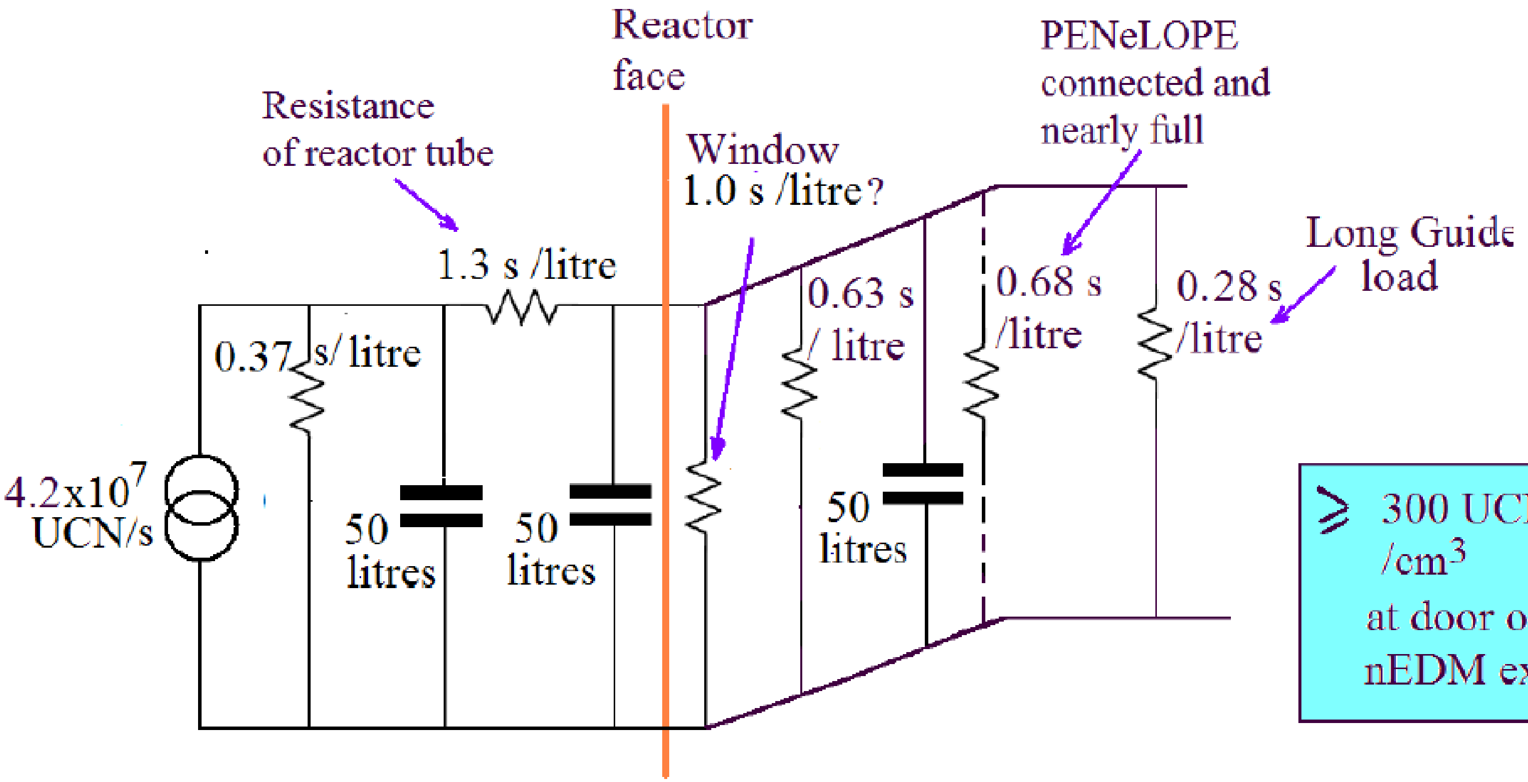


Sectra of UCN in the external guide after it has risen upwards by 0.95 m

The formula for the conductance C of a long guide of length Z is:

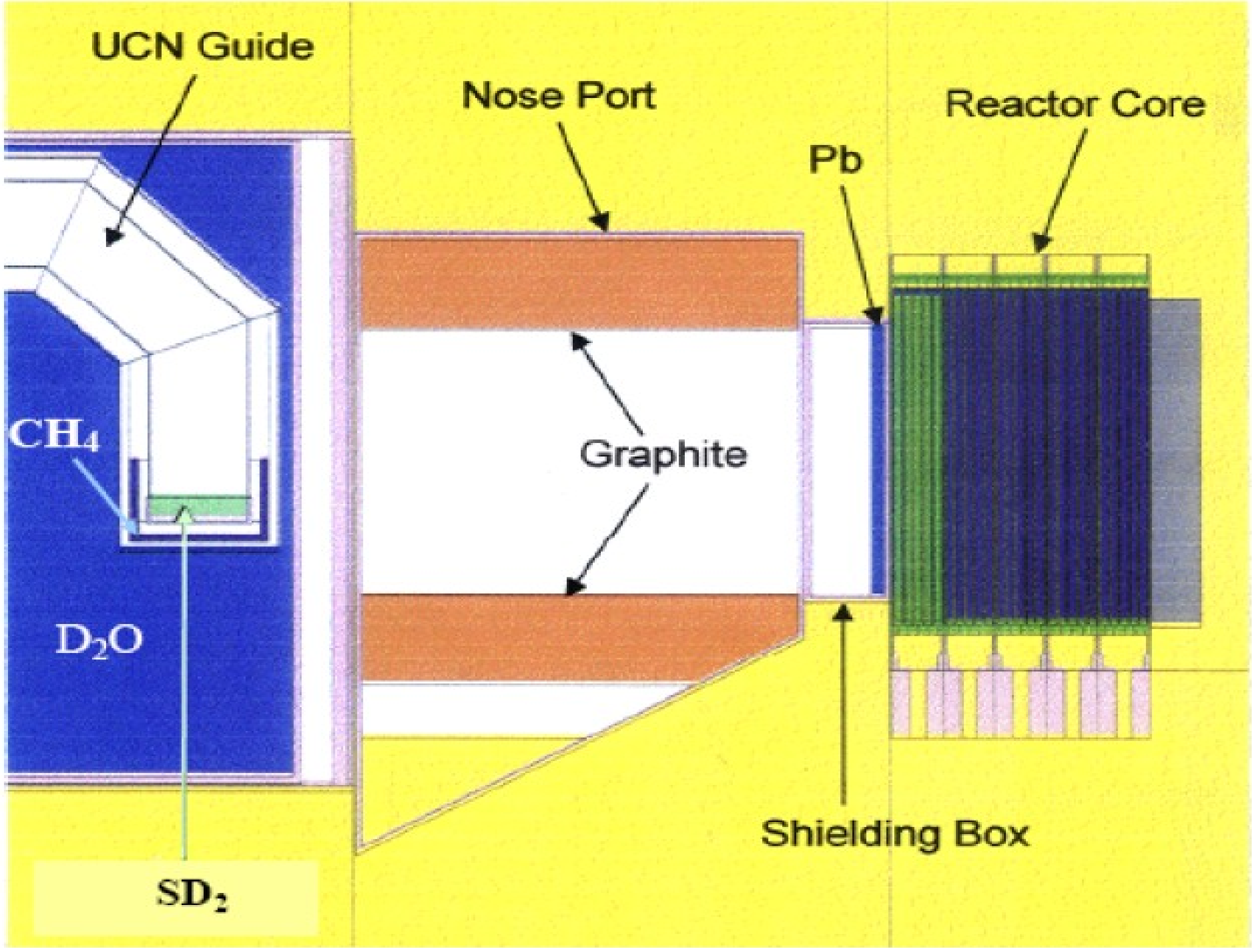
$$C = \left(\frac{\upsilon A}{4}\right)\left[\frac{8R(2-f)}{3Z\;f}\right] \simeq \frac{4\upsilon R^3}{3Z\;f}$$

where f is the probability that any wall reflection is diffuse.

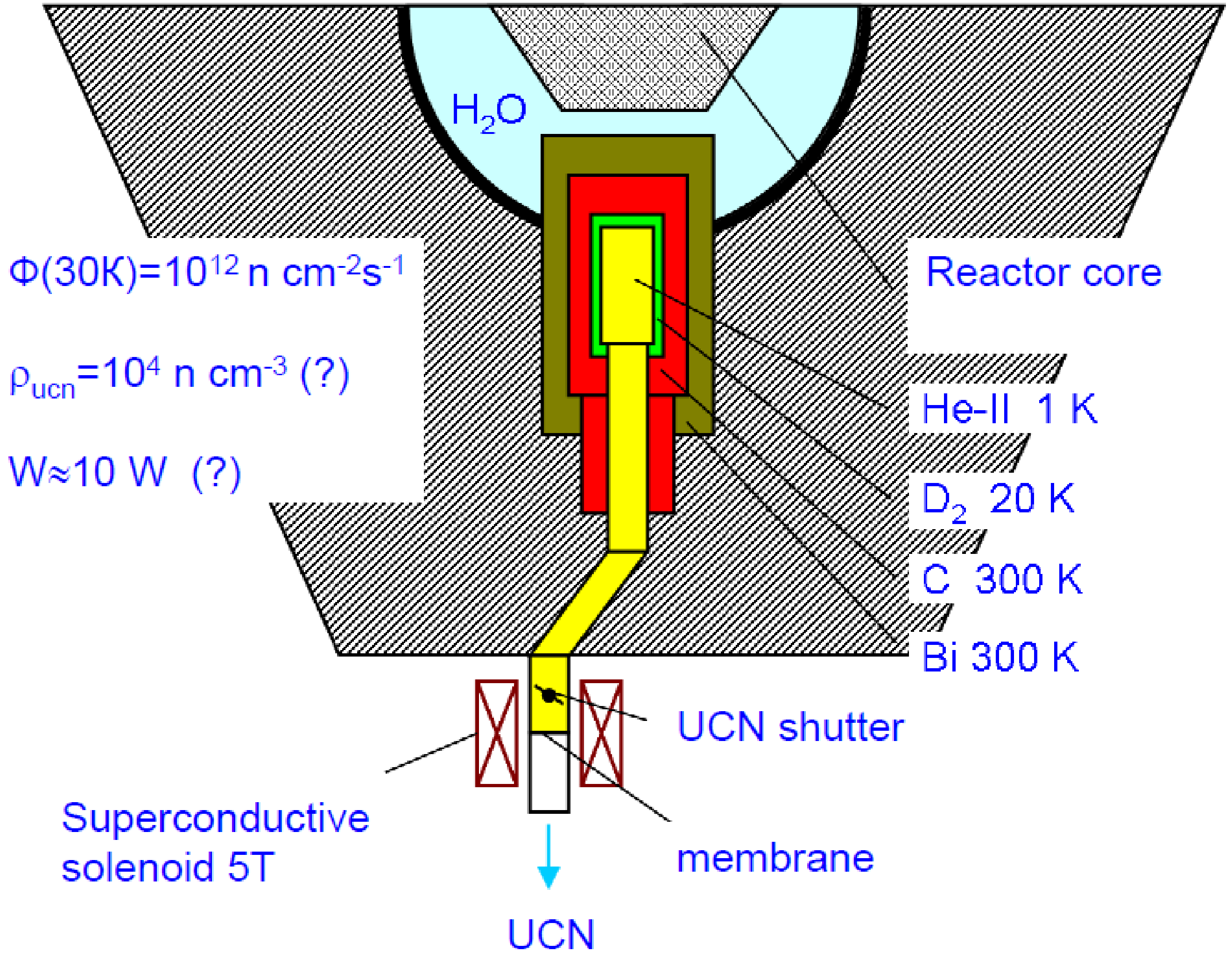


≥ 300 UCN /cm^3 at door of nEDM expt

UCN Source under construction at NCSU



Conceptual idea of UCN source at WWR-M reactor



$\Phi(30K)=10^{12}$ n $cm^{-2}s^{-1}$

$\rho_{ucn}=10^4$ n cm^{-3} (?)

W≈10 W (?)