World wide UCN sources
and
Possibility at TRIUMF

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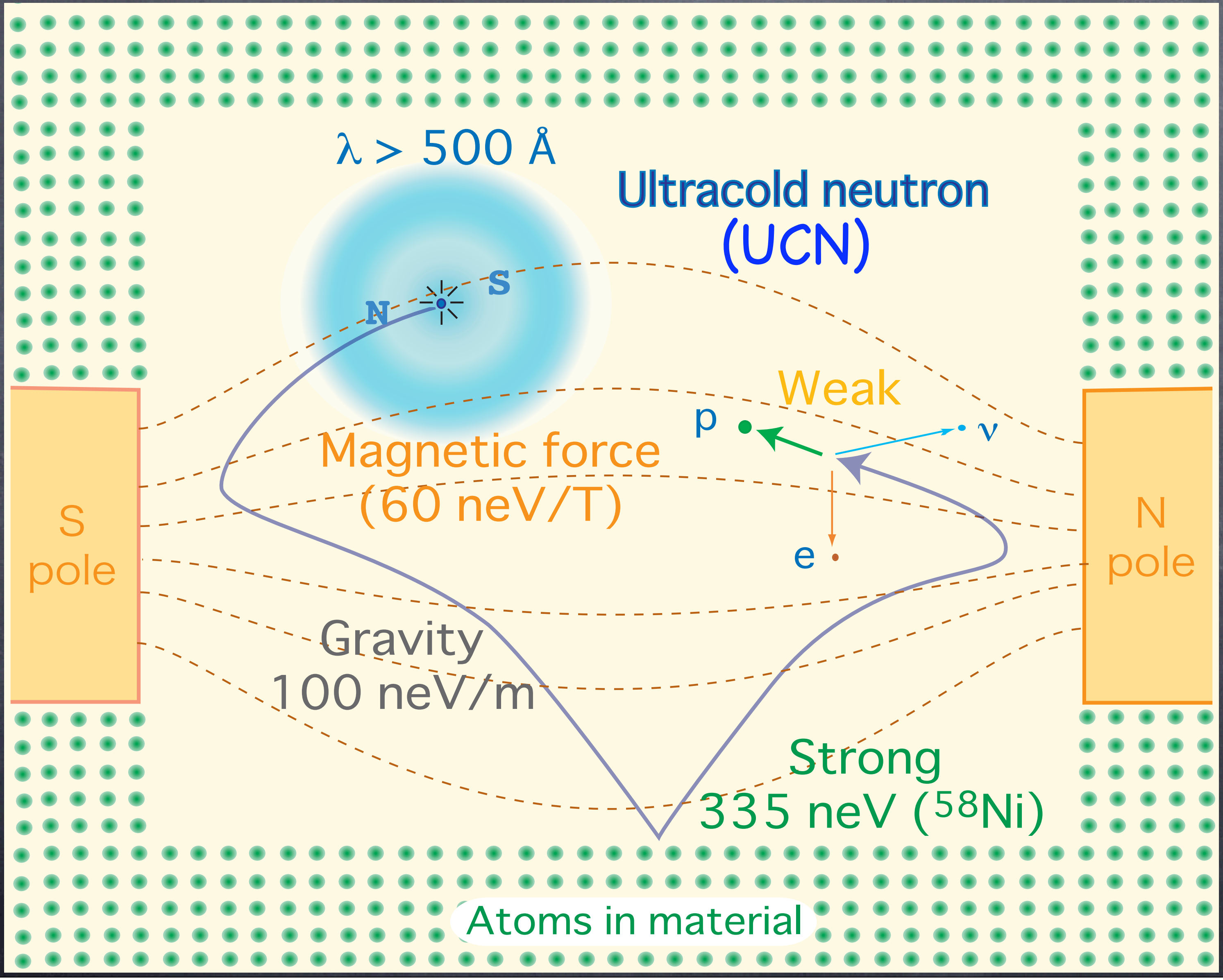
TRIUMF
Aug. 1, 2007

Neutron confinement



Physics with UCN

- n lifetime

  885.7±0.8 s, PDG ↔

  878±0.7±0.3 s,
  Serebrov et al. Phys. Lett. B592 (2004)

  For 10^{-4} measurement: 50 $\mathrm{UCN/cm^3}$

- n β decay asymmetry

  For test of CKM unitarity, V_{ud} with 10^{-3}:

  16 $\mathrm{UCN/cm^3}$ at $\tau_s = 2.6$ s

Physics with UCN 2

- n EDM

  $\delta d_n \sim 10^{-28}$ cm: SUSY, Multi-Higgs, Left-Right
  $E = 50$ kV/cm, $\tau_c = 130$ s, $\rho = 300$ UCN/cm^3

- n-nbar oscillation

  cold n beam > 8.8×10^7 s (1994), Fréjus > 1.2×10^8 s (1990), Kamioka > 1.2×10^8 s (1986)

  SUSY with neutrino mass and See-Saw model → $10^9 \sim 10^{10}$ s:

  1.3×10^8 UCN/s (5×10^5 UCN/cm^3 in 40 liter) → 10^{10} s

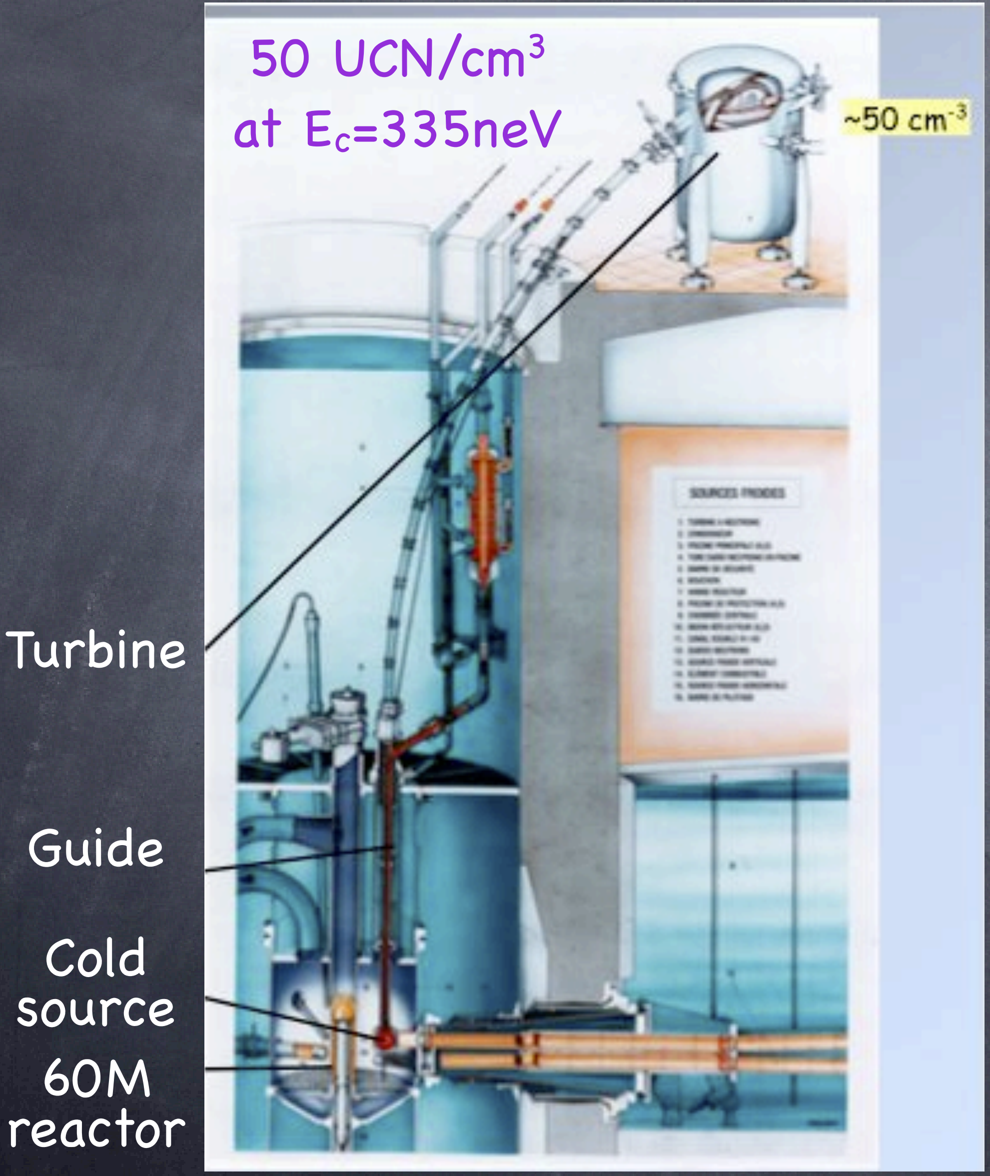
For UCN physics

UCN density is the most important

UCN source at ILL

http://www.ill.fr/nfp/npp/Pf2.htm

UCN density at ILL



50 UCN/cm^3
at E_C=335neV

2 to 3 UCN/cm^3
in an experimental
bottle of E_c = 109 neV
0.7 UCN/cm^3
in EDM cell

UCN density is limited
by Liouville's theorem

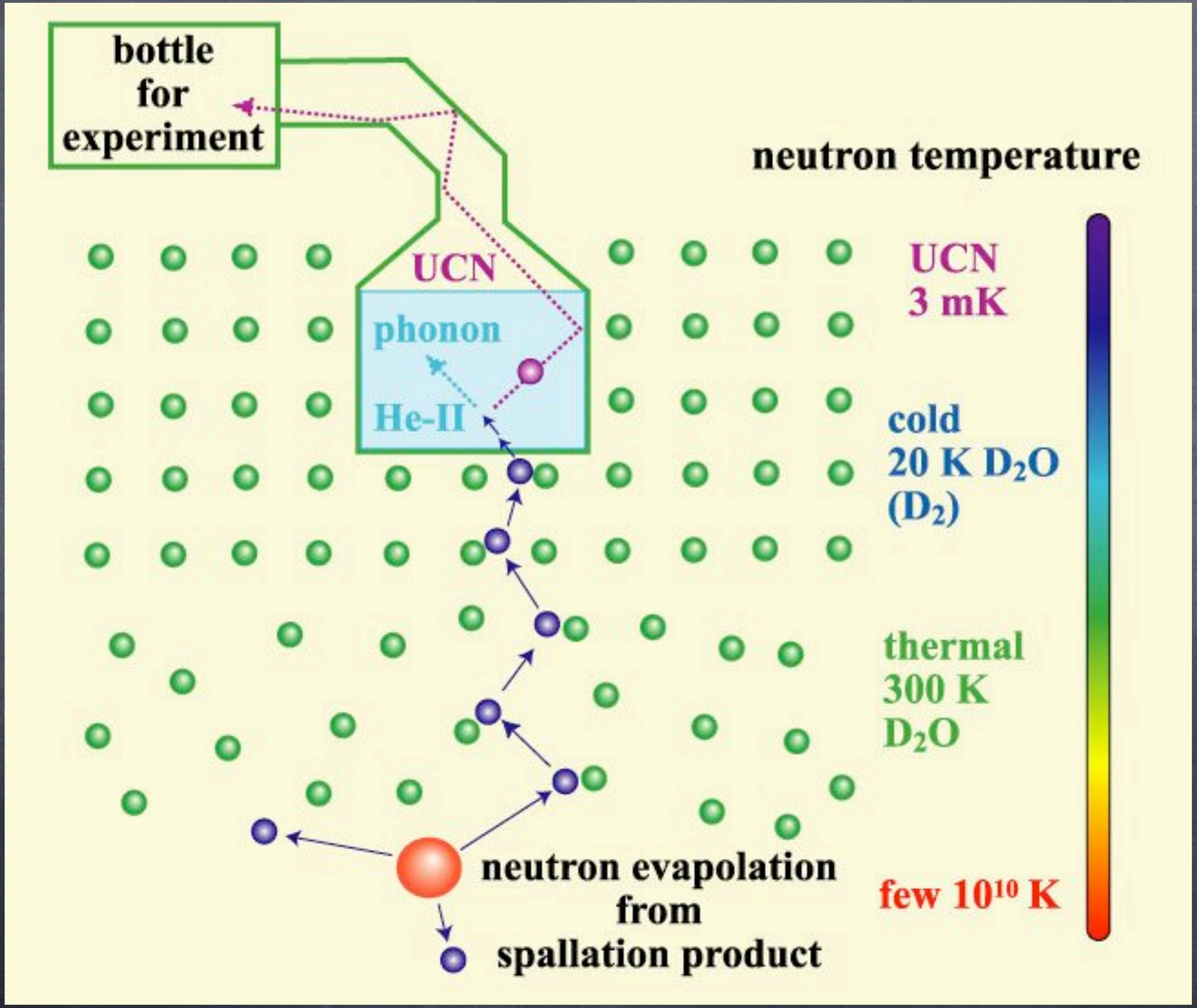
for the deceleration
by gravity and
Doppler effect

New generation UCN sources

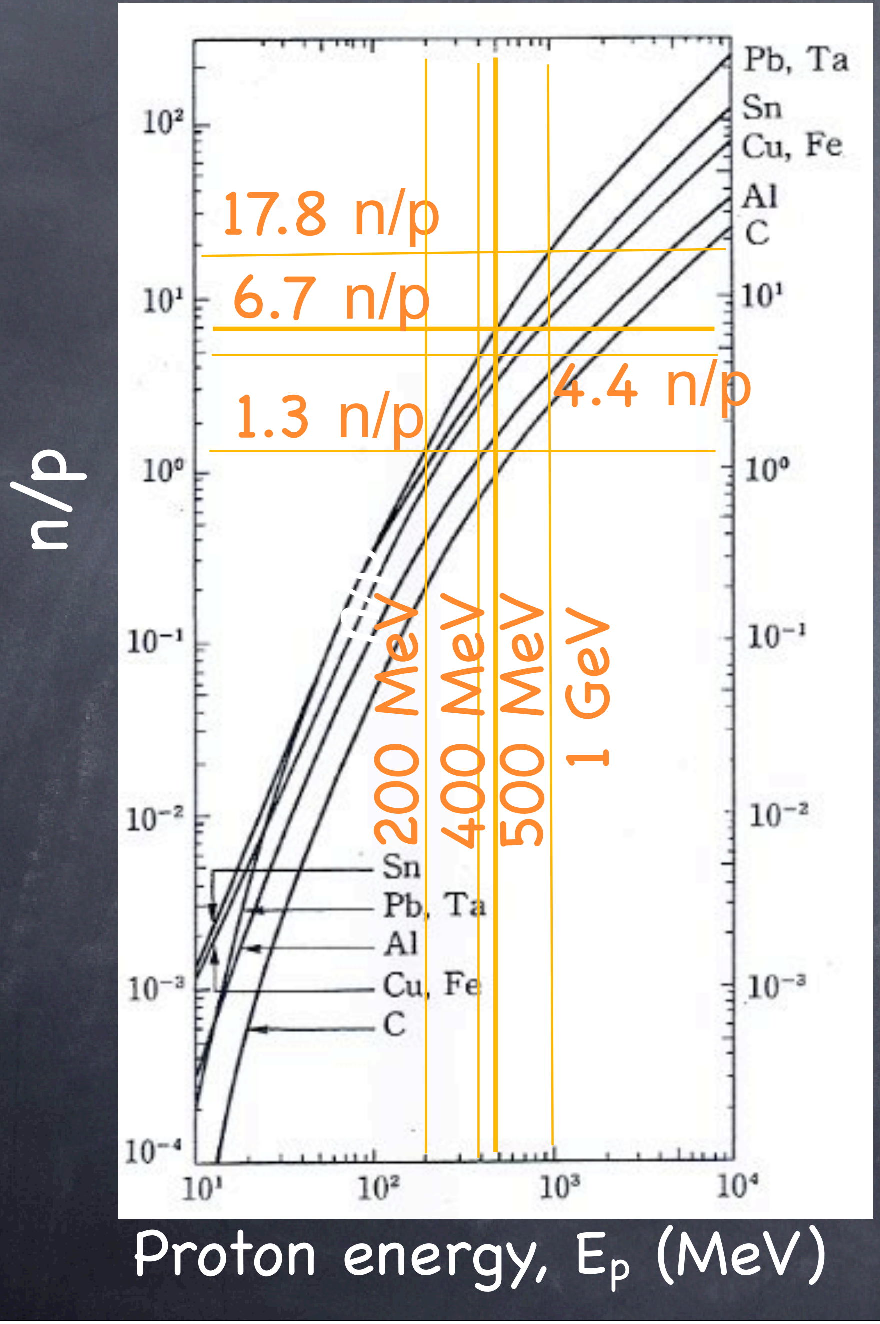
New UCN sources use phonons
for UCN production.
UCN density is not limited by Liouville's theorem.

He-II or SD_2
in cold n source or beam

He-II in spallation source



Spallation neutron production

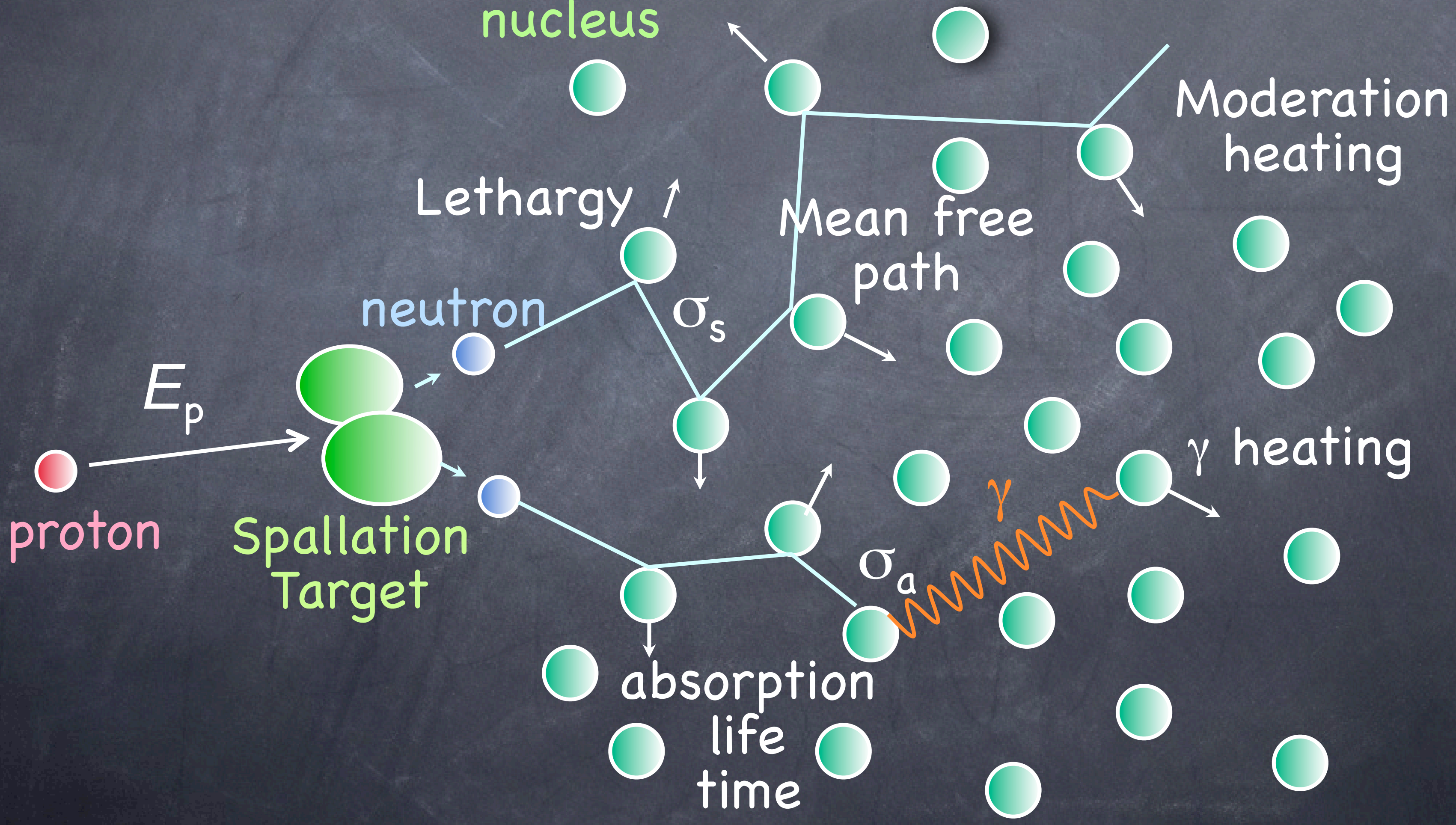


E_p	n/power
3 GeV	1.2
1 GeV	1
500 MeV	0.75
400 MeV	0.62
200 MeV	0.37

K. Tesch, Radiat.Protec. Dosim. 11 (1985)165

Neutron source parameters

moderation, diffusion, dwelling time, heating



Moderator for UCN

High Φ_n (at 1 meV for He-II):

high lethargy and short mean free path

at inelastic scattering,

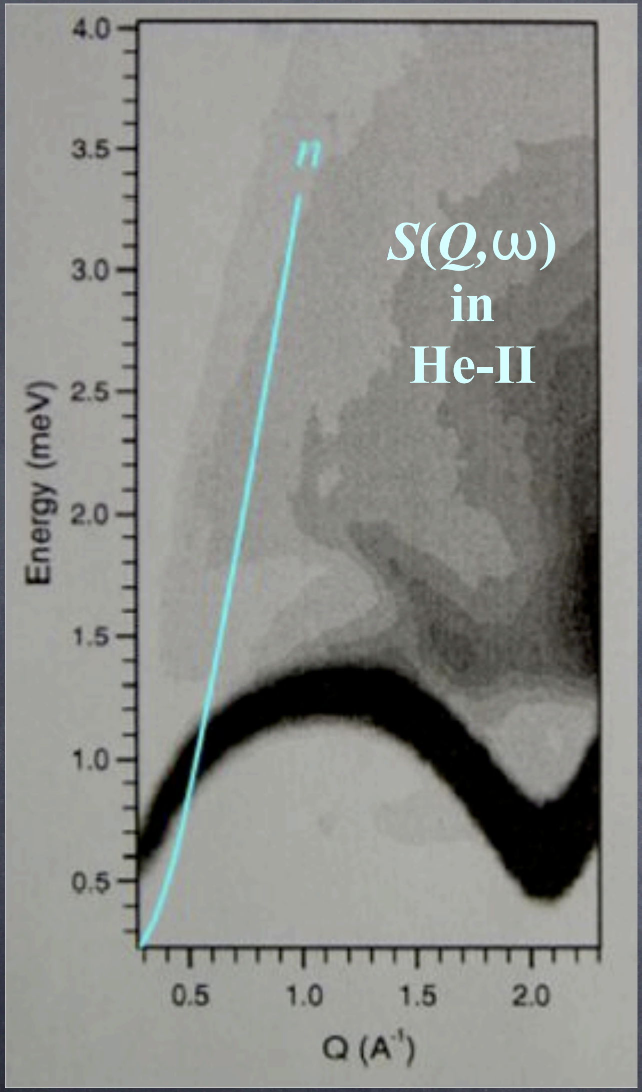
low absorption

Low γ heating

Moderator material

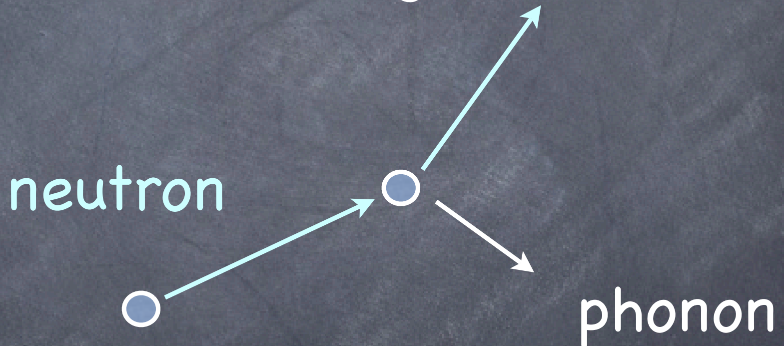
	H_2O	D_2O	D_2	Be	C	Pb
Lethargy	0.95	0.57	0.75	0.21	0.16	0.01
ξ = -ave(ln(E_f/E_i))						
= $2/(M/m + 2/3)$, m: neutron mass, M: target nucleus mass						
Mean free path	0.29	2.2	6.0	1.2	2.6	2.7
(cm) $\lambda = 1/(N\sigma_s)$						
Density N (10^{23}/cm^3)	**0.34**	**0.33**	**0.25**	**1.24**	**0.80**	**0.33**
Scattering σ_s (b)	**103**	**13.6**	**6.8**	**7.0**	**4.8**	**11.3**
Life time (ms)	0.21	100	177	3.46	13	0.81
$\tau_a = 1/(N\sigma_a v)$						
Absorption σ_a (mb)	**665**	**1.23**	**1.04**	**7.6**	**3.53**	**171**
γ heating						

Superthermal UCN production in He-II



M.R. Gibbs et al. (1999)

Coherent inelastic neutron scattering in He-II



Born approximation

$$d^2\sigma/dQd\omega$$
$$= k_f/k_i \, a^2 \, S(Q,\omega)$$
$$= \sigma_{coh}/4\pi \cdot k_f/k_i \cdot S(Q,\omega)$$

UCN density in source

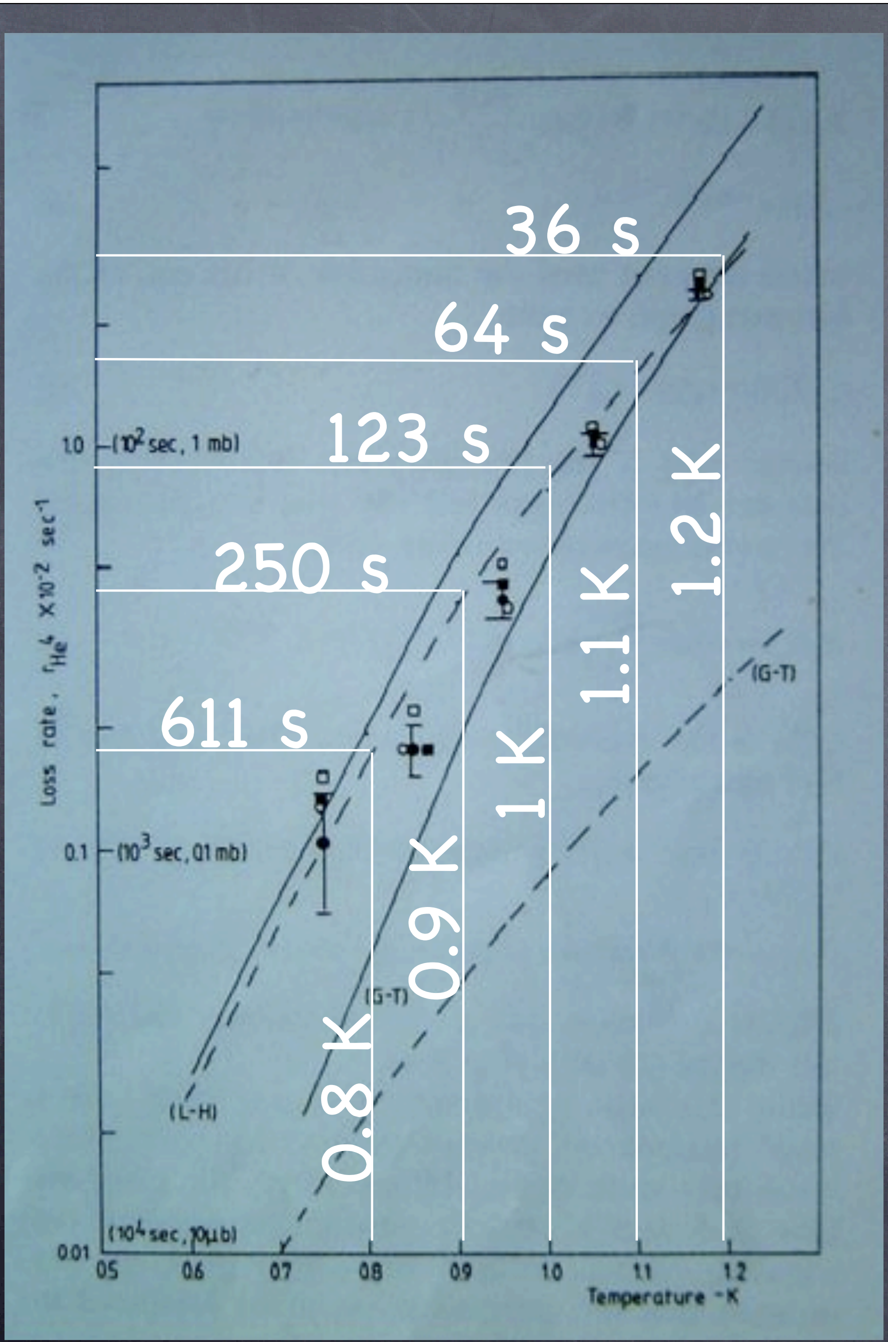
$$\rho = \int_0^{E_c} \sigma_{coh}(E_{in} \rightarrow E)\, N_{He}\, \Phi_n\, \tau_s\, dE$$

Φ_n : cold neutron flux ∝ proton beam power

τ_s : storage time
depends on ^{3}He impurity and He-II temperature

$E_c^{3/2}$: volumr of momentum space
E_c: maximum UCN energy

τ_s



phonon upscattering

in He-II

$1/\tau \propto T^7$

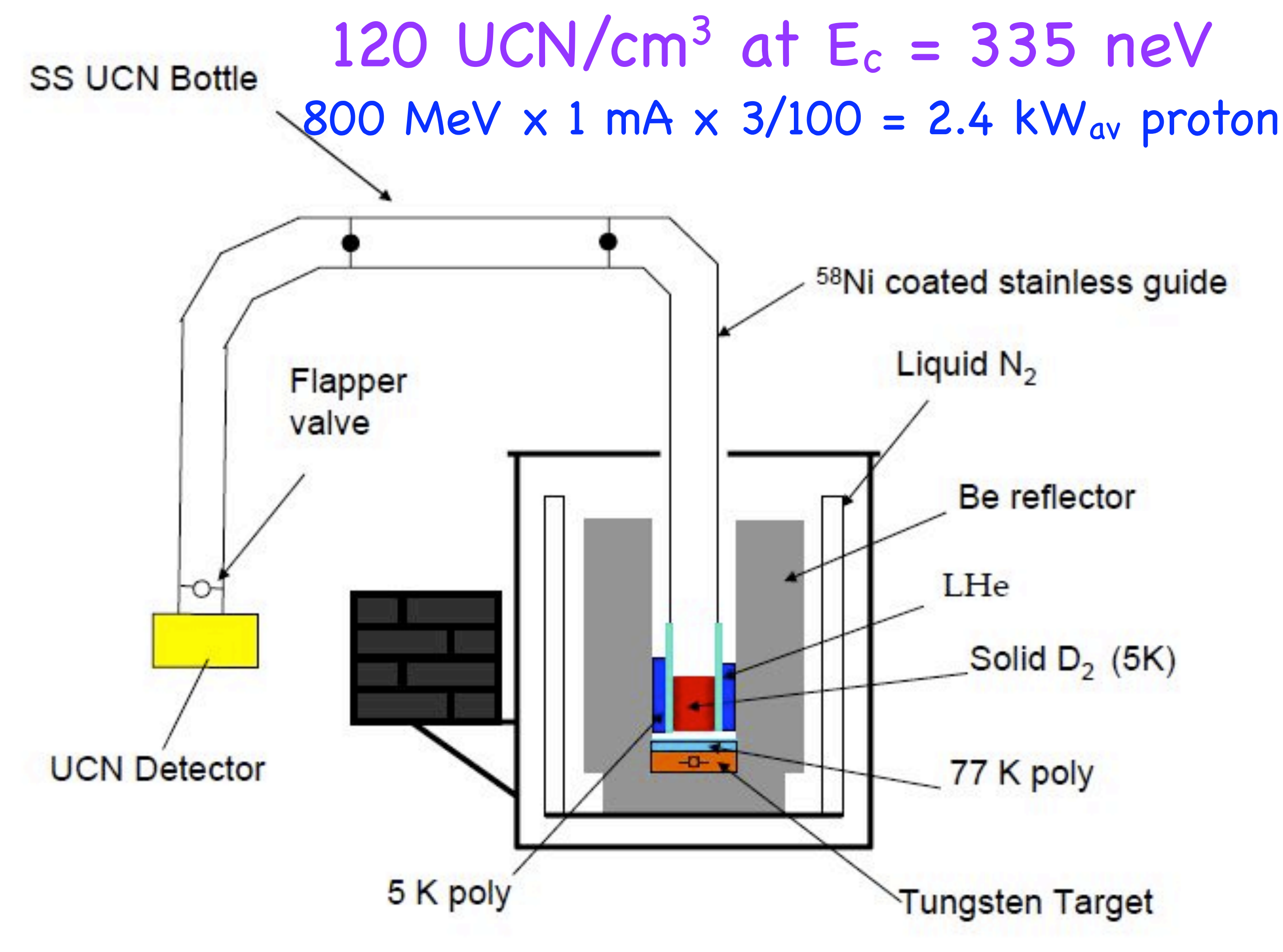
Golub et al. (1983)

SD_2 in spallation n source

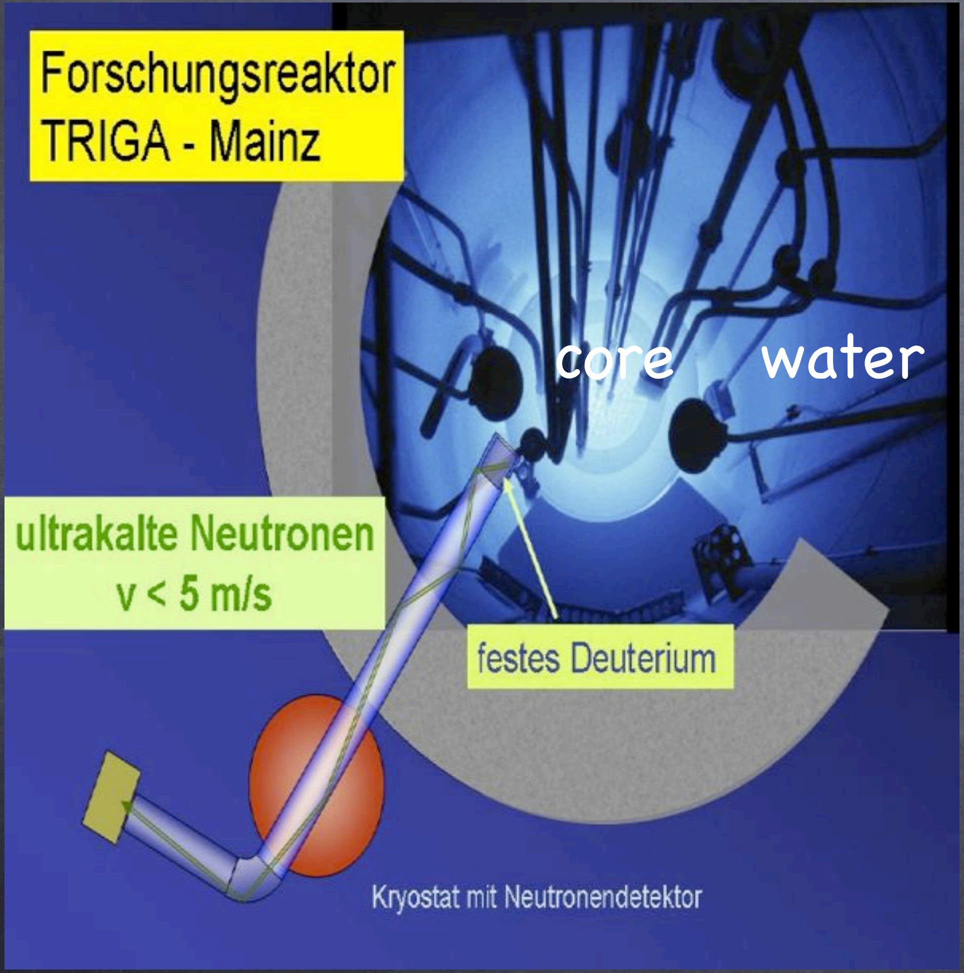
Los Alamos 2002

120 UCN/cm^3 at E_c = 335 neV

800 MeV x 1 mA x 3/100 = 2.4 kW_{av} proton



SD_2 in TRIGA reactor



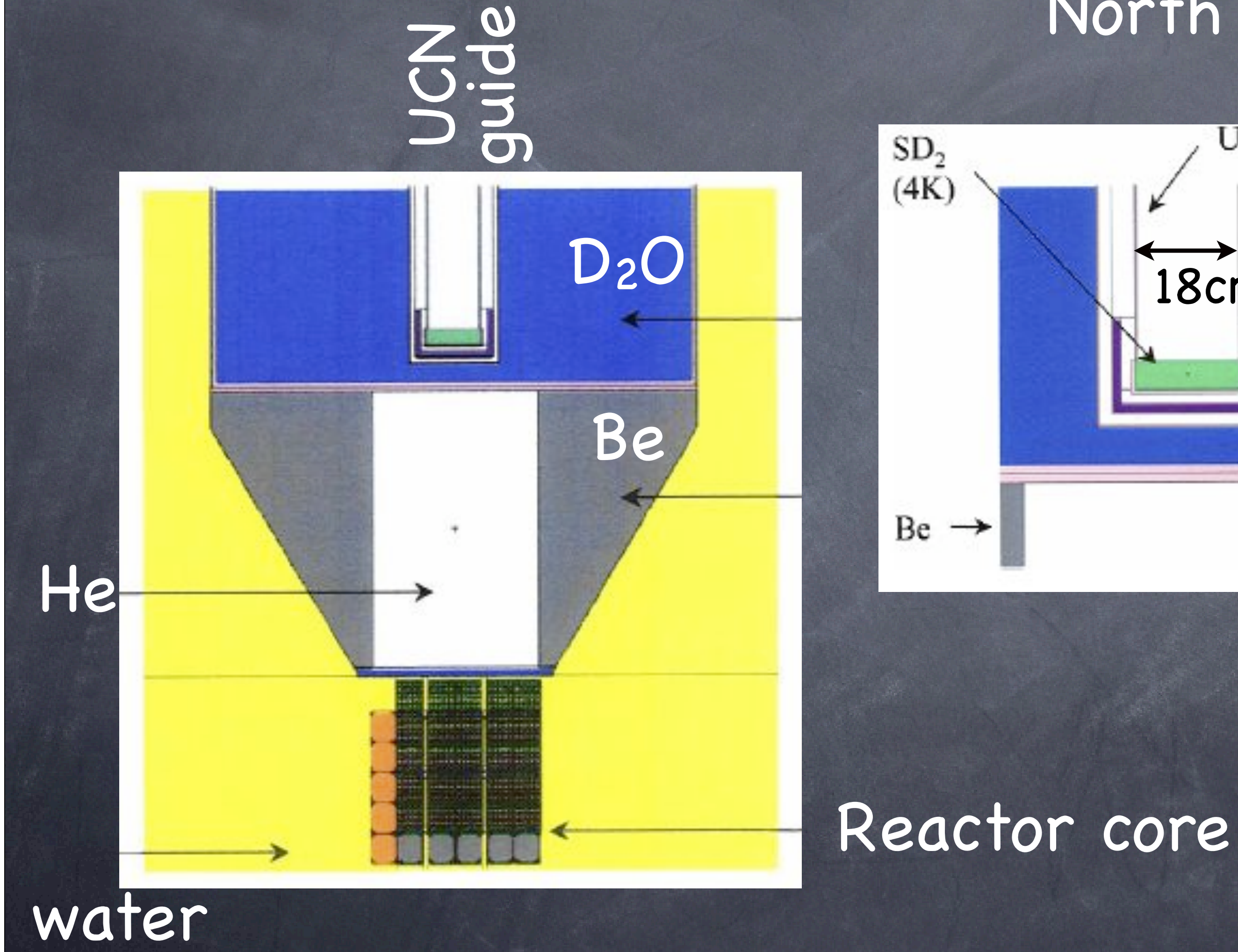
Mainz 2005
1st step to FRM-2
Munich
250 MW 30 ms pulse
10^{15} n/s.cm^2
(steady 100 kW)

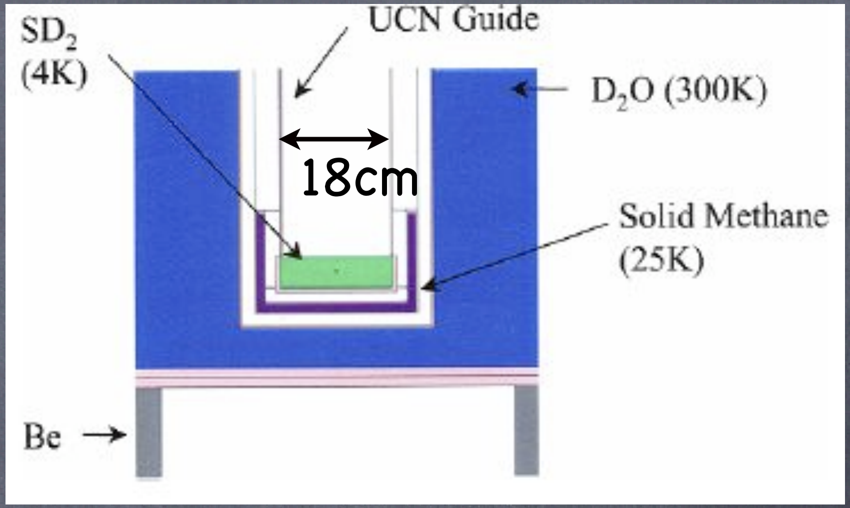
Jan. 2006

80000 UCN/10 liter
= 8 UCN/cm^3/pulse
in source
at E_c = 250 neV

SD_2 in PULSTAR reactor

North Carolina

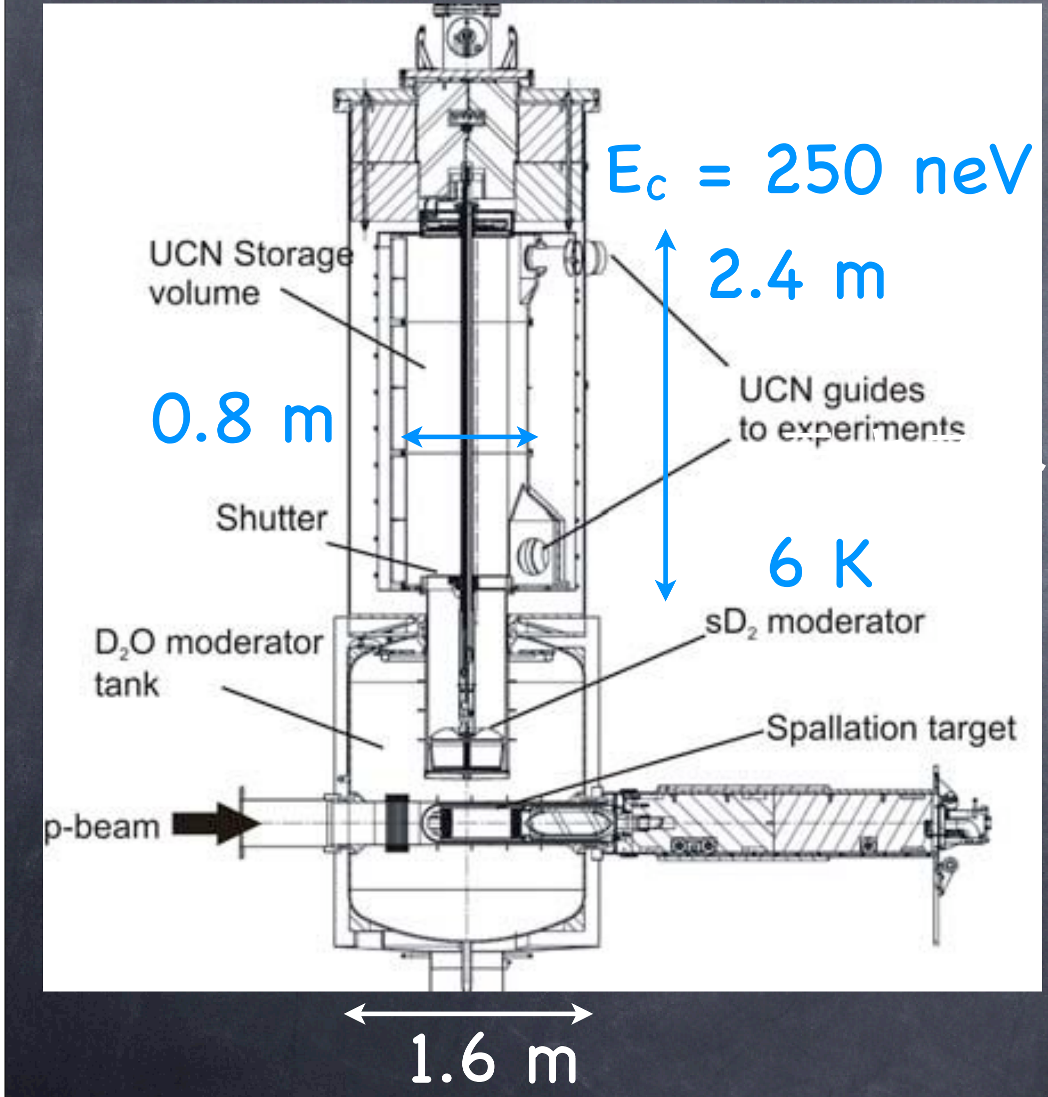


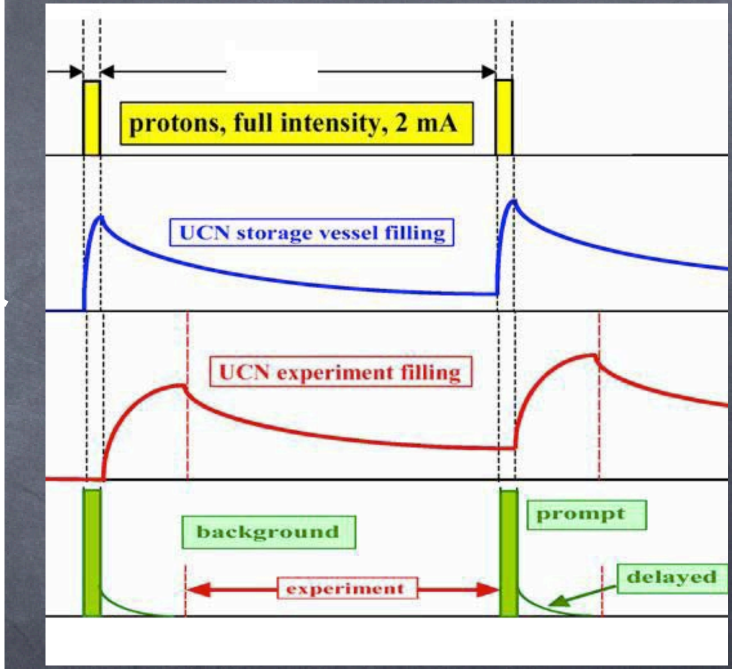


SD_2 in spallation source

PSI

ICANS2007



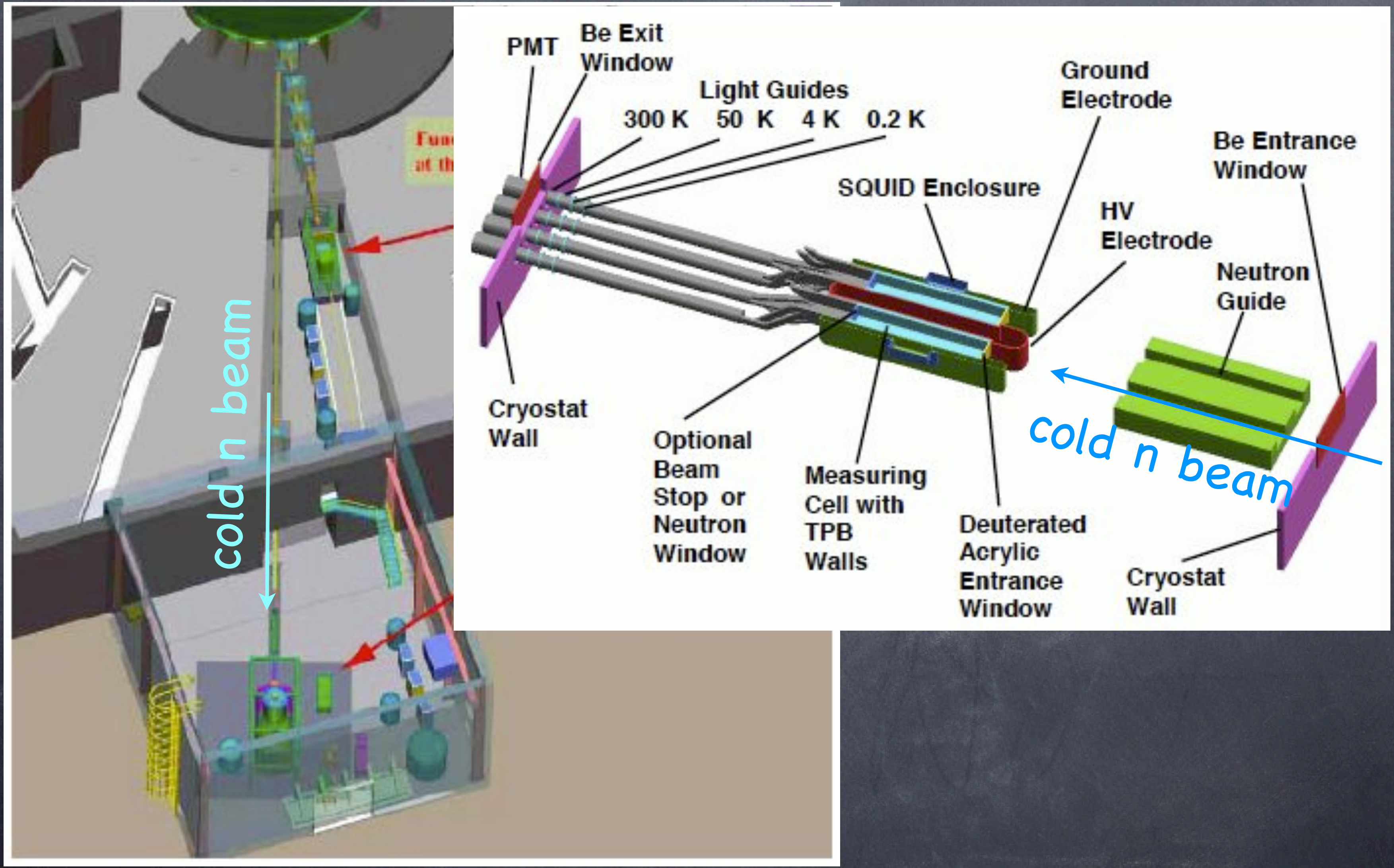


590 MeV x 2 mA = 1MW

4 to 8 s proton pulse

1 % duty cycle

He-II in SNS beam line



He-II or SD_2

		He-II	SD_2
UCN production	cross section	$\sigma_{coh} = 0.76$ b	$\sigma_{coh} = 2.48$ b
	dispersion curve	single overlap	better overlap
Loss	$\tau_a = 1/(\rho v \sigma_a)$	∞	0.2 s
	structure	almost vacuum	dislocation, defect ortho/para
	mean free path	>> 1 m	several cm
Extraction	Fermi potential	negligibly small	109 neV acceleration
Thermal condition	operating temperature	< 1 K	5 or 6 K
	heat conduction	excellent, no local heating	problem local heating

Source or beam

Cold neutron flux Φ_n

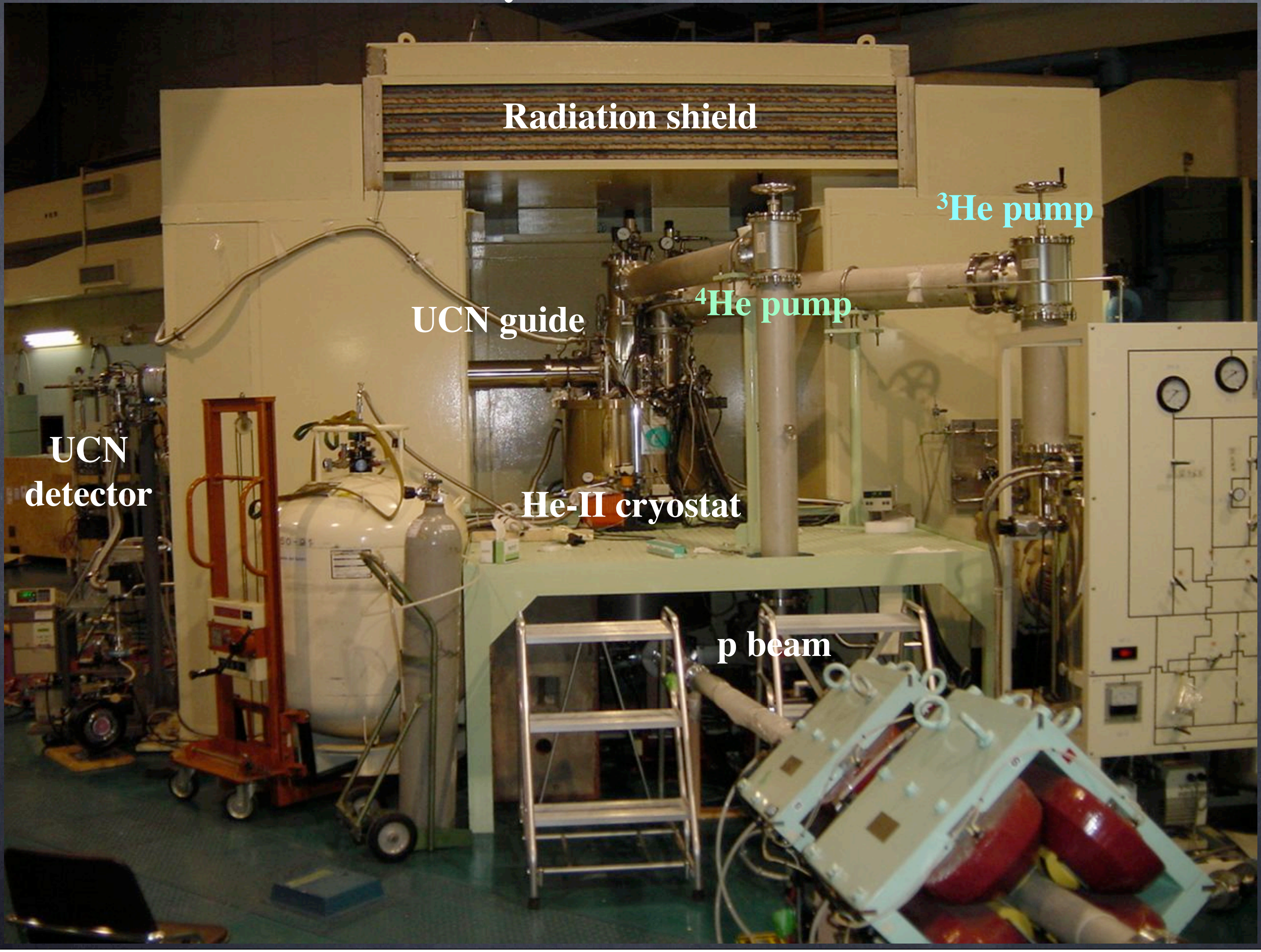
= 3 x 10^9 n/s.cm^2 in ILL PF1

= 1.6 x 10^9 n/s.cm^2 in the SNS ? << ILL PFI
assuming cold neutron flux of 2 x 10^{12}/s.cm^2
at the moderator surface and cold neutron
guide capture rate of 1.7 x 10^{-4}

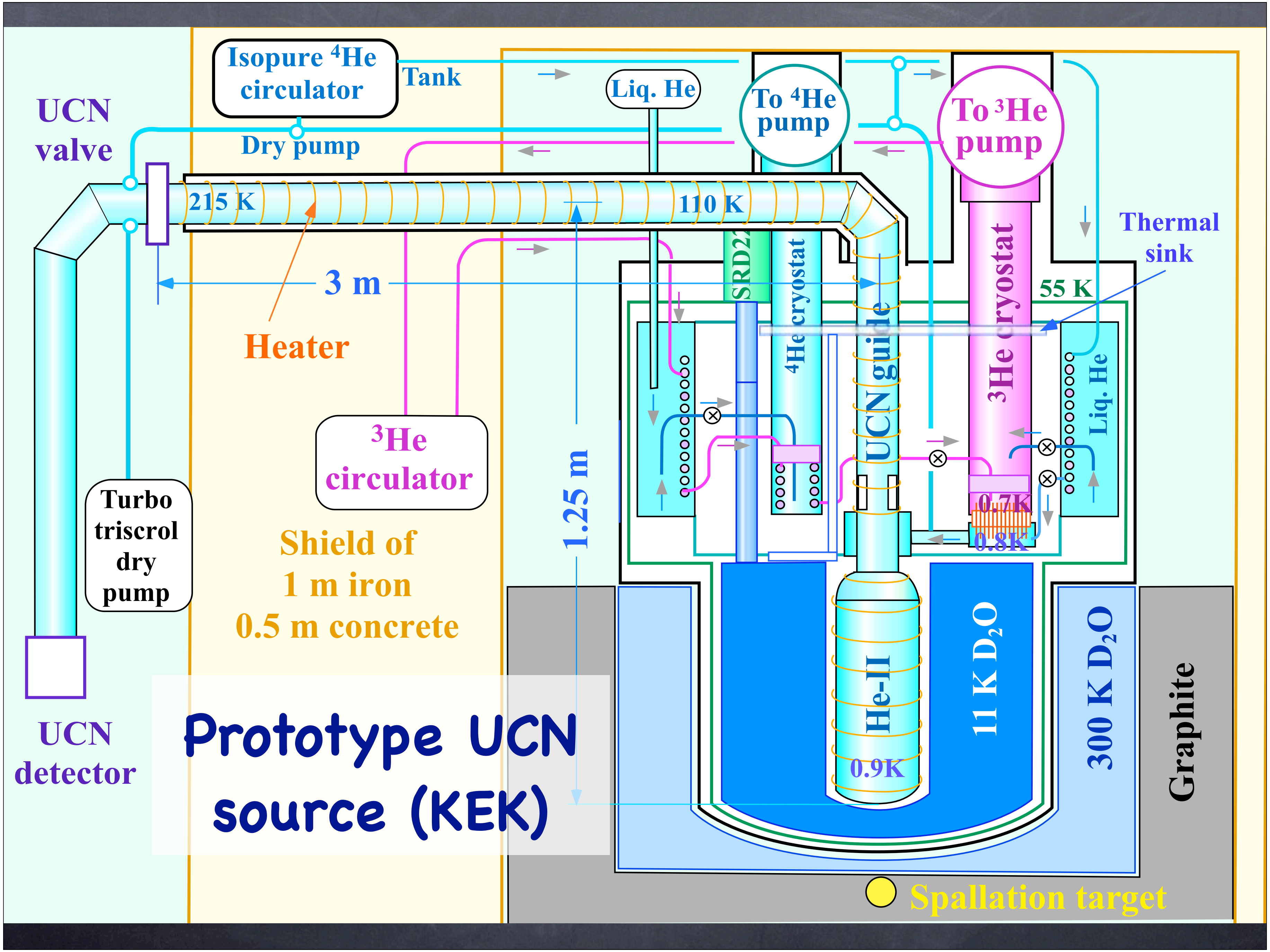
↕

can be 10^{12}/s.cm^2 in the spallation source

He-II in spallation source

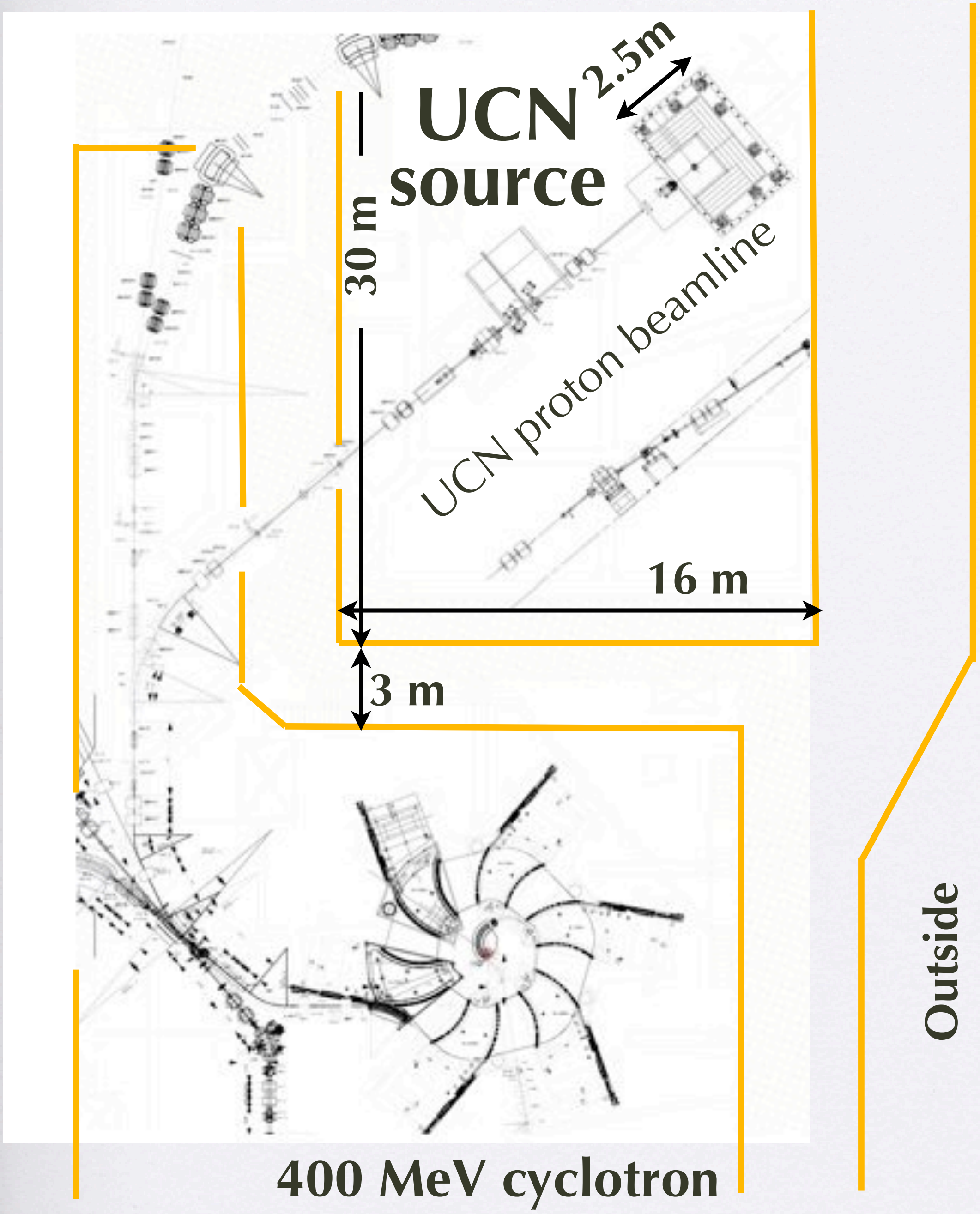


Prototype UCN source (KEK)



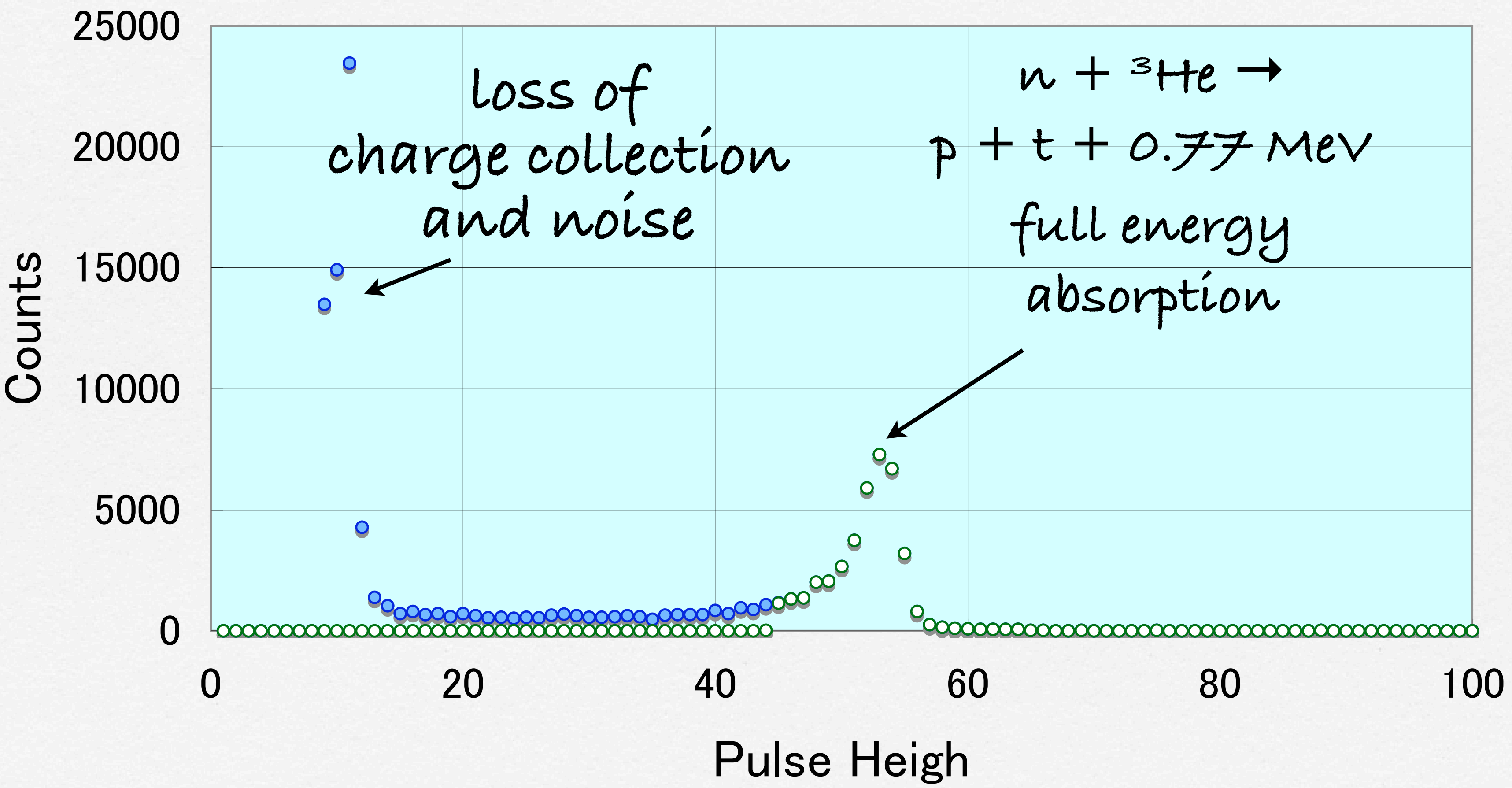
Proton beam line

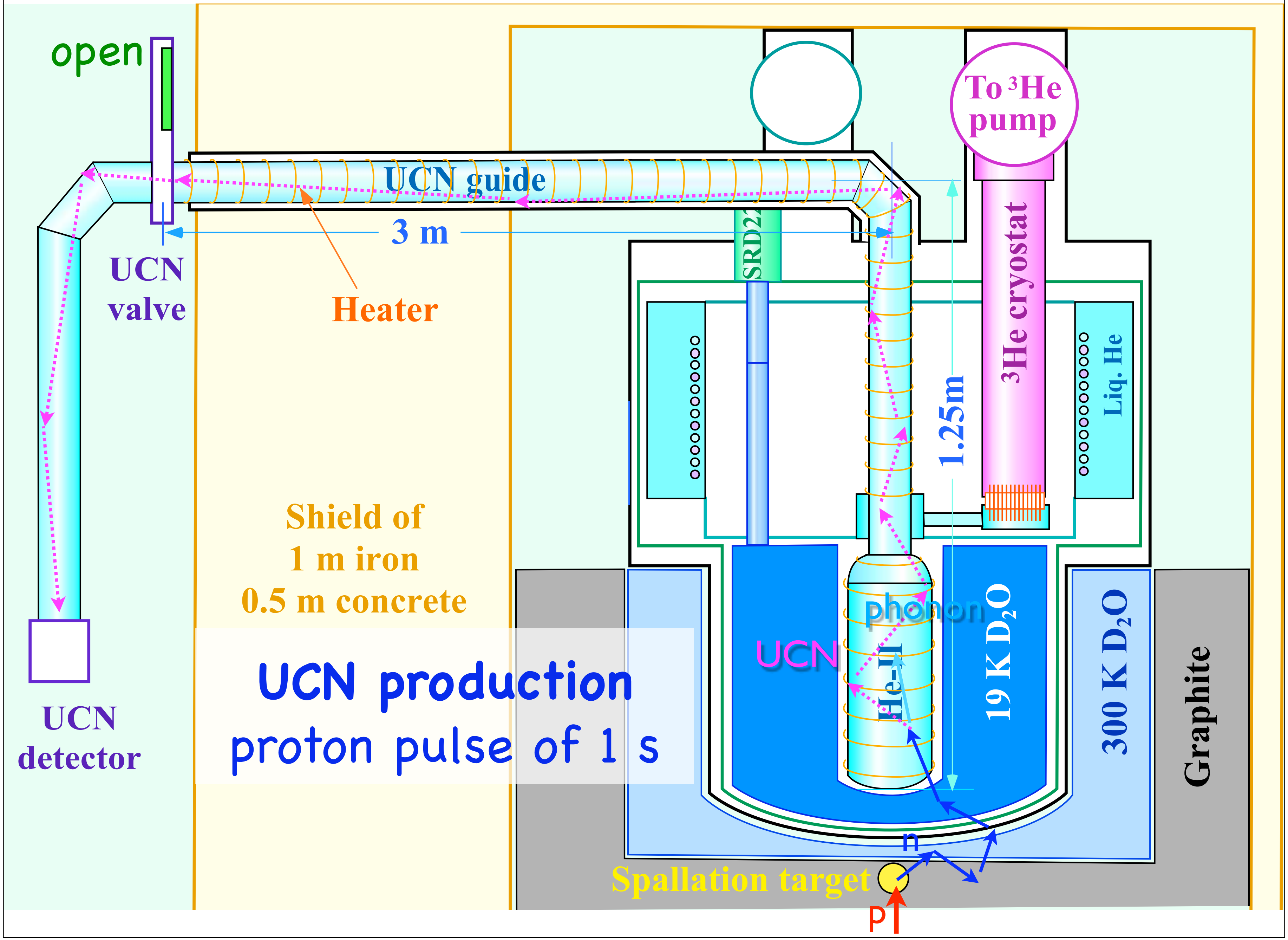
(RCNP, Osaka)



Data

UCN counter Pulse Height Spectrum

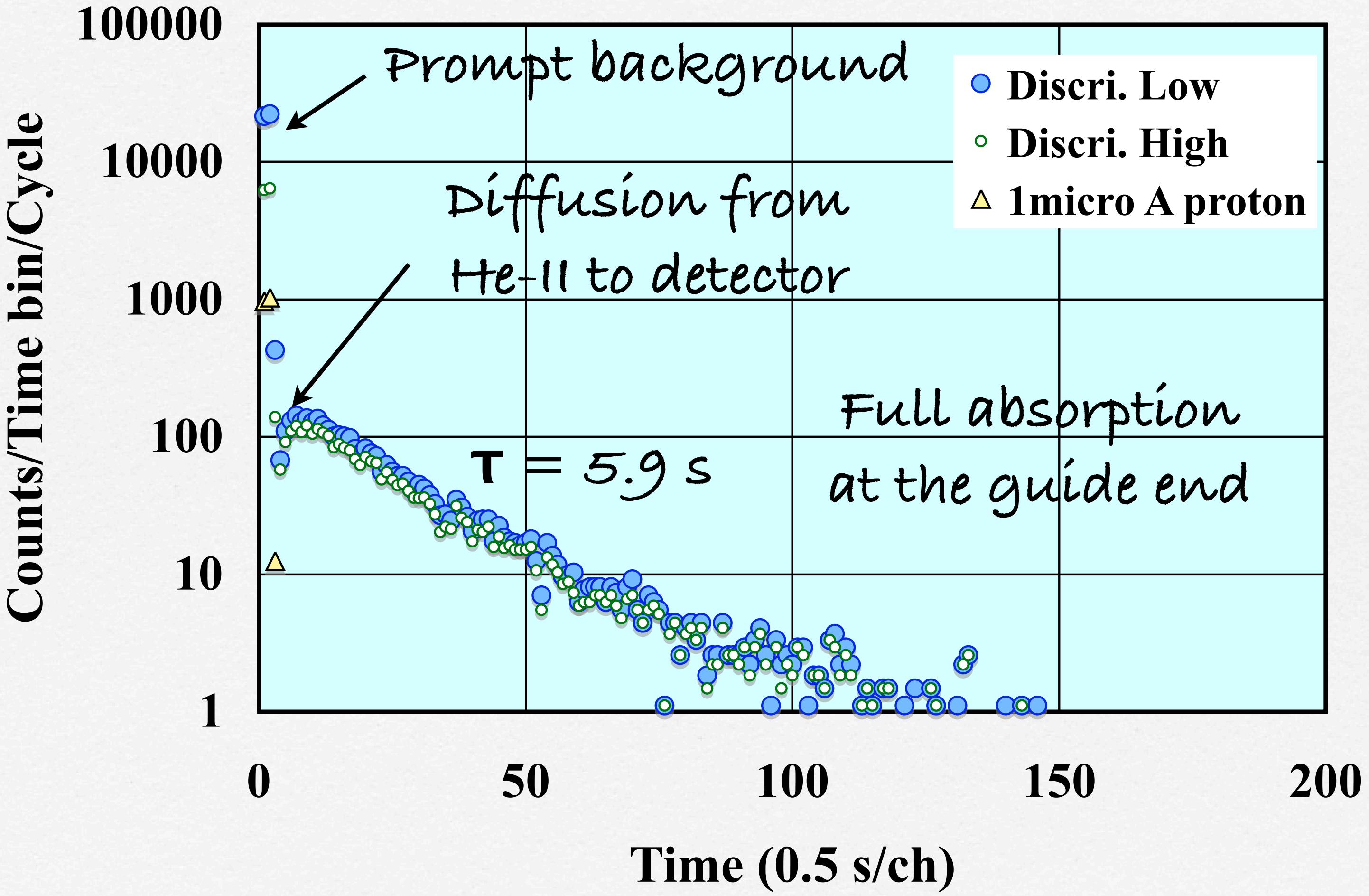


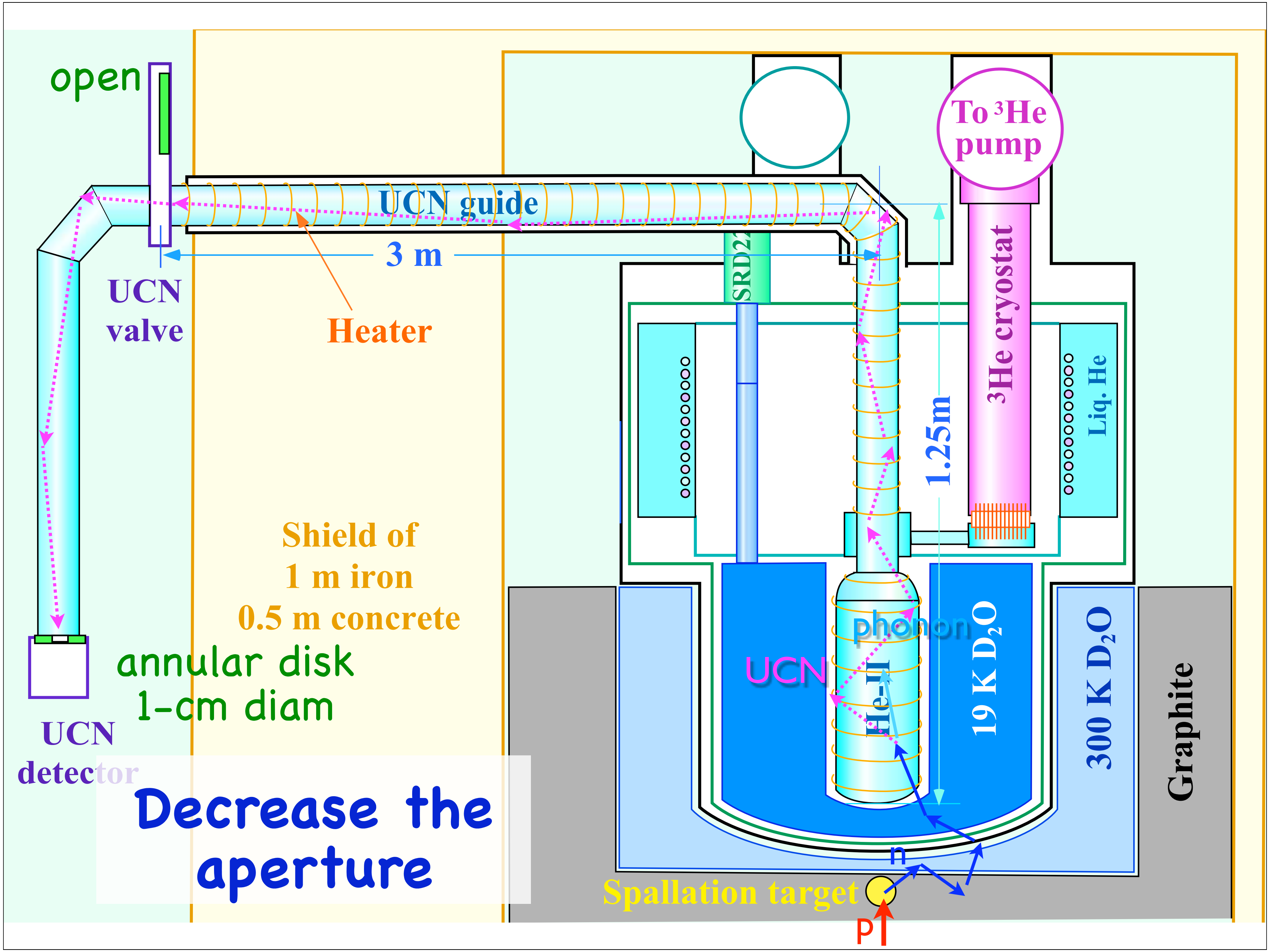


UCN production

proton pulse of 1 s

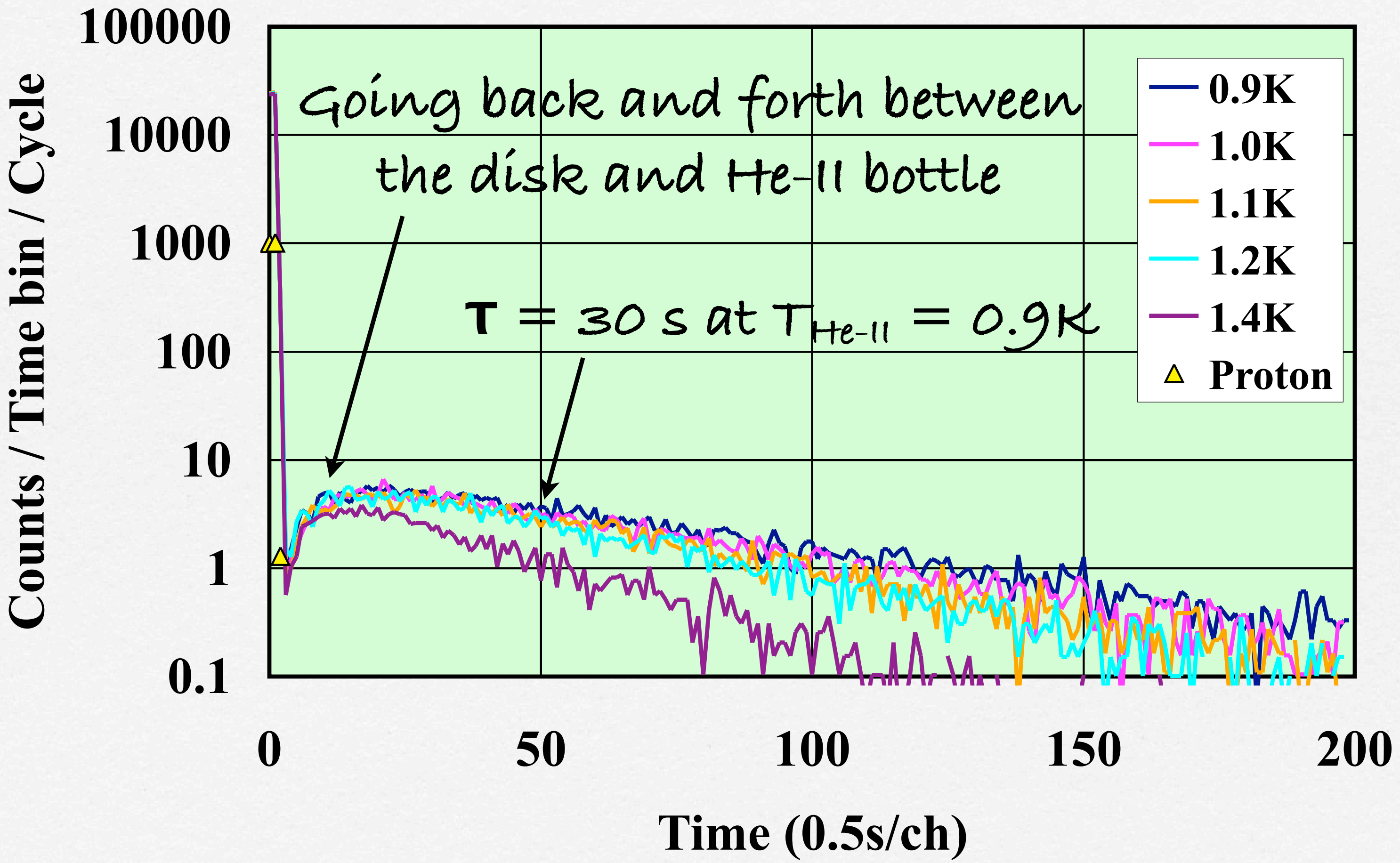
UCN production with a proton pulse of 1s





Decrease the aperture

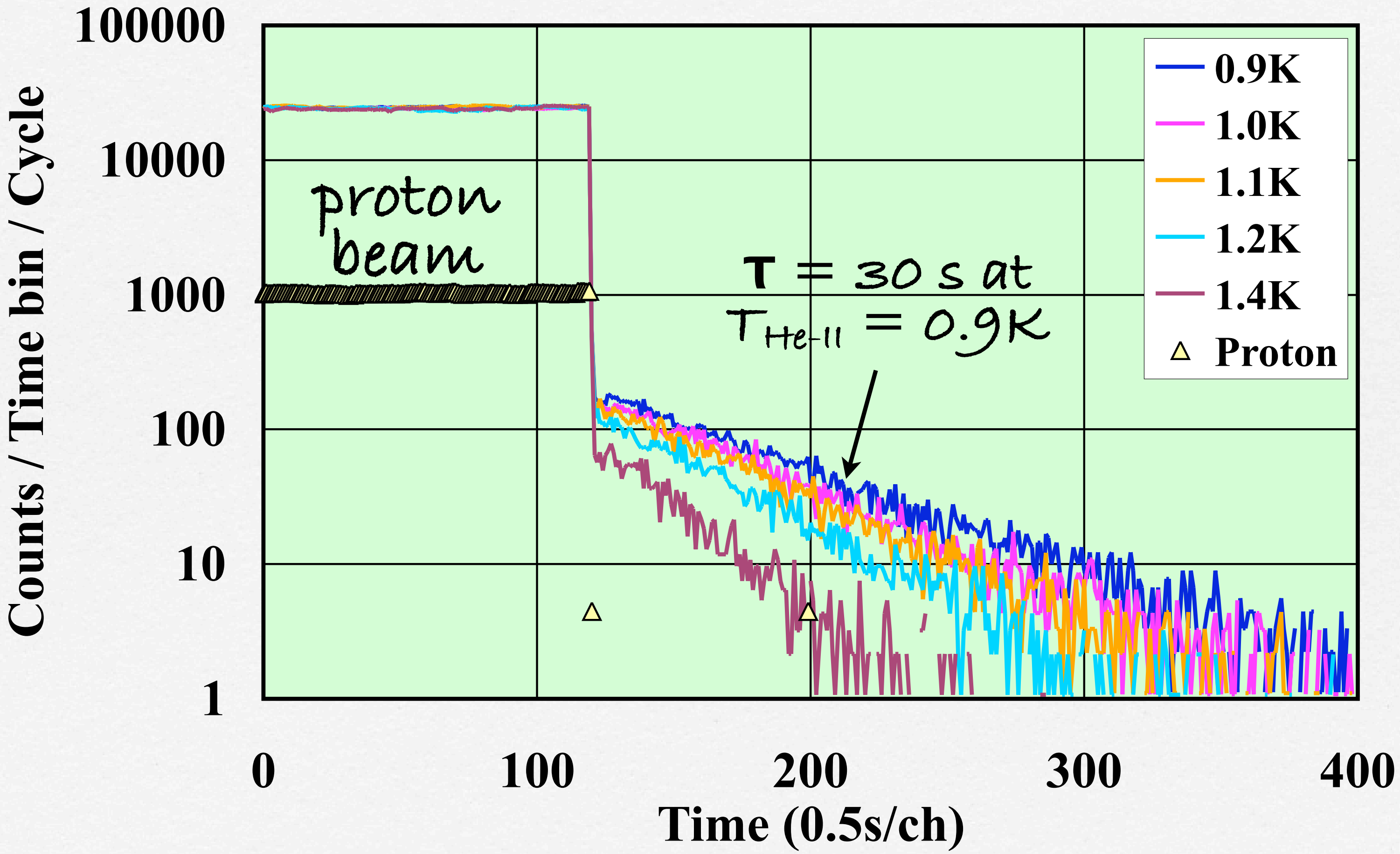
With the annular disk



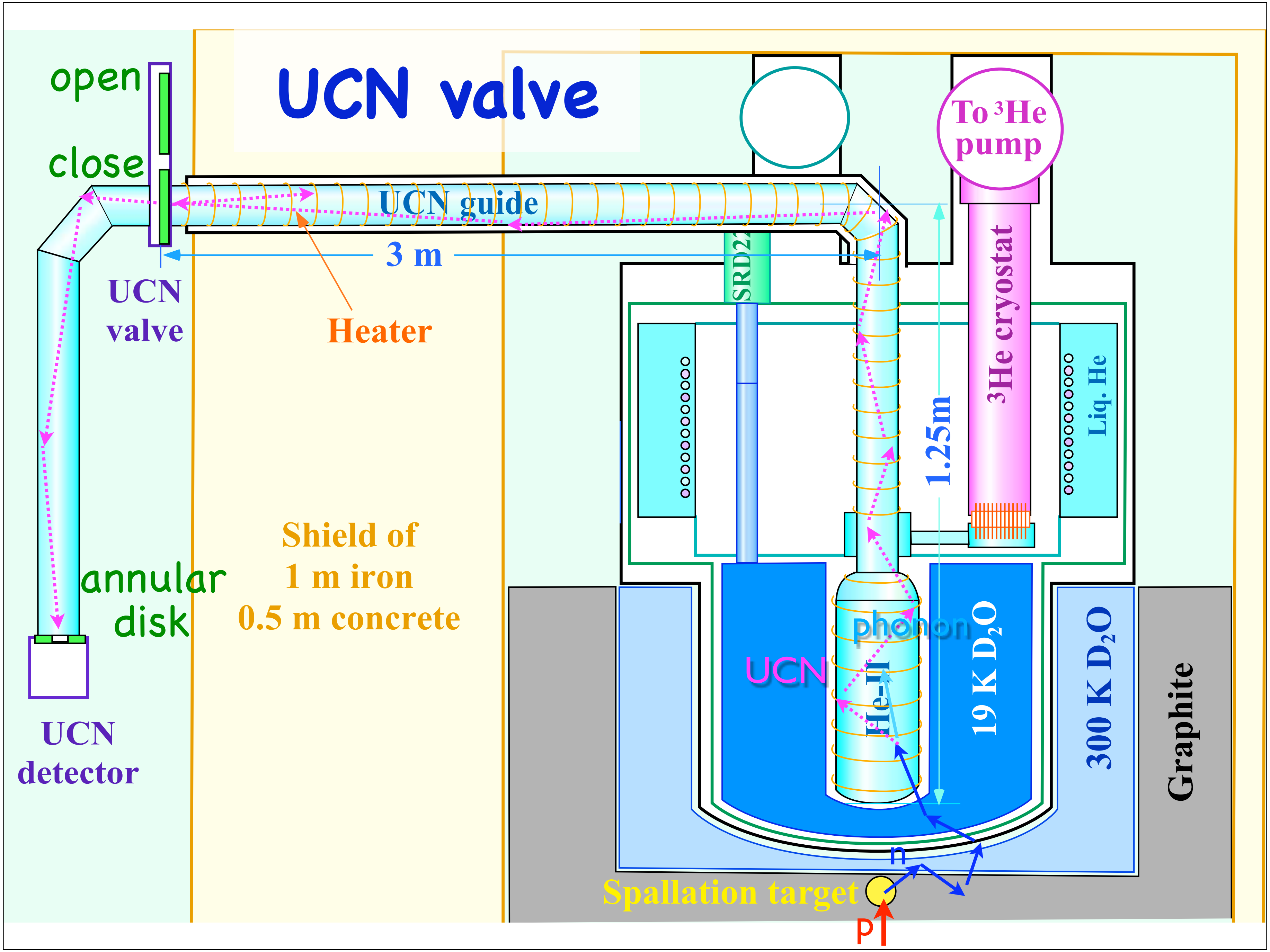
Going back and forth between the disk and He-II bottle

τ = 30 s at $T_{He\text{-}II}$ = 0.9K

UCN production with a proton pulse of 60 s

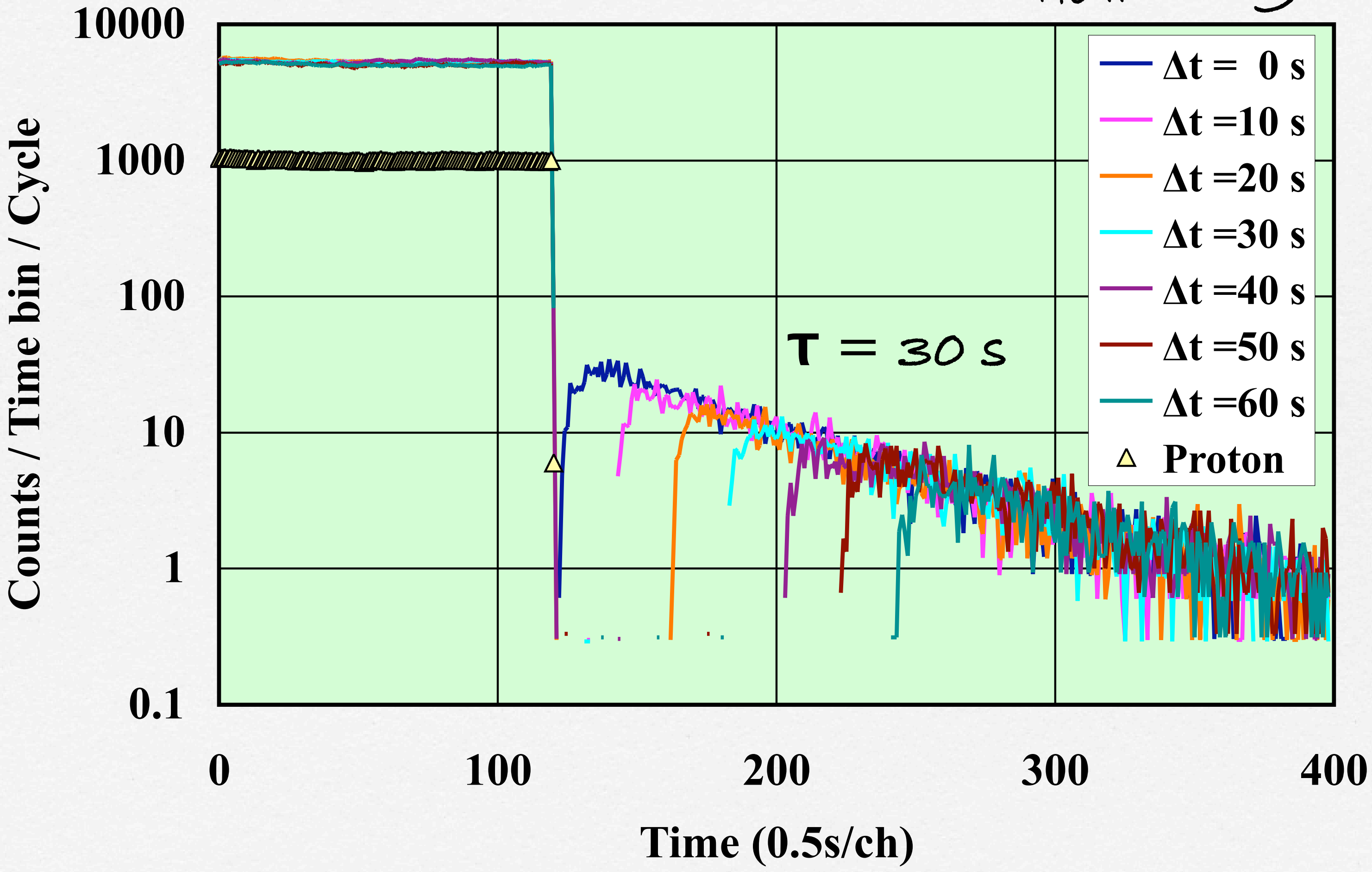


UCN valve

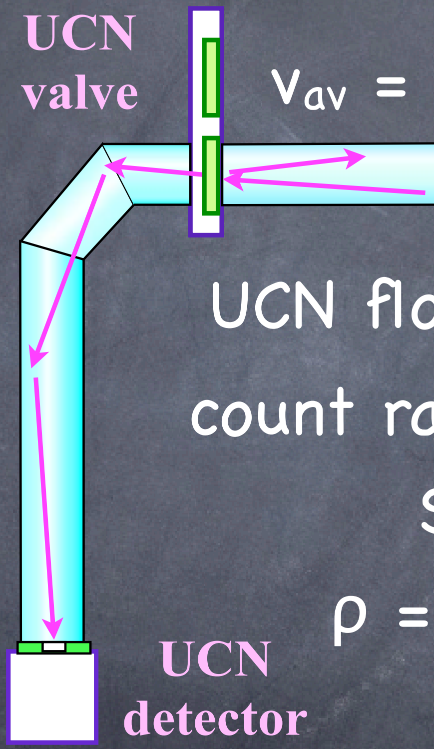

open
close
UCN valve
UCN guide
3 m
Heater
Shield of
1 m iron
0.5 m concrete
annular
disk
UCN
detector
SRD22
To ^{3}He
pump
3He cryostat
Liq. He
1.25m
phonon
UCN
He-II
19 K D_2O
300 K D_2O
Graphite
n
Spallation target
p

Effect of UCN valve

$T_{He-II} = 0.9K$



UCN density



v_{av} = 3.1 m/s at E_c = 90 neV

UCN flow rate = $1/4 \cdot \rho v_{av} S$

count rate = $1/4 \cdot \rho v_{av} S_d \cdot \epsilon$ = 409 counts/s

$S_d = 0.5^2 \pi$ cm^2, ϵ = 0.68

ρ = 10 UCN/cm^3 World's highest !

Grenoble

ρ = 2 to 3 UCN/cm^3 at E_c = 109 neV

World status

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours 100 W_{av} proton	0.9K He-II	E_c = 90 neV τ_s = 30 s	10 at experimental port
Grenoble 60MW reactor	Turbine	E_c = 335 neV	50 in source
SNS cold neutron beam	0.3K He-II		
Munich 20MW reactor	SD_2		
North Carolina 1 MW reactor	SD_2		
PSI 12 kW_{av} proton	SD_2		
Los Alamos 2.4 kW_{av} proton	SD_2		

World status

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours 100 W_{av} proton	0.9K He-II	E_c = 90 neV τ_s = 30 s	10 at experimental port
Grenoble 60MW reactor	Turbine	E_c = 90 neV	7 in source 2~3 in experiment
SNS cold neutron beam	0.3K He-II		
Munich 20MW reactor	SD_2		
North Carolina 1 MW reactor	SD_2		
PSI 12 kW_{av} proton	SD_2		
Los Alamos 2.4 kW_{av} proton	SD_2		

World comparison

	Source type	E_c and τ_s	UCN density ρ_{UCN}(UCN/cm^3)
Ours 100 W_{av} proton	0.9K He-II	E_c = 90 neV τ_s = 30 s	10 at experiment port
Grenoble 60MW reactor	0.5K He-II	E_c = 250 neV τ_s = 150 s	1000 in He-II
SNS cold neutron beam	0.3K He-II	E_c = 134 neV τ_s = 500 s	430 in He-II
Munich 20MW reactor	SD_2	E_c = 250 neV	10^4 in source
North Carolina 1 MW reactor	SD_2	E_c = 335 neV	1300 in source
PSI 12 kW_{av} proton	SD_2	E_c = 250 neV τ_s = 888 s	2000 in source
Los Alamos 2.4 kW_{av} proton	SD_2	E_c = 250 neV τ_s = 2.6 s	120 in source

World comparison

	Source type	E_c and τ_s	UCN density $\rho_{UCN}(\mathrm{UCN/cm^3})$
Ours 100 W_{av} proton	0.9K He-II	E_c = 90 neV τ_s = 30 s	10 at experimental port
Grenoble 60MW reactor	0.5K He-II	E_c = 90 neV τ_s = 150 s	216 in He-II
SNS cold neutron beam	0.3K He-II	E_c = 90 neV τ_s = 150 s	71 in He-II
Munich 20MW reactor	SD_2	E_c = 90 neV	2160 in source
North Carolina 1 MW reactor	SD_2	E_c = 90 neV	181 in source
PSI 12 kW_{av} proton	SD_2	E_c = 90 neV τ_s = 888 s	432 in source
Los Alamos 2.4 kW_{av} proton	SD_2	E_c = 90 neV τ_s = 2.6 s	26 in source

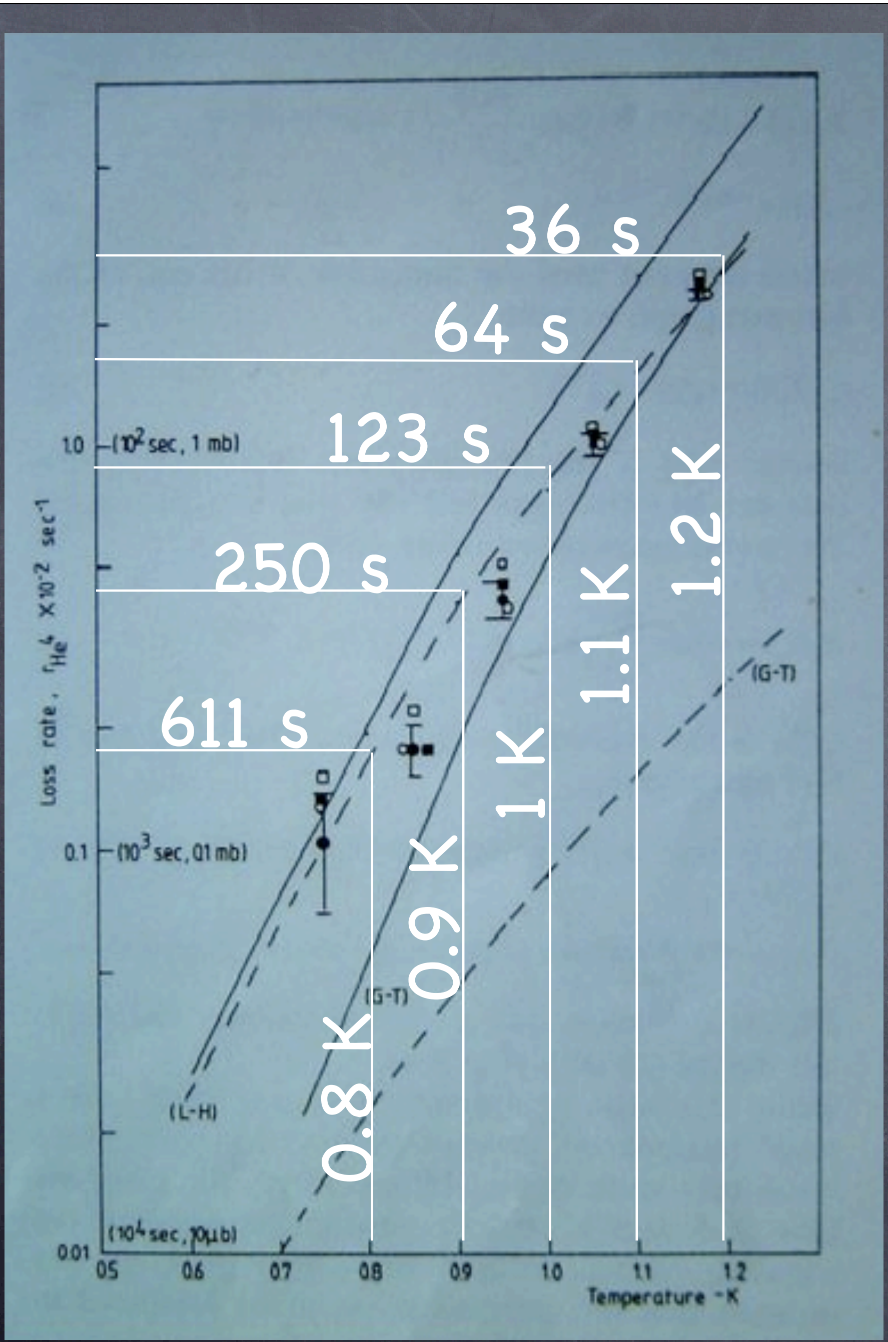
Possibility at TRIUMF

Increase UCN density

$$\rho = \int_0^{E_c} \sigma_{coh}(E_{in} \rightarrow E)\, N_{He}\, \Phi_n\, \tau_s\, dE$$

Increase
cold neutron flux, Φ_n
storage time, τ_s
momentum space, $E_c^{3/2}$

UCN transport efficiency



τ_s improvement

Increase storage time: x5

$T_{He\text{-}II}$ 0.9 → 0.8 K

phonon upscattering

^{3}He impurity → $< 1\text{x}10^{-10}$

$\tau_{3He} > 389$ s

Clean-up UCN bottle

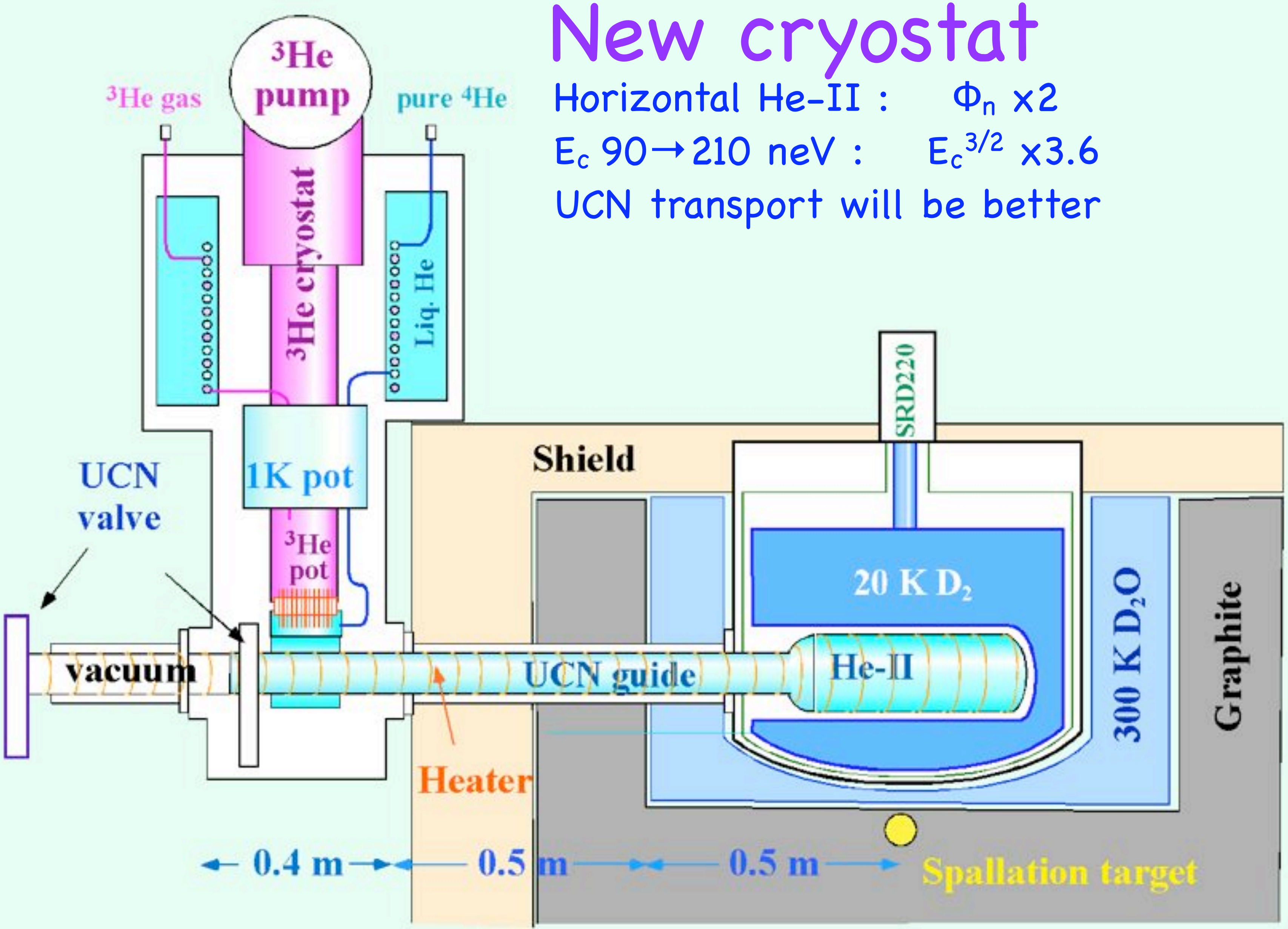
decrease diffusion loss: x2

New cryostat

Horizontal He-II : Φ_n x2

E_c 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better



New cryostat

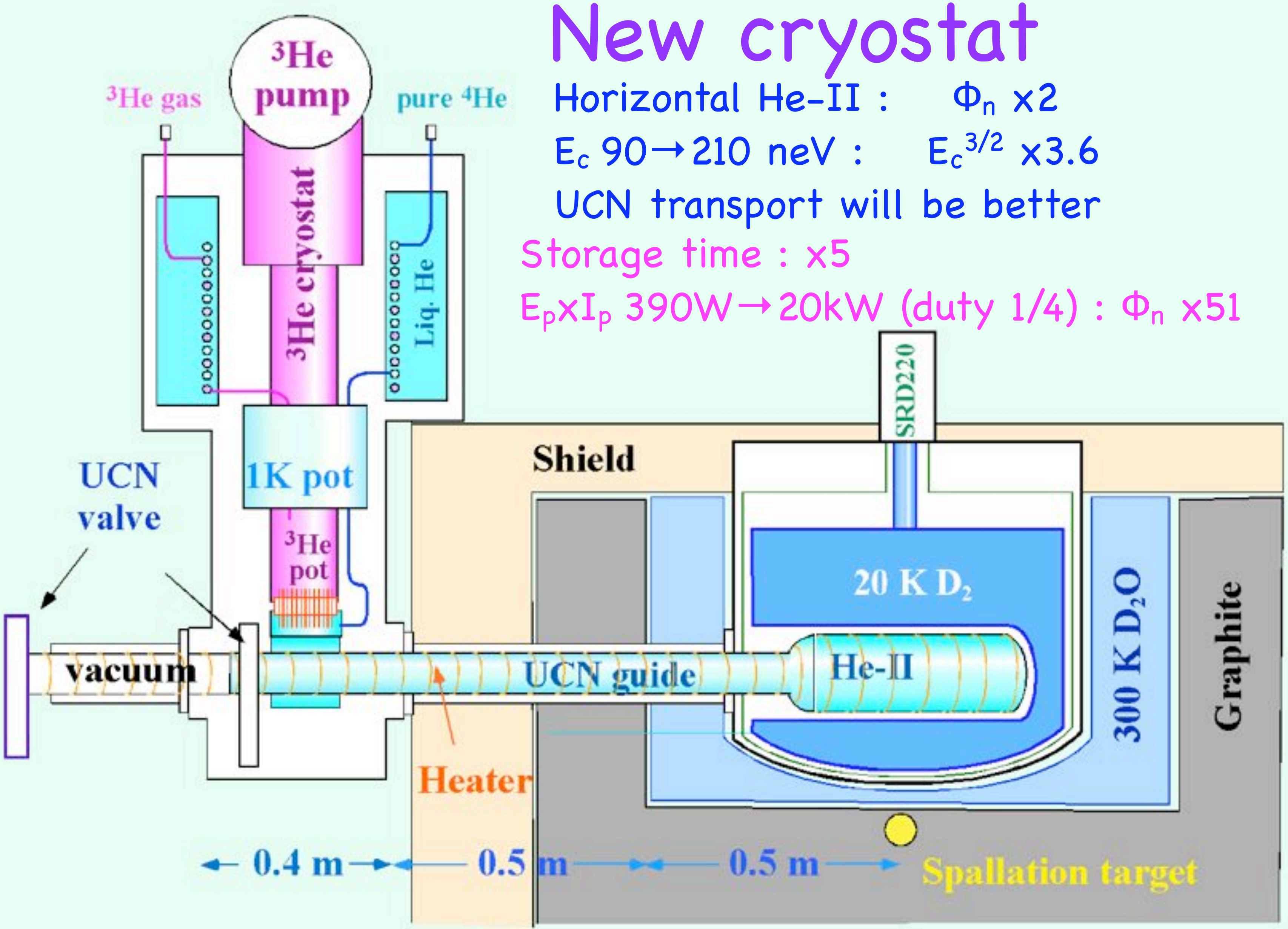
Horizontal He-II : Φ_n x2

E_c 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better

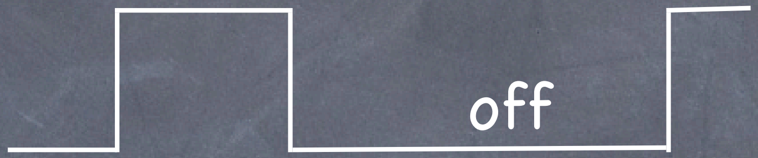
Storage time : x5

$E_p \times I_p$ 390W→20kW (duty 1/4) : Φ_n x51



UCN density

p beam of 500MeV 40μA on, duty 1/4



$5 \times \ 2 \times 3.6 \ \times 51 \times \ 10 = 1.8 \times 10^4$ UCN/cm^3

τ_s horizontal

Additional factor :

small loss at diffusion, x2 ?

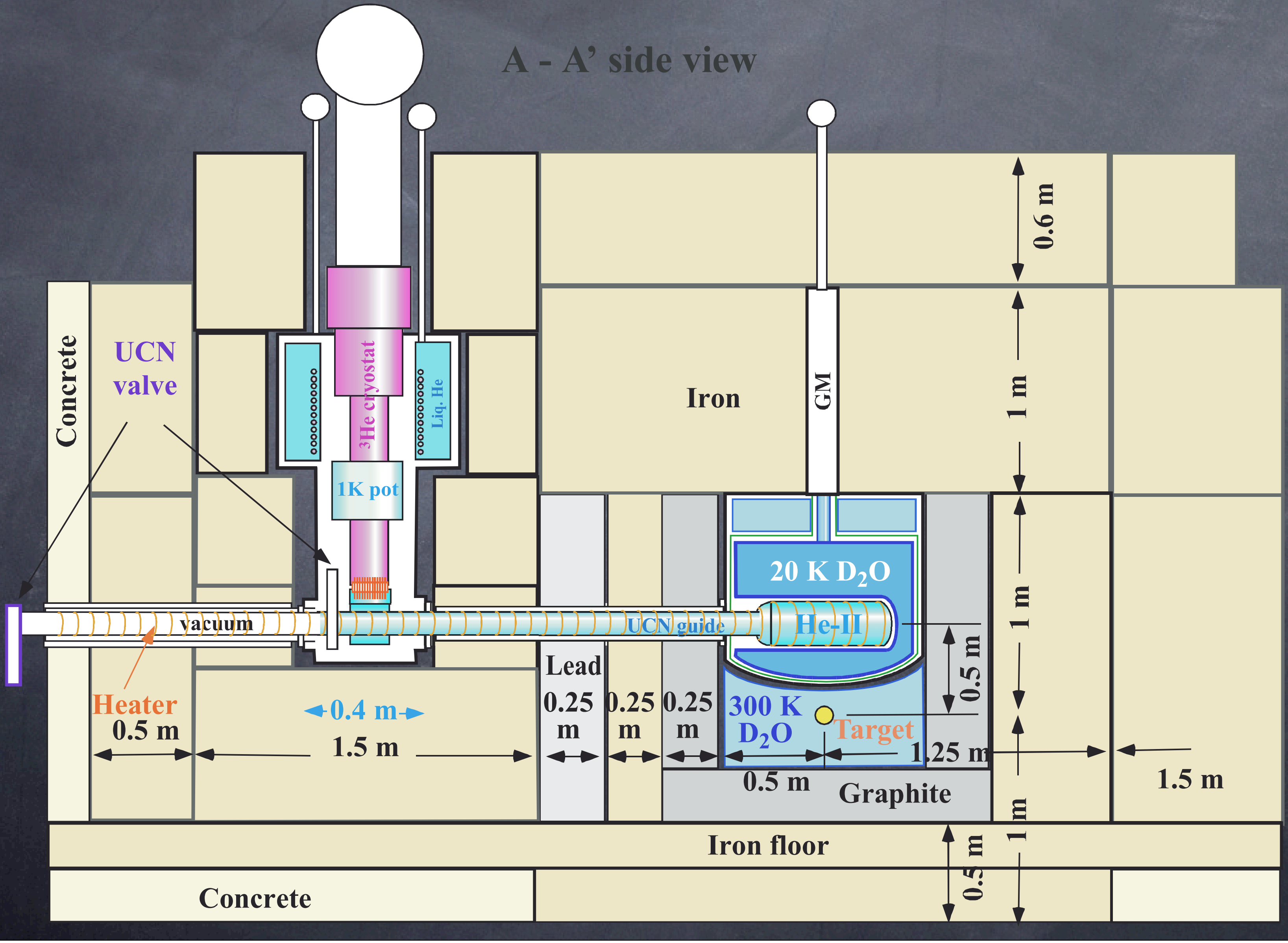
efficient UCN transfer, x2 ?

transmission through window, x0.7 ?

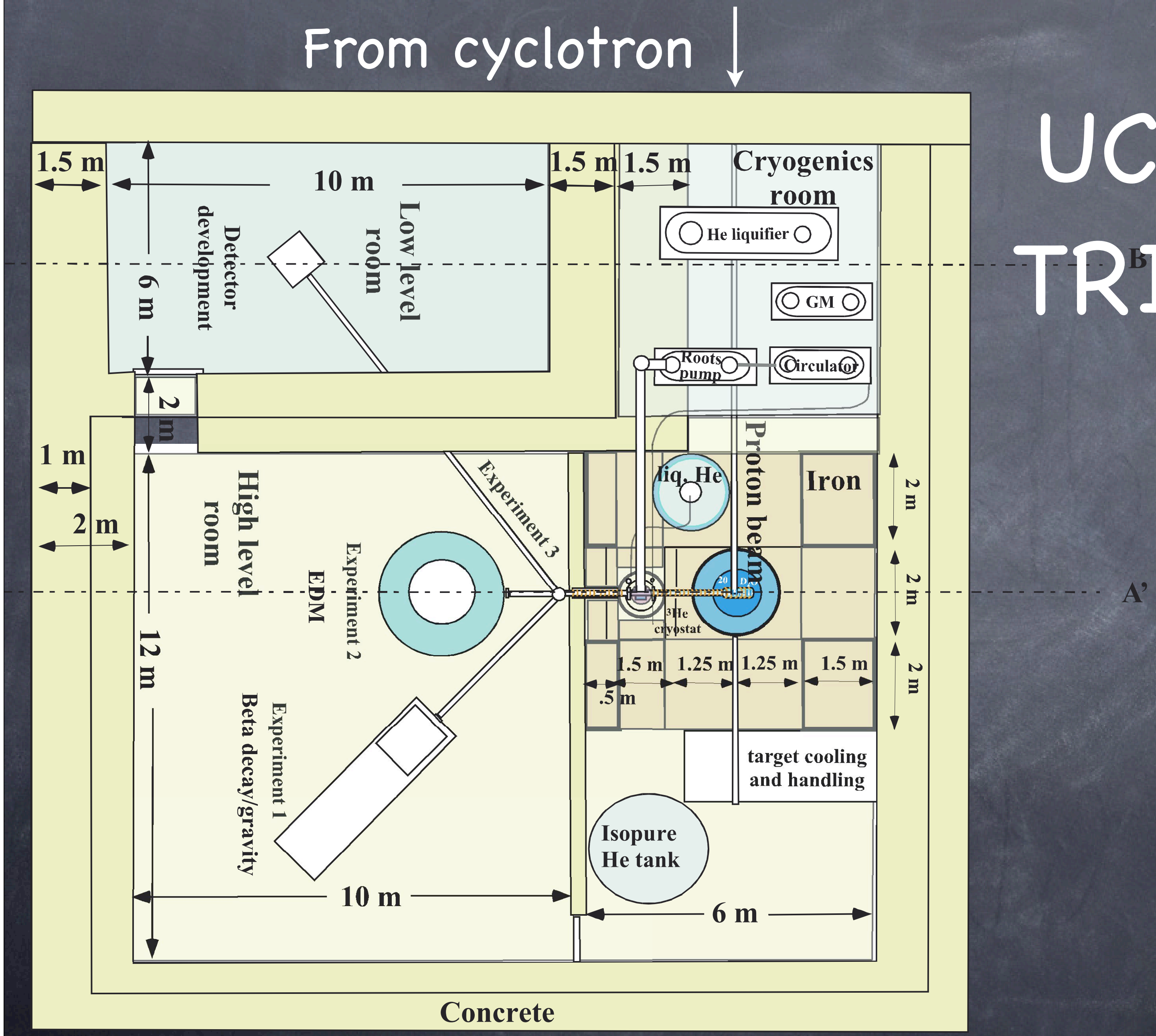
2nd step

50 kW$_{peak}$: x2.5, $D_2O \rightarrow D_2$: x8

Radiation shield for 20/4 = 5 kW



UCN at TRIUMF ?



World comparison

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TRIUMF 5 kW$_{av}$ proton	0.8K He-II	E_c = 210 neV τ_s = 150 s	1.8 x 10^4 at experimental port
Grenoble 60MW reactor	0.5K He-II	E_c = 250 neV τ_s = 150 s	1000 in He-II
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Thanks