核変換技術の展開 – 医用RI製造と核廃棄物処分
大阪大学核物理研究センター4階講義室
2011年12月2日（金）～3日（土）

核破砕中性子科学の新しい展開

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RCNP, Osaka University

内容

- Fast neutron source
- Spallation neutron の利用

  （物質科学）

  超冷中性子

$^{2}H + {}^{3}H \longrightarrow {}^{4}He + n$ (14.3 MeV)

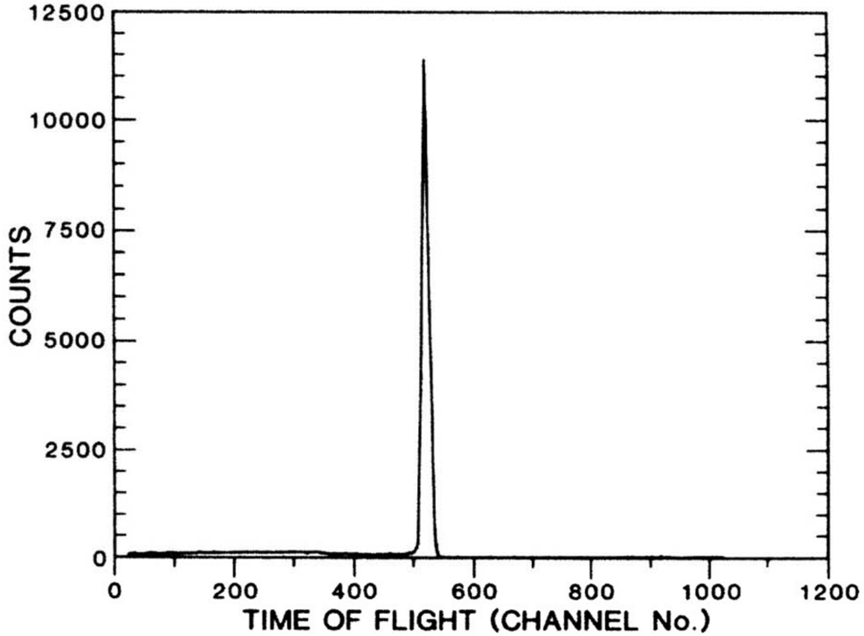


FIG. 3. Time-of-flight spectrum (pulse-shape gated) in the neutron detector for the $^{3}H(d,n)$ reaction. The peak at about channel 520 is due to 14 MeV neutrons.

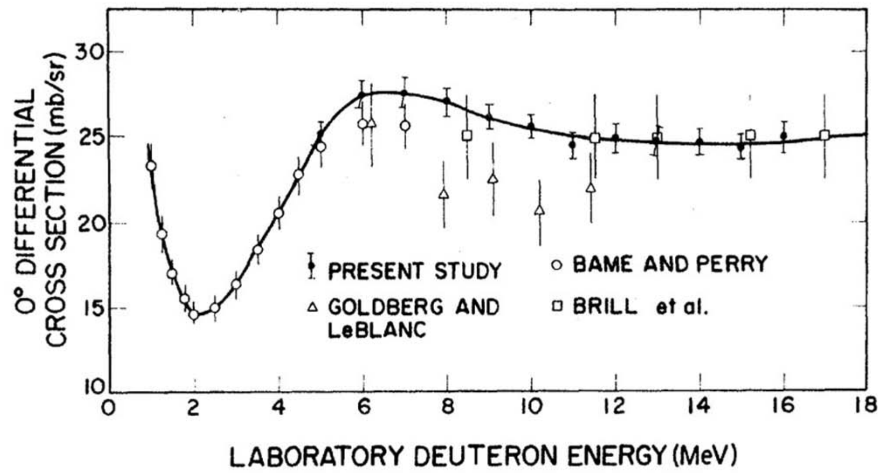
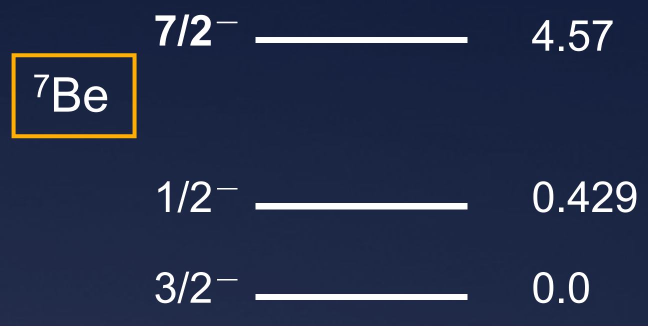


FIG. 7. The $T(d,n)^{4}He$ differential cross section at 0° plotted as a function of lab deuteron energy. The solid curve was drawn as a guide to the eye to indicate the trend of the data.

P + ^{7}Li —> ^{7}Be* + n



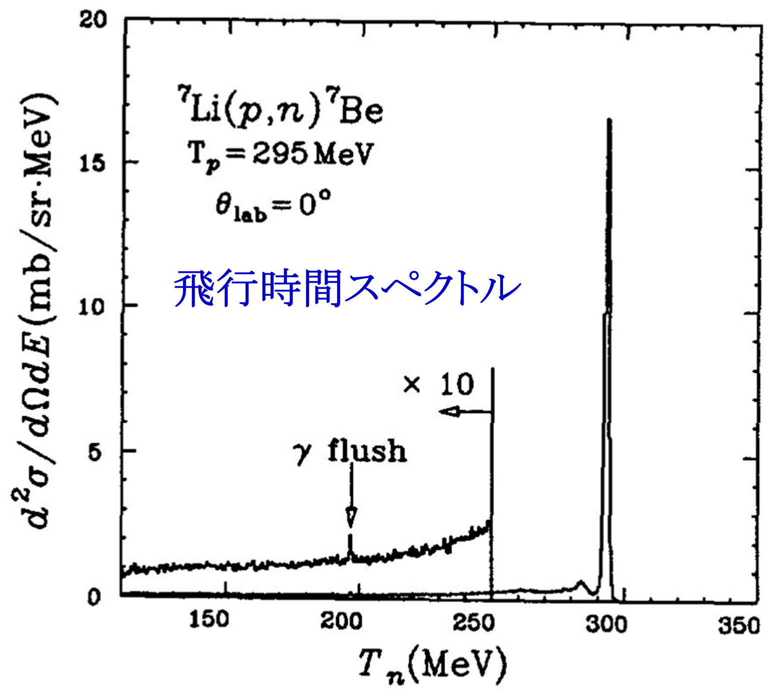


Fig. 11. Neutron energy spectrum for the ^{7}Li(p, n)^{7}Be reaction at 295 MeV and 0°. See text for detail.

H. Sakai et al.,

Nucl. Instr. Meth. A 369 (1996) 120-134

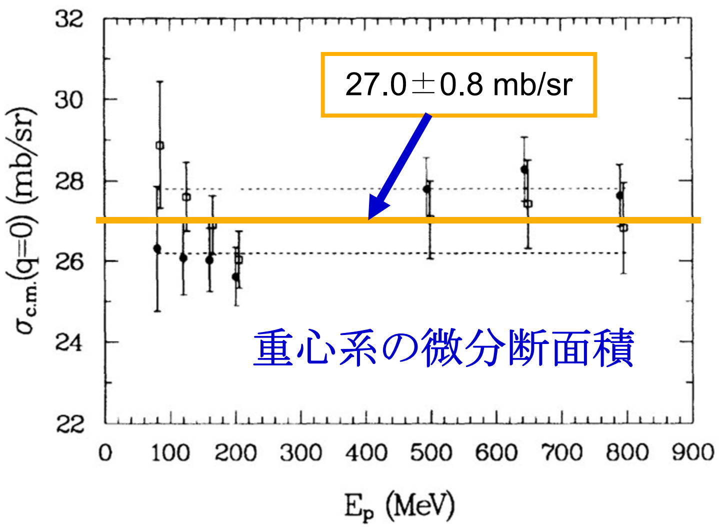


FIG. 8. Zero-momentum-transfer cross sections (c.m.) obtained from Gaussian fits to the experimental cross-section distributions. The solid circles correspond to normalization based upon a constant value for I_q [Eq. (5)]. The open squares correspond to normalization based upon the parametrization of Eq. (1). The dotted line corresponds to a constant c.m. cross section σ_0=27.0±0.8 mb/sr. The dashed lines represent the one standard deviation limits.

T.N. Taddeucci et al.,

Phys. Rev. C 41 (1990) 2548-2555

$d + A \longrightarrow X + p + n$

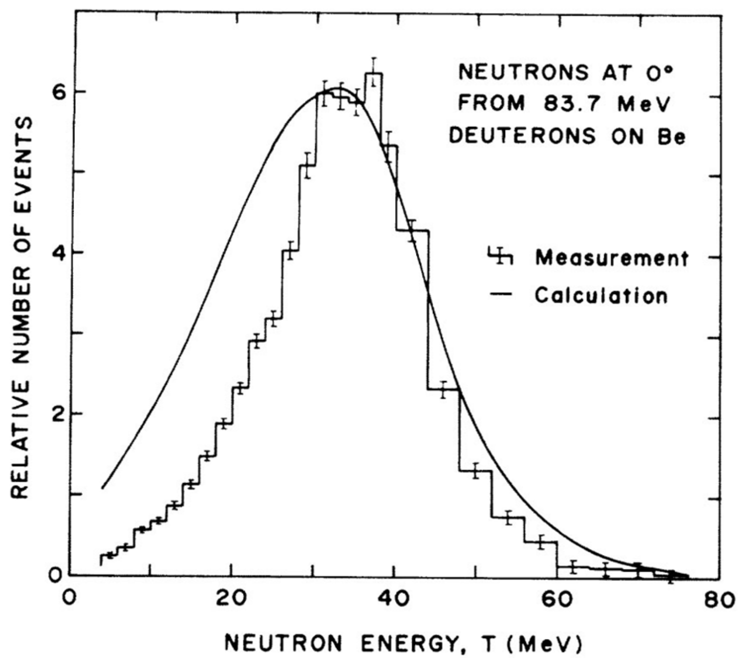


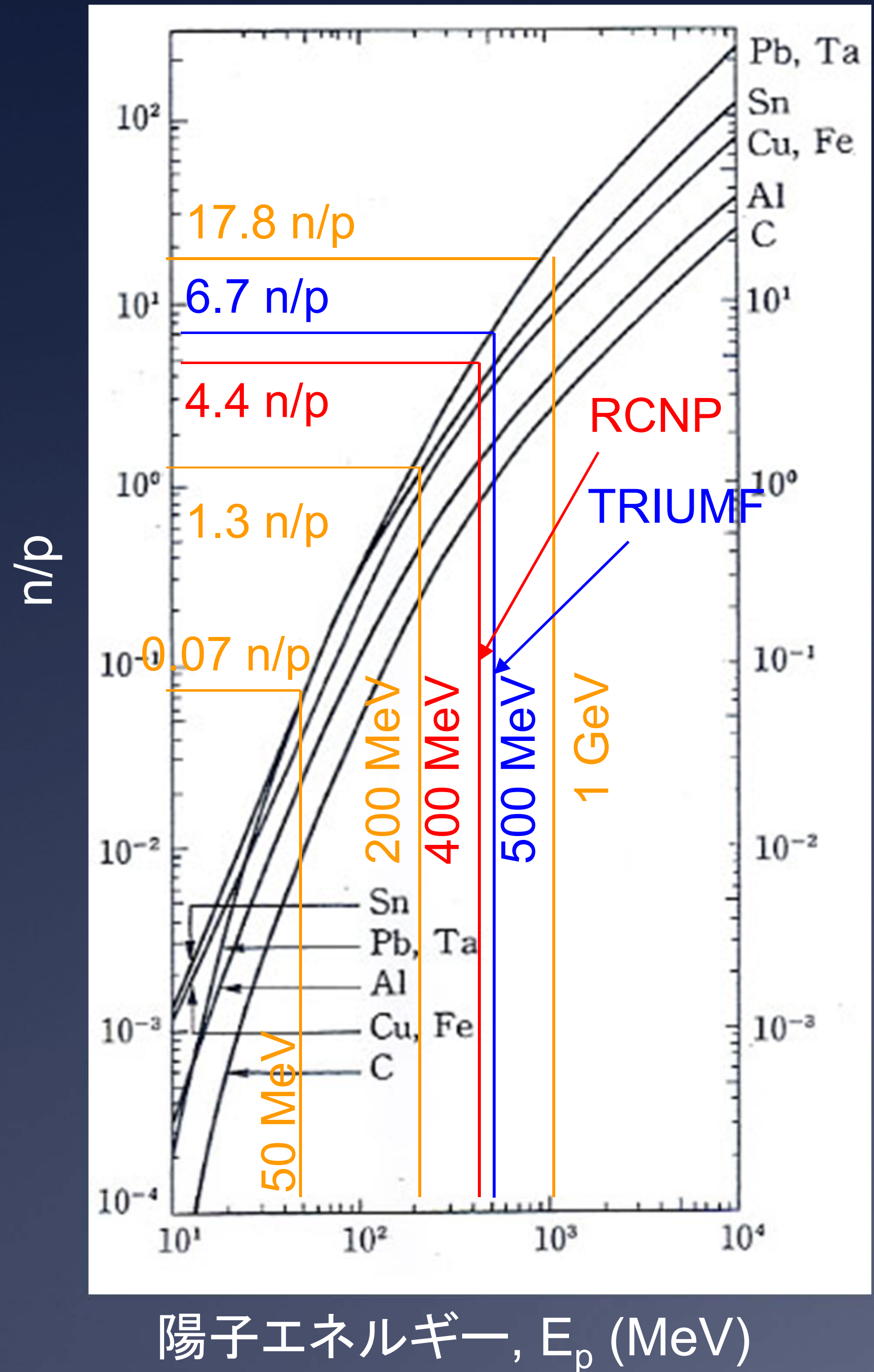
FIG. 3. The measured energy spectrum of neutrons emitted at 0° from 83.7 MeV deuteron bombardment of a 2.2 cm thick beryllium target and that calculated from the Serber (Ref. 11) model for deuteron stripping.

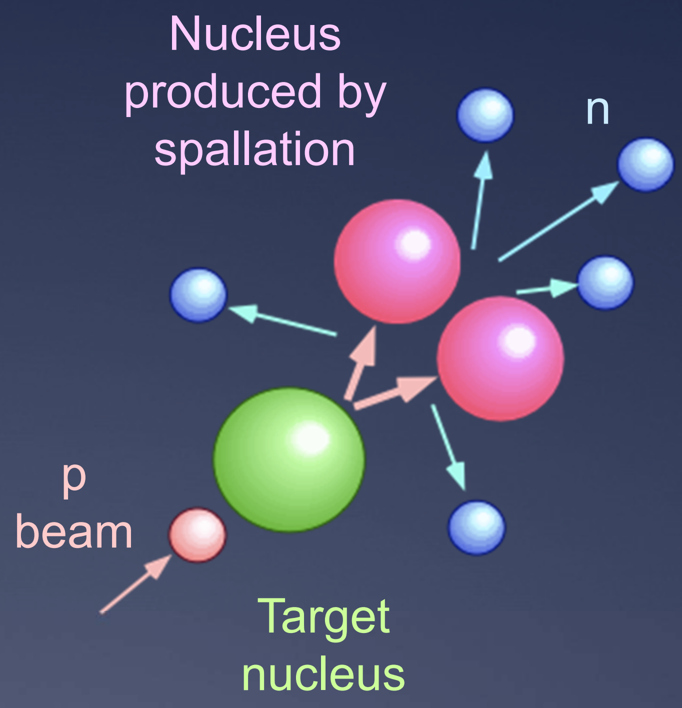
重い標的原子核による重陽子分解反応

1. 中心エネルギーは入射重陽子エネルギーの約半分
2. 収量が比較的多い

R. Madey et al.,
Phys. Rev. C 14 (1976) 801-806

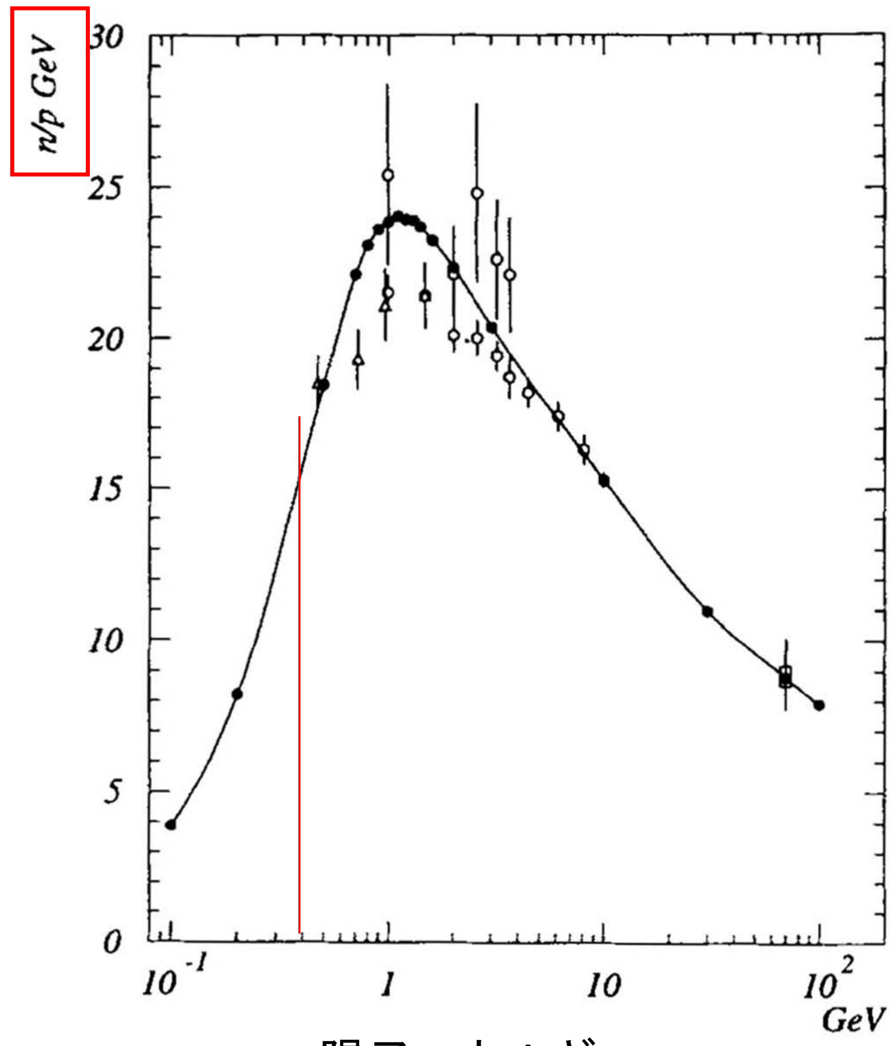
核破砕中性子の生成





K. Tesch (1985)

中性子生成のエネルギー価

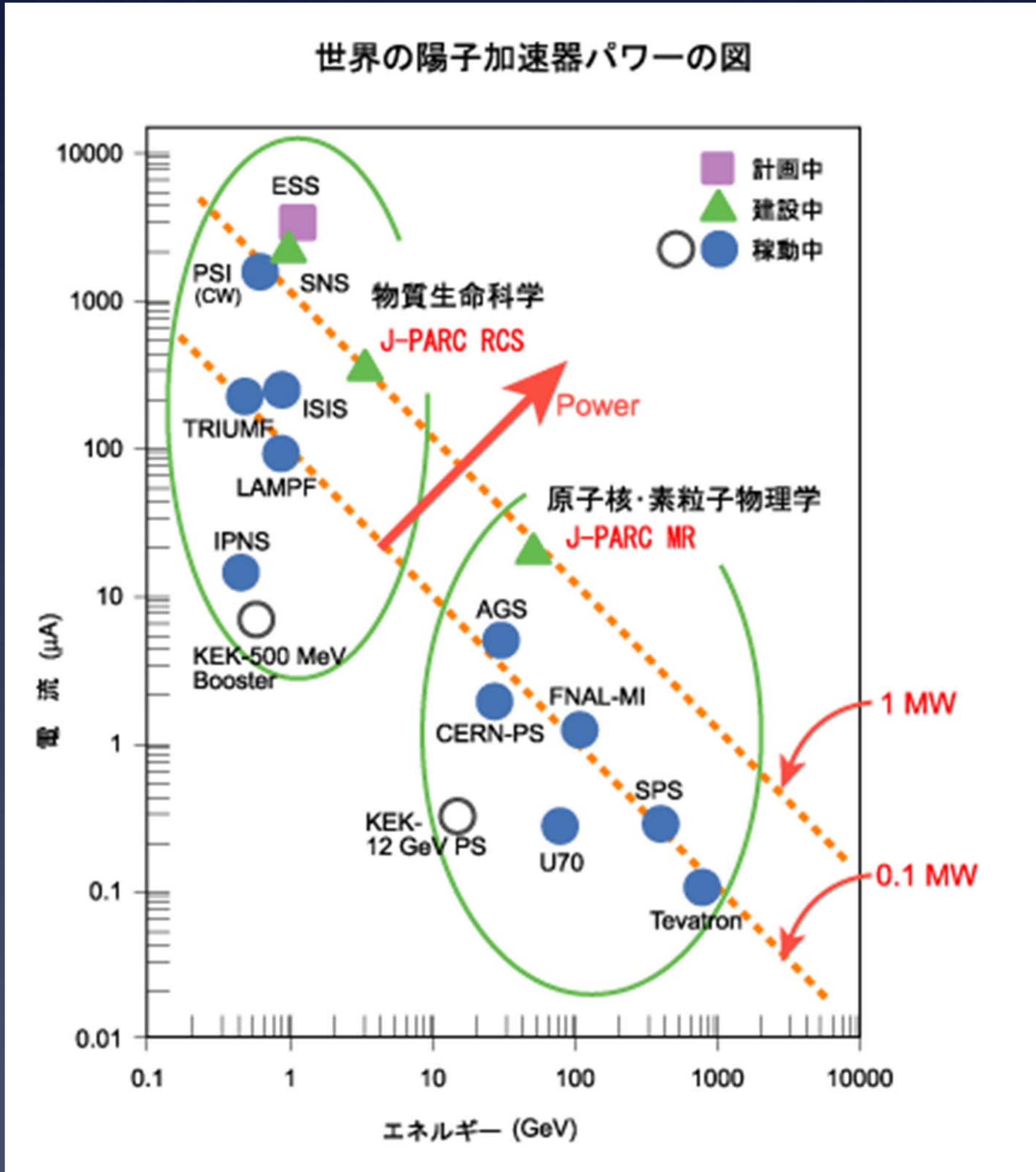


Yield of neutrons with energies below 10.5 MeV from the whole surface of the cylindric lead target (ϕ = 20 cm, L = 60 cm) in dependence on the incident proton energy: ● – our calculations, the curve is drawn through the points to guide an eye; △ – experimental data of Tunnicliffe et al. (extracted from the review of Barashenkov [1]); ○ – experimental data [2]; □ – experimental data [3], recounted from tungsten to lead (see text).

A.V. Dementyev et al., NIMA374 (1996) 70-72

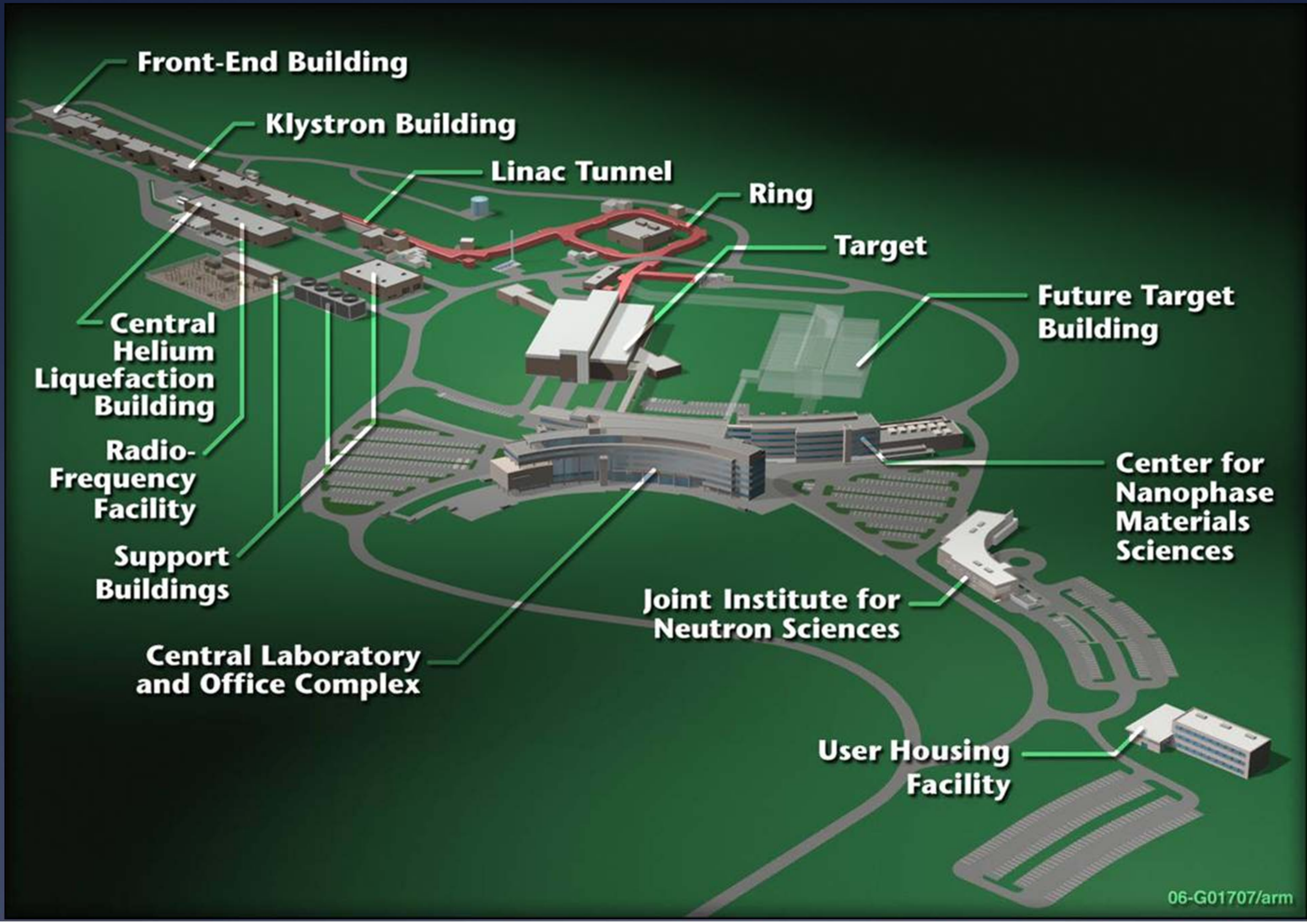
High power proton accelerators

Institute	Main Accelerator	Ep (MeV)	Power (MW) Design (Upgrade)
TRIUMF	Cyclotron	500	0.02
PSI	Cyclotron	590	1.30 (2.00)
LAMPF	Linac	800	0.80
ISIS	Synchrotron	800	0.80
J-PARC	Synchrotron	3,000	1.00
SNS	Linac	1,000	1.00 (2.00)
ESS	Linac	2,500	5.00
CSNS	Synchrotron	1,600	0.10 (0.50)



世界の陽子加速器パワーの図
計画中
建設中
稼動中
ESS
PSI
(CW)
SNS
物質生命科学
J-PARC RCS
ISIS
TRIUMF
LAMPF
Power
IPNS
KEK-500 MeV
Booster
原子核・素粒子物理学
J-PARC MR
AGS
FNAL-MI
CERN-PS
SPS
KEK-
12 GeV PS
U70
Tevatron
1 MW
0.1 MW
電流 (μA)
エネルギー (GeV)
10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000

Spallation Neutron Source, ORNL



Spallation Neutron Source (SNS)

Neutron yield and power

- Accelerator

  Energy ~ a few to a few 10s MeV

  Number of thermal neutrons after moderation

  20 ~ 30 / a 1GeV proton

  → one thermal neutrons / 30 ~ 50 MeV

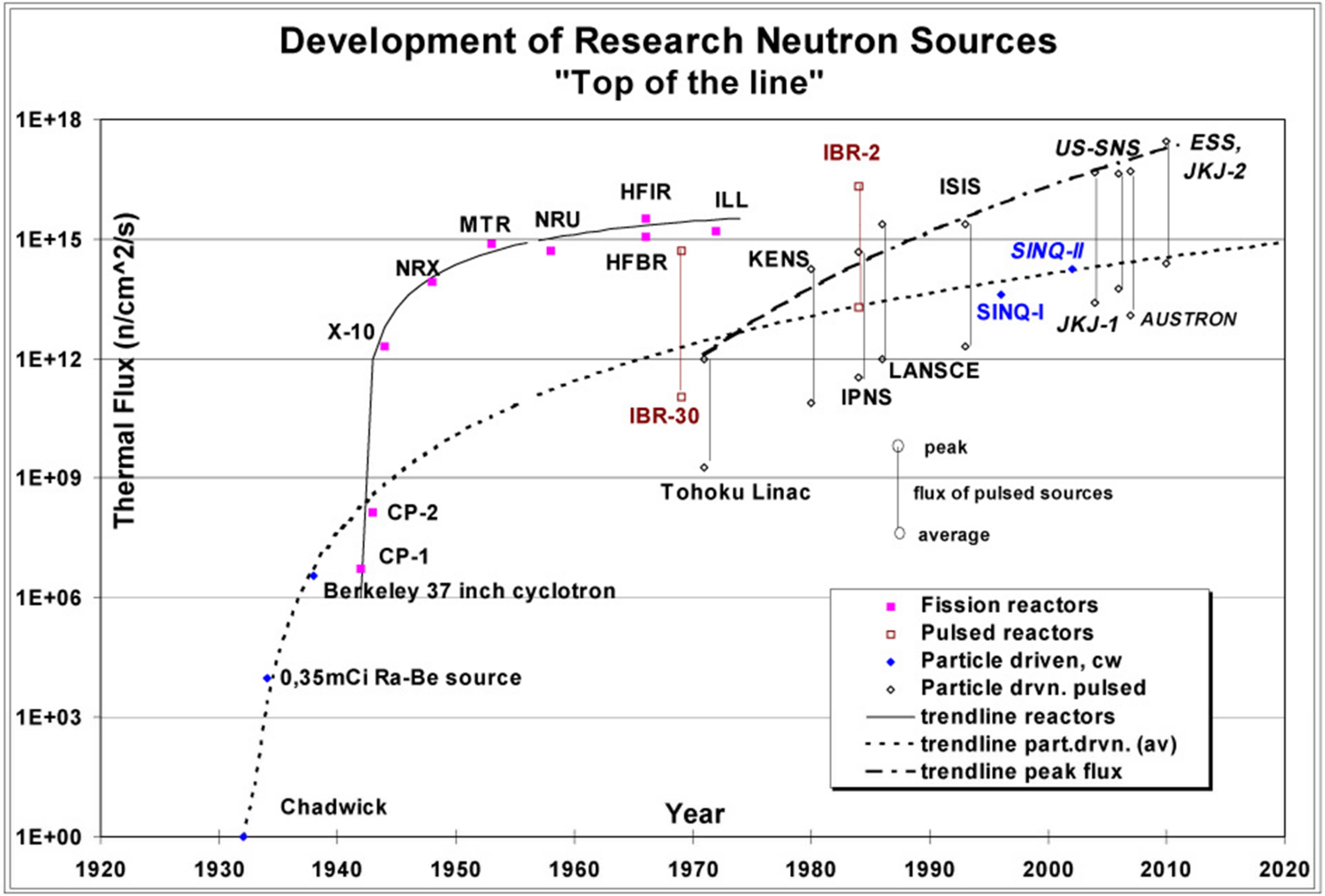
- Reactor

  Energy ~ several MeV

  Number of thermal neutrons after moderation

  ~ 1 / 270 MeV worth fission energy

Equivalent flux / power : A/R = 6 ~ 9



Development of Research Neutron Sources
"Top of the line"
Thermal Flux (n/cm^2/s)
1E+18
1E+15
1E+12
1E+09
1E+06
1E+03
1E+00
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
Chadwick
0,35mCi Ra-Be source
Berkeley 37 inch cyclotron
CP-1
CP-2
X-10
NRX
MTR
NRU
HFIR
HFBR
ILL
IBR-30
IBR-2
Tohoku Linac
KENS
IPNS
LANSCE
ISIS
SINQ-I
SINQ-II
US-SNS
JKJ-1
AUSTRON
ESS,
JKJ-2
peak
flux of pulsed sources
average
Fission reactors
Pulsed reactors
Particle driven, cw
Particle drvn. pulsed
trendline reactors
trendline part.drvn. (av)
trendline peak flux

超冷中性子の応用

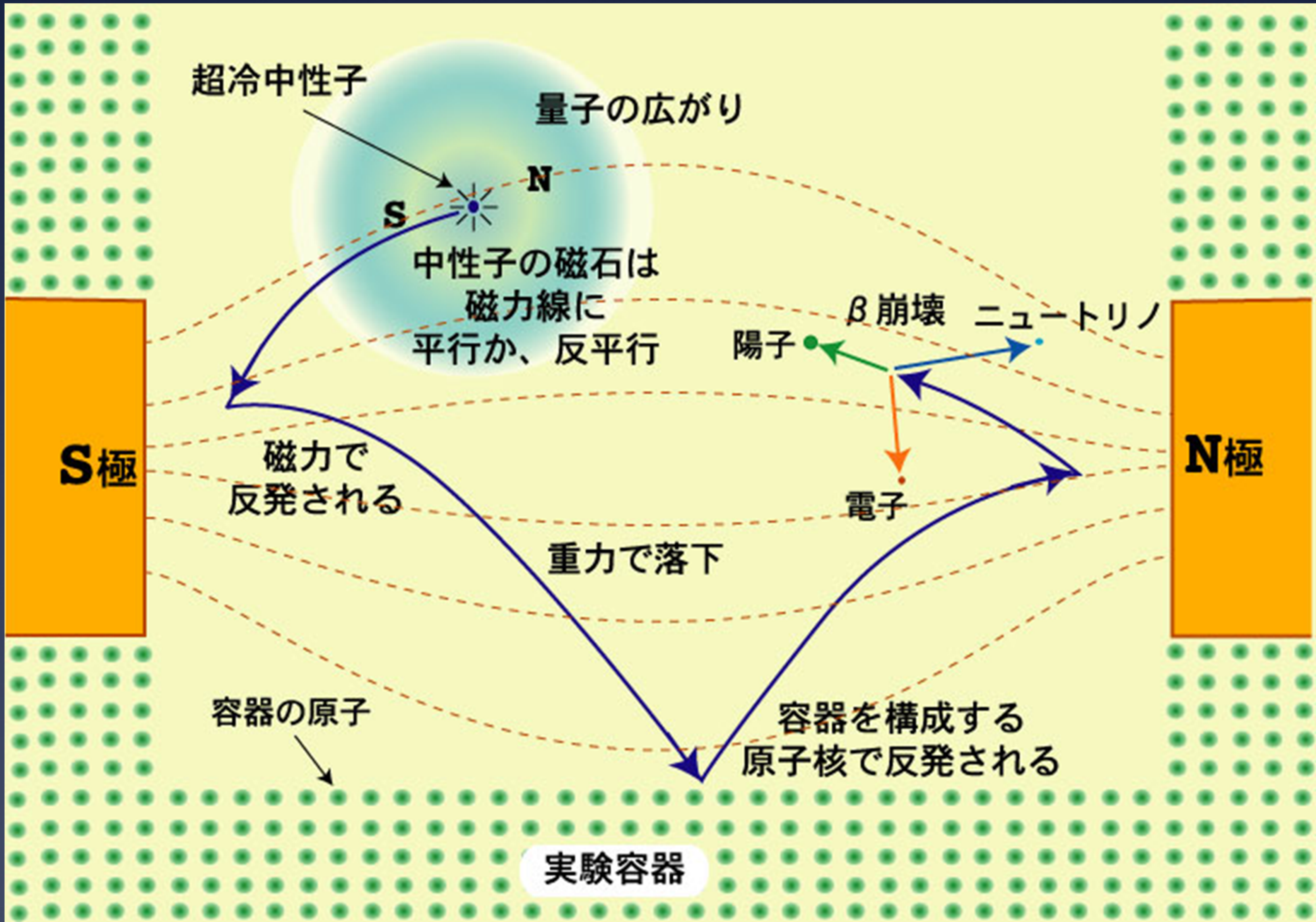
ビッグバン後における中性子による元素合成

空間反転実験による素粒子の標準理論の検証

物質の表面状態の研究

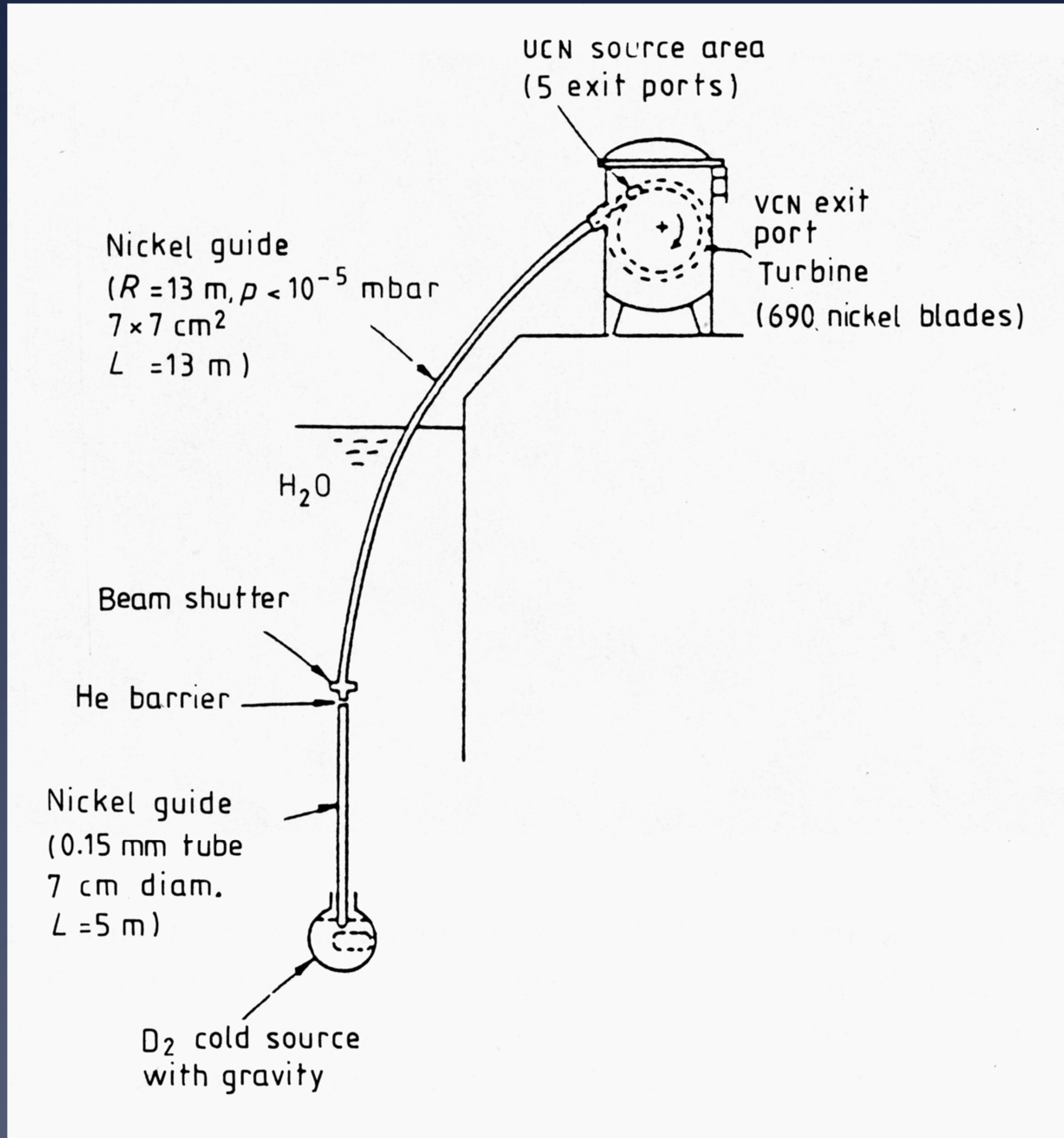
重力の研究

超冷中性子のふるまい


超冷中性子
量子の広がり
N
S
中性子の磁石は
磁力線に
平行か、反平行
β崩壊
ニュートリノ
陽子
S極
N極
磁力で
反発される
電子
重力で落下
容器の原子
容器を構成する
原子核で反発される
実験容器

UCN at ILL (Grenoble)

Gravity &
Turbine



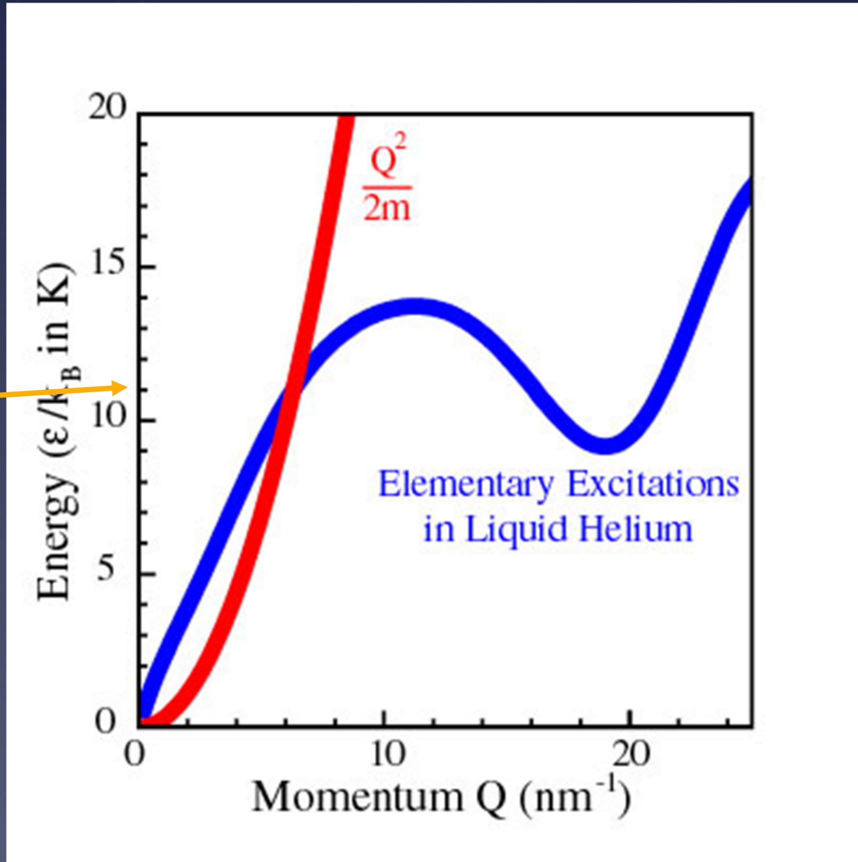
Higher Density UCN Sources

Use non-equilibrium system

1. Superfluid ^4He

   (T<1K)

   11K incident n produces roton becomes UCN



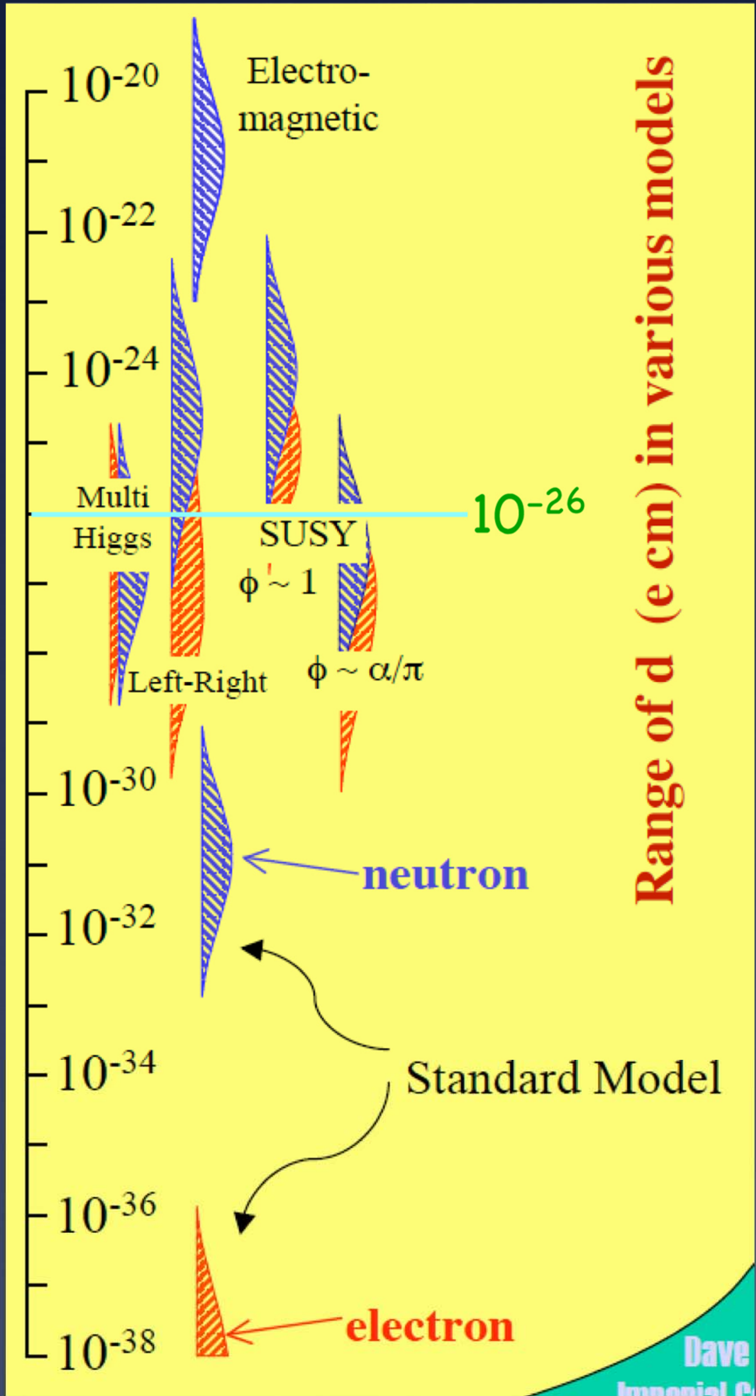
2. Solid deuterium (SD2)

   Thermal excitations due to phonons (massless)

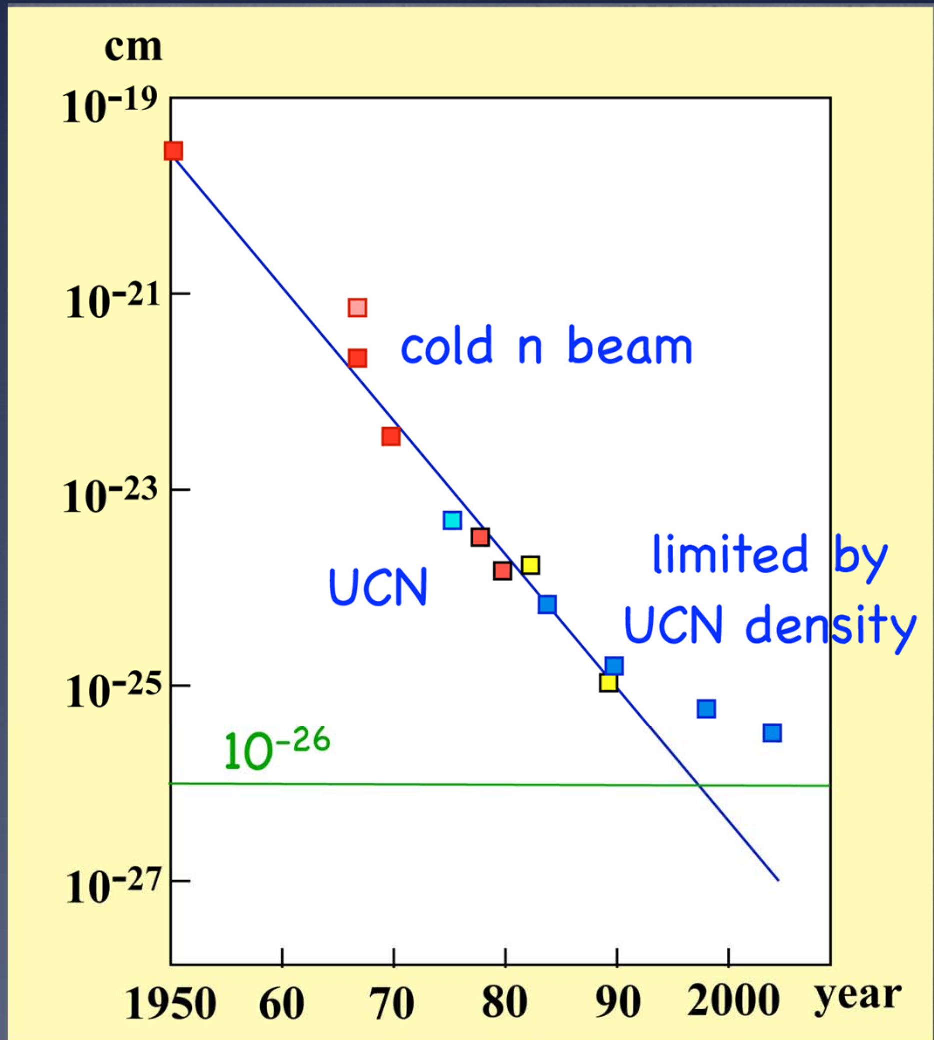
   Cooling: phonon production

EDM history

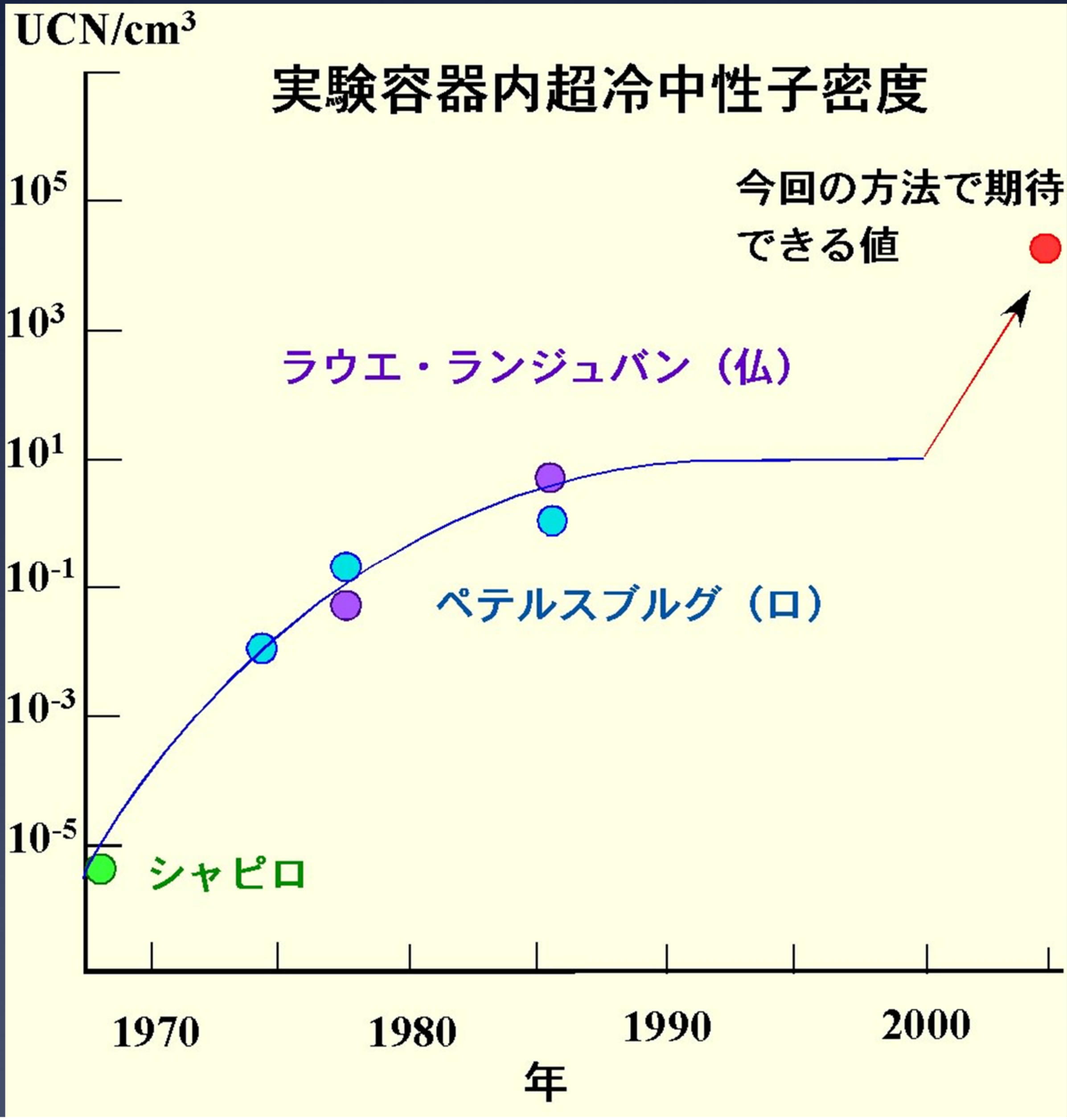
Theory



Experiment

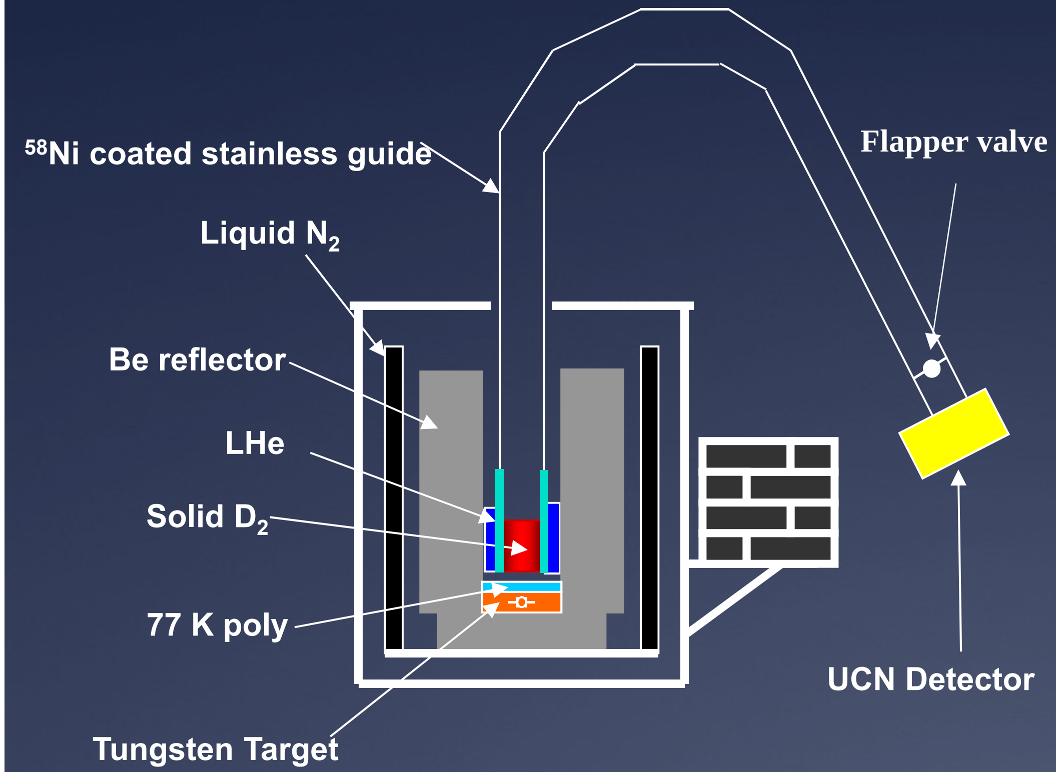


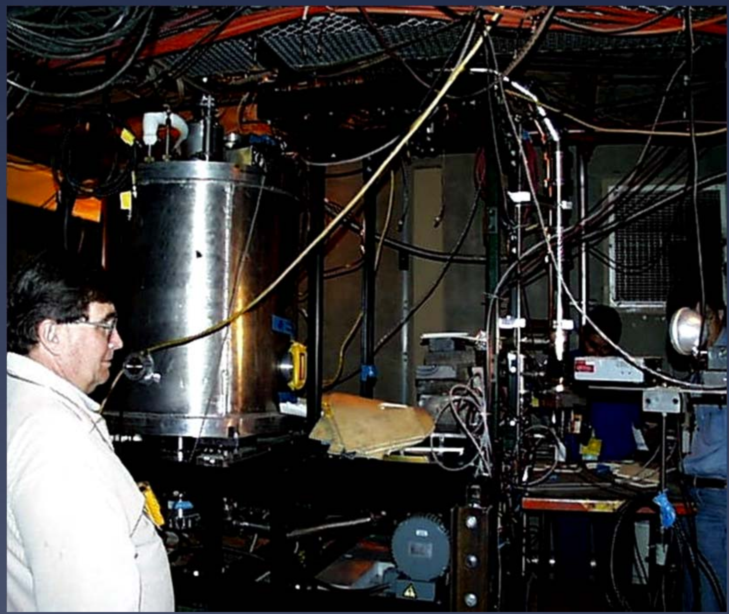
超冷中性子発生の歴史


UCN/cm³
実験容器内超冷中性子密度
10⁵
10³
10¹
10-1
10-3
10-5
今回の方法で期待
できる値
ラウエ・ランジュバン（仏）
ペテルスブルグ（ロ）
シャピロ
1970
1980
1990
2000
年

Los Alamos Neutron Science Center
LANSCE

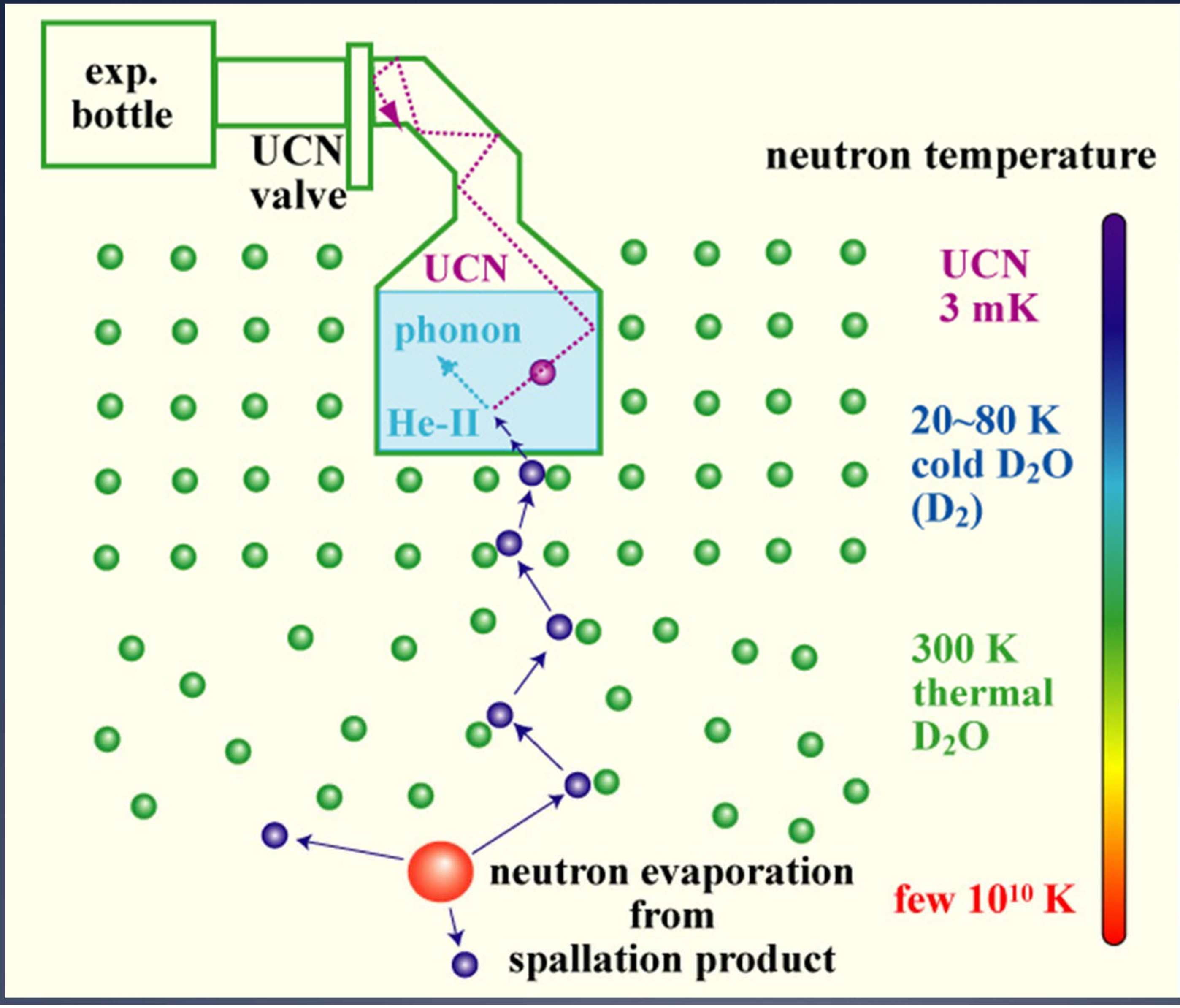
Schematic of prototype SD_2 source



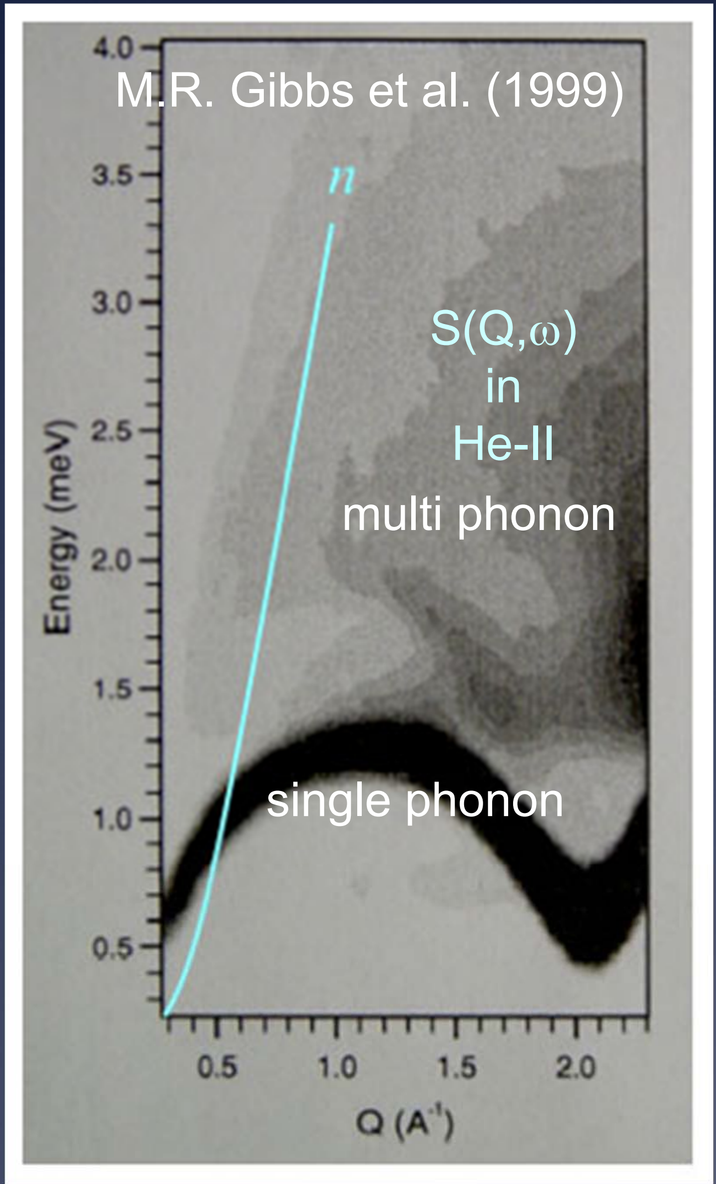


(LANL/Caltech/ILL/Kyoto/Princeton/VaTech/NCState collaboration)

UCN production by He-II



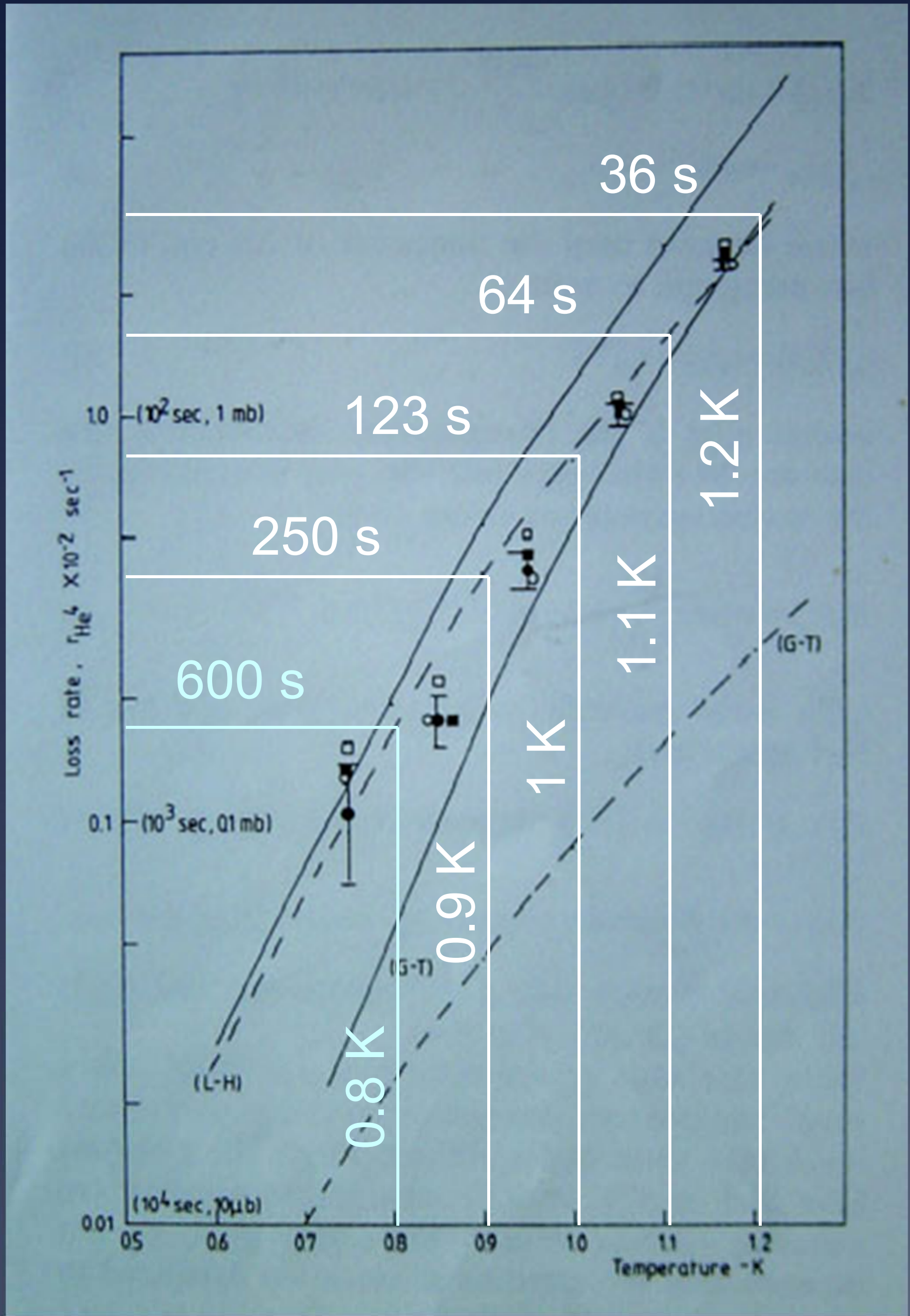
UCN production rate P_{UCN}



In our He-II
$P_{UCN} = (2 - 4) \times 10^{-9}\ \Phi_n/cm^3/s$,
$= 0.37 - 0.73 \times 10^4$ UCN/cm^3/s
Phys. Lett. A 301(2002)462
20 kW p

In Los Alamos sD_2
$P_{UCN} = 4.4 \times 10^4$ UCN/cm^3/s
Phys. Lett. B 593(2004)55
76 kW

In PSI sD_2
$P_{UCN} = 2.9 \times 10^5$ UCN/cm^3/s
Phys. Rev. C 71(2005)054601
1.2 MW



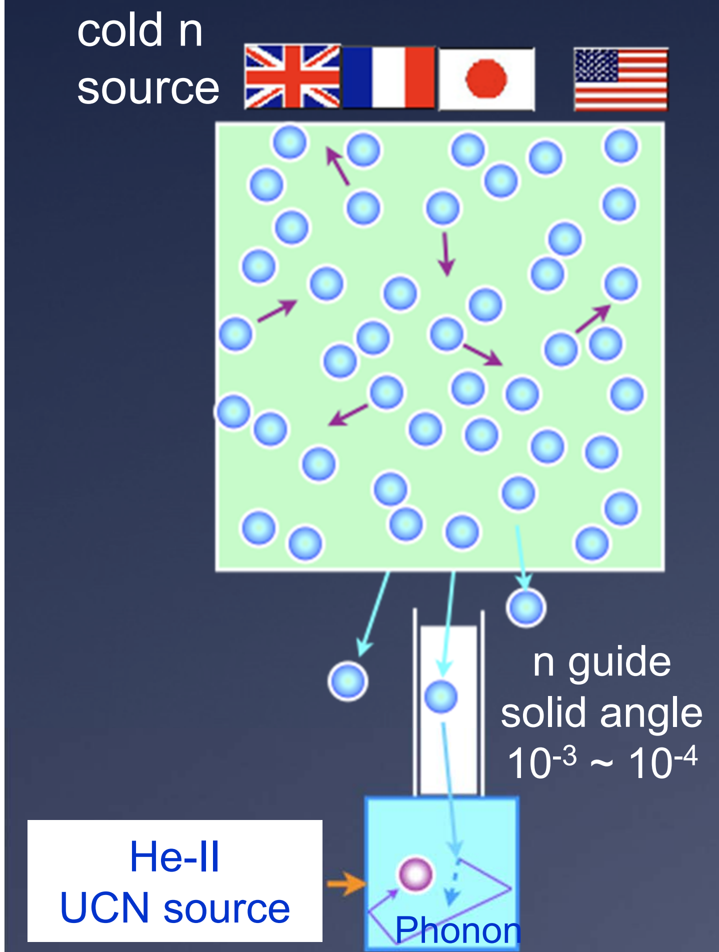
Storage time T_s

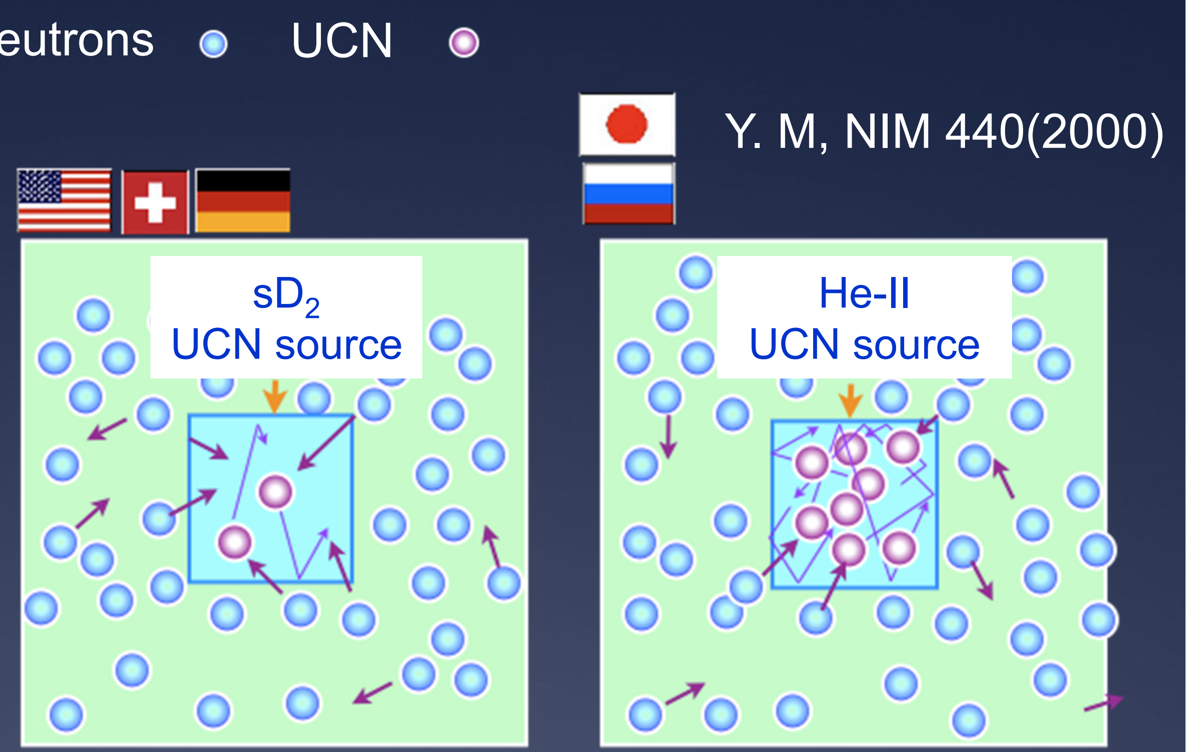
He-II [Golub et al. (1983)]
phonon up-scattering, $1/\tau_{ph} \propto T^7$
τ_{ph}= 600 s at 0.8 K
τ_β = 886 s (β decay)
τ_w = 300 s (wall loss)
$\tau_s = 1/\{1/t_{\pi h} + 1/\tau_\beta + 1/\tau_w\}$=150 s

sD_2 [Phys. Rev. C 71(2005)054601]
τ_{ph} = 40 ms at 8 K
$\tau_{ortho\text{-}para}$ = 100 ms
τ_a = 150 ms
τ_s = 24 ms

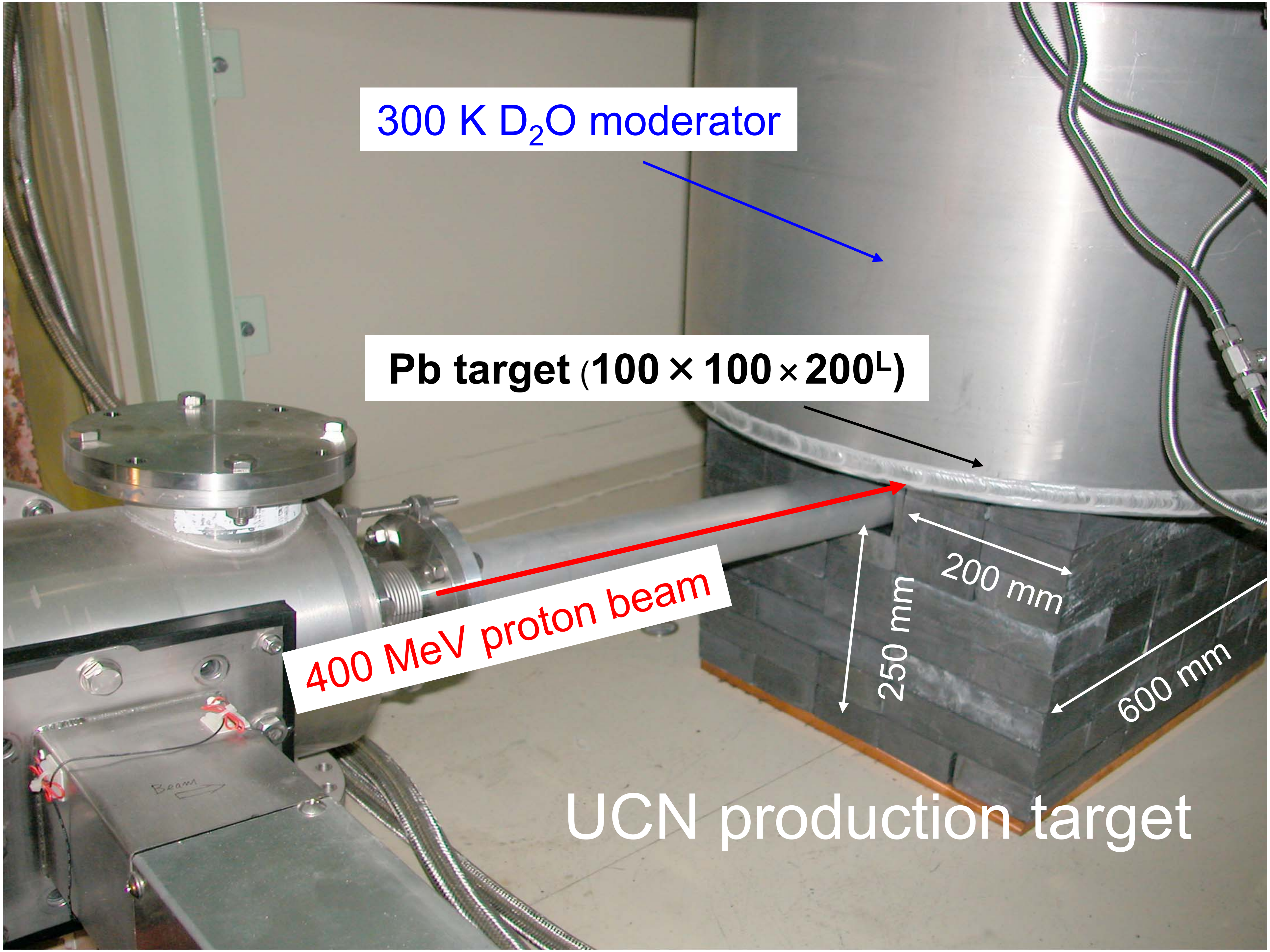
diluted in vacuum
τ_s = 1.6 s, 0.24→9.6L Los Alamos
τ_s = 6 s, 27L→2 m^3 PSI

World's new (super-thermal) UCN sources



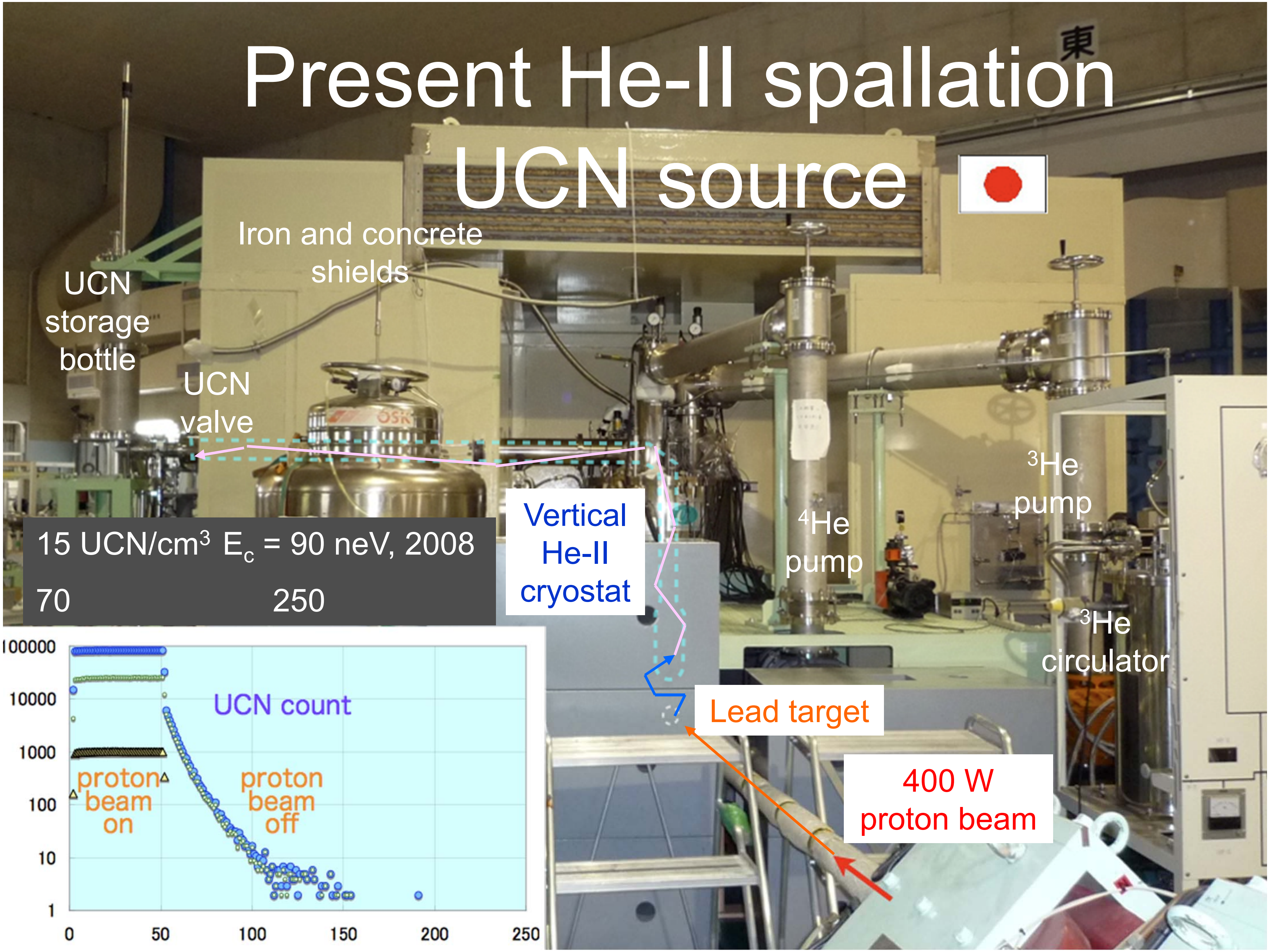


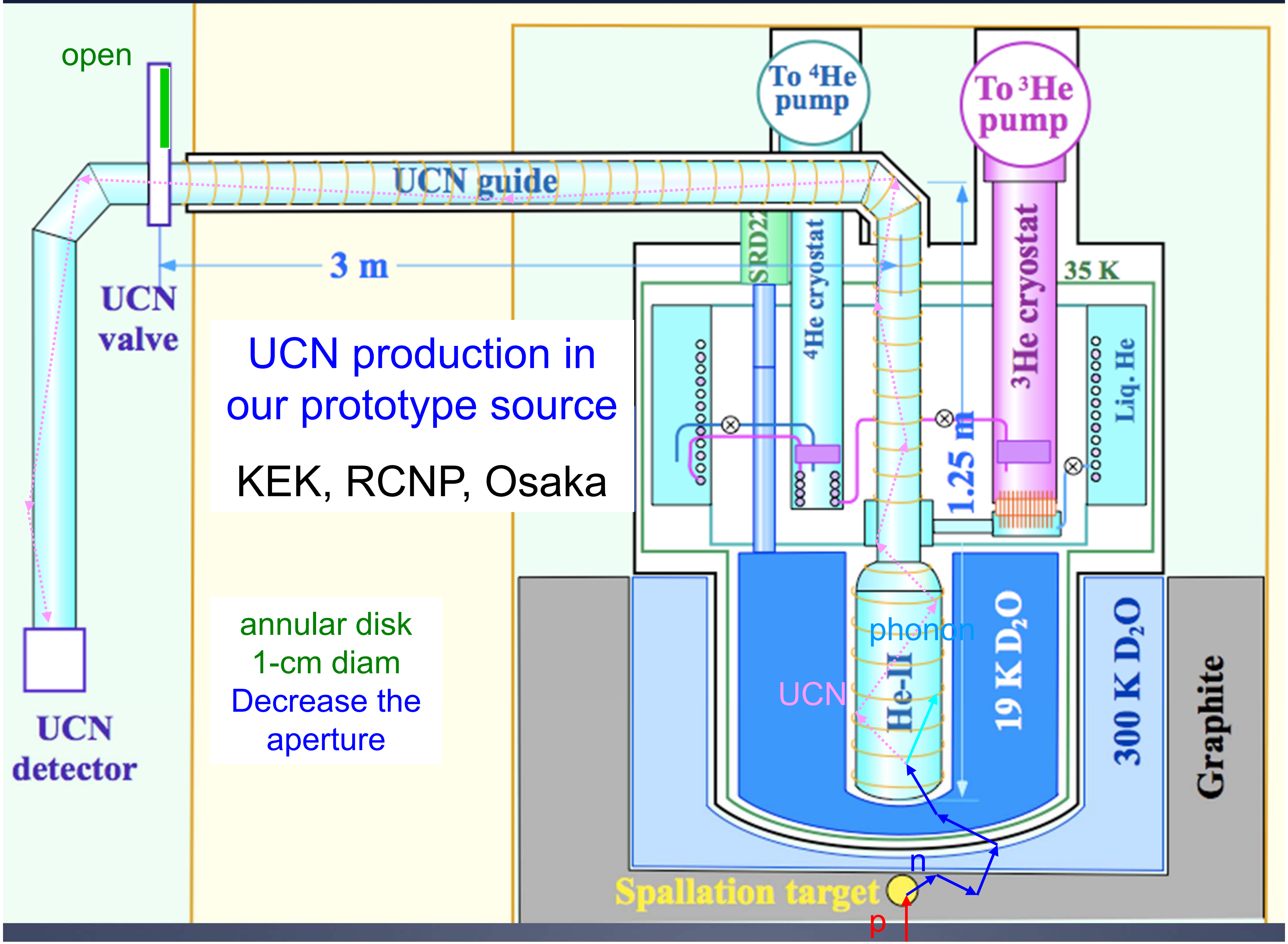
	sD_2 UCN source	He-II UCN source
Production rate	large	small
Lifetime	short	long
Extraction rate	small	large



300 K D2O moderator
Pb target (100 × 100 × 200L)
400 MeV proton beam
200 mm
250 mm
600 mm
UCN production target

Present He-II spallation UCN source





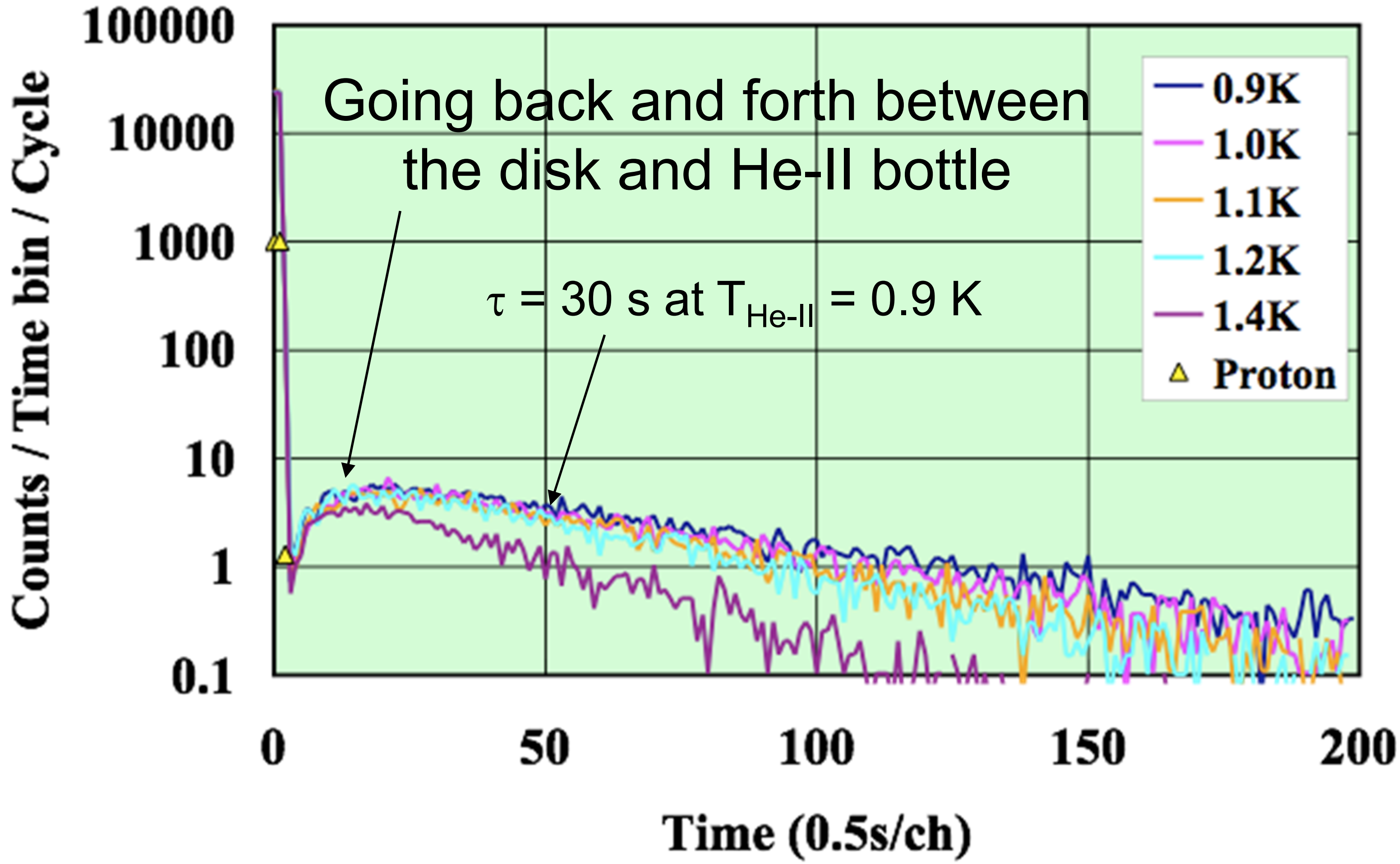
UCN production in our prototype source

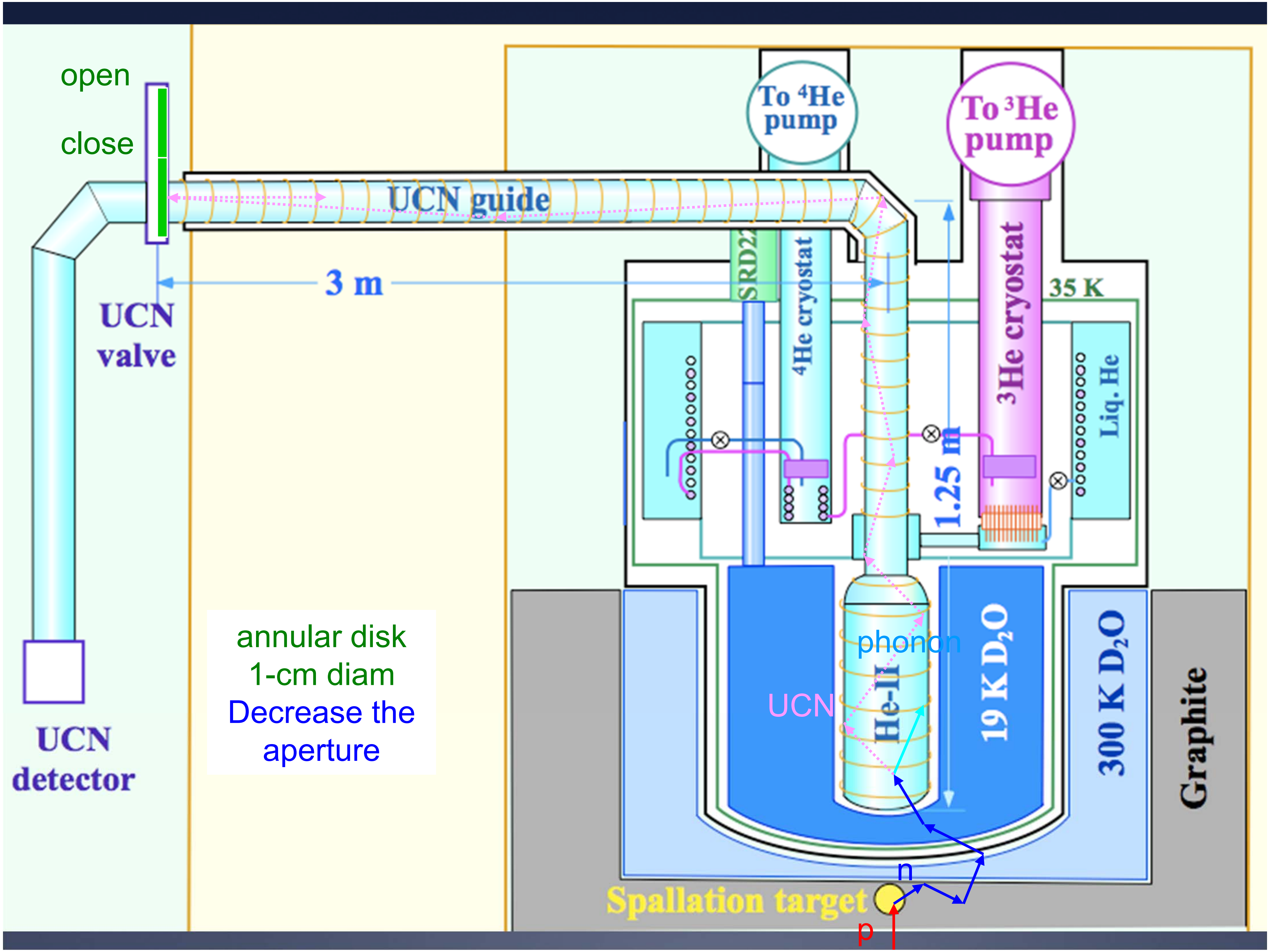
KEK, RCNP, Osaka

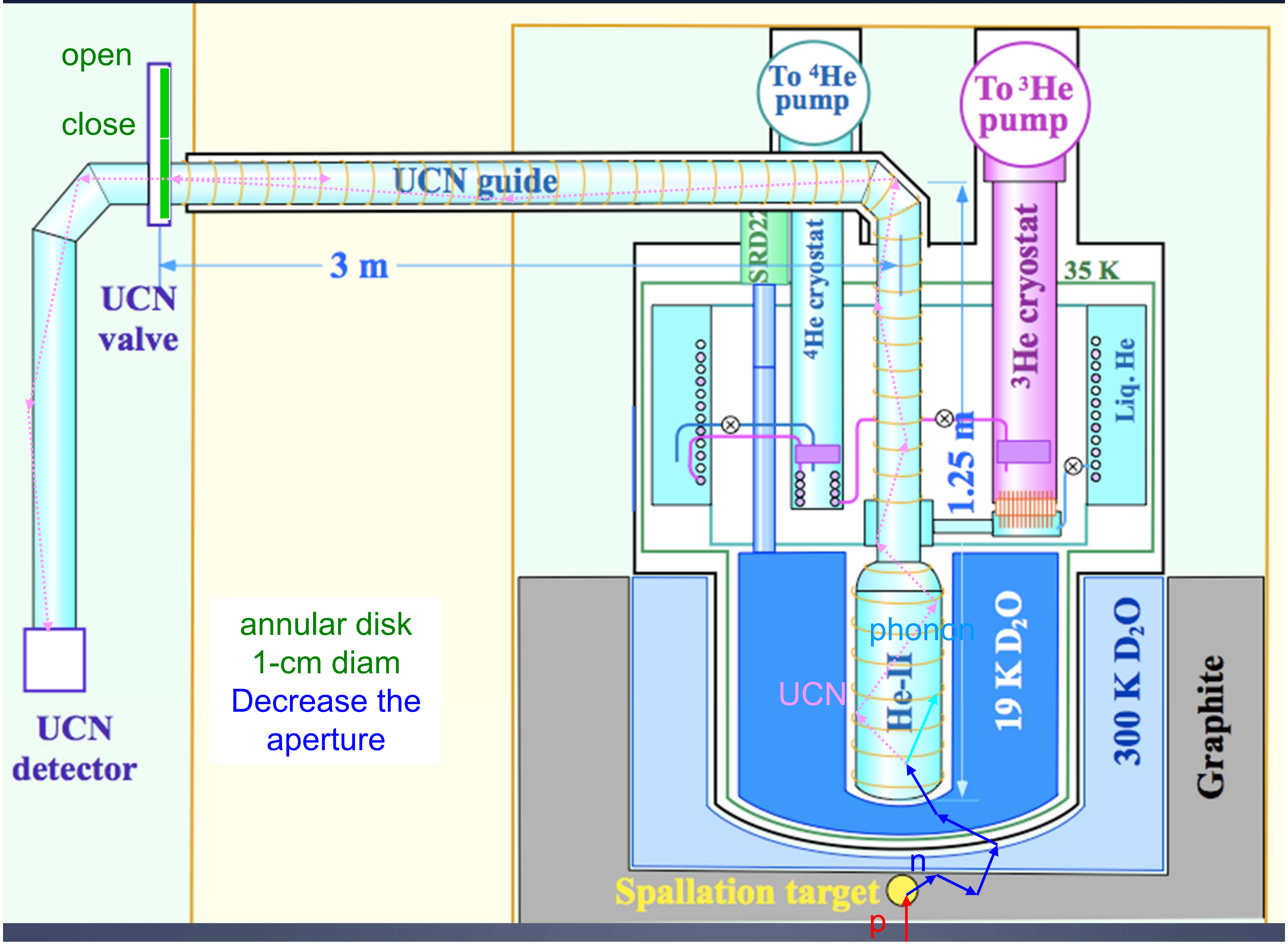
annular disk
1-cm diam
Decrease the aperture

With a proton pulse of 1s

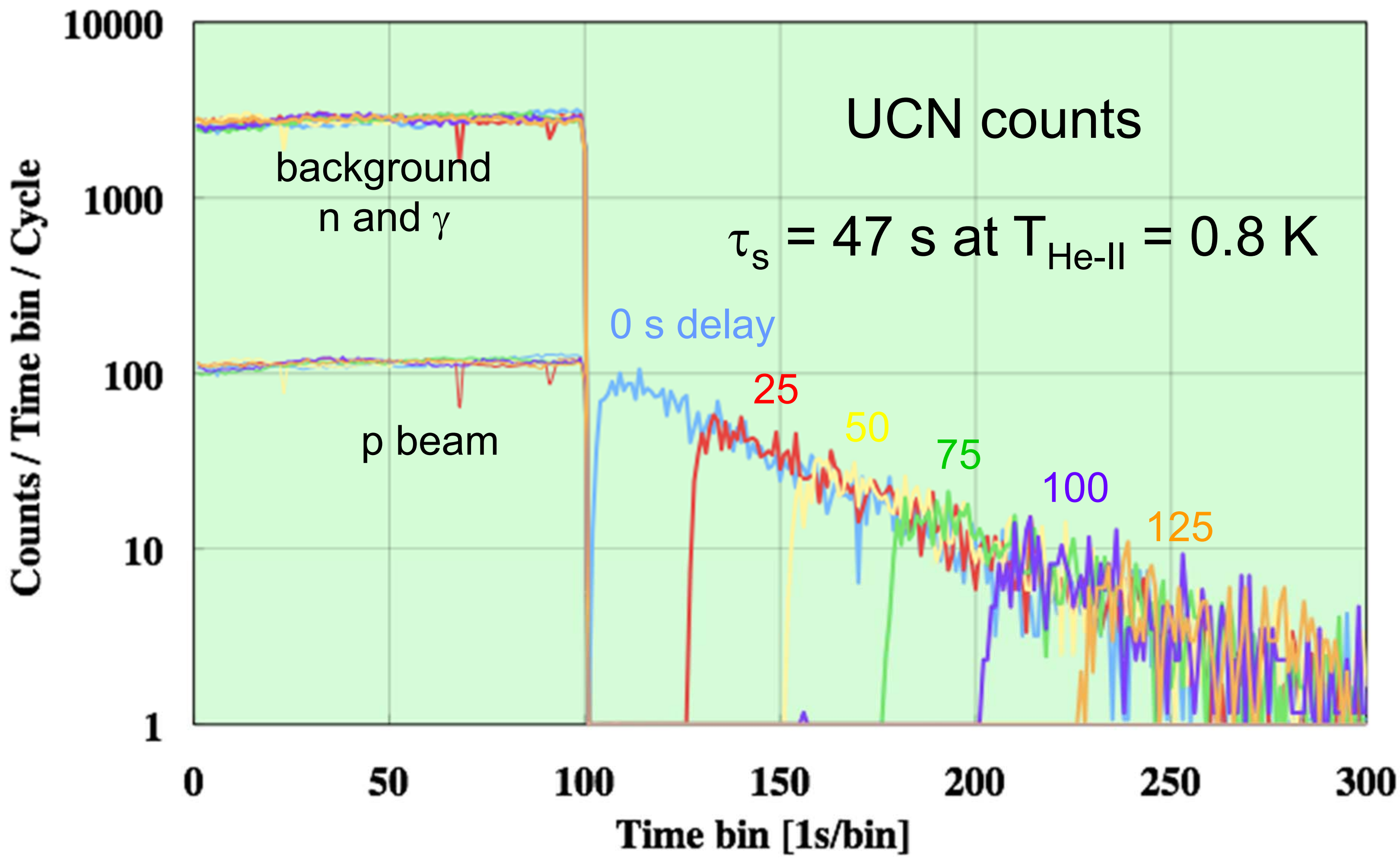
With the annular disk



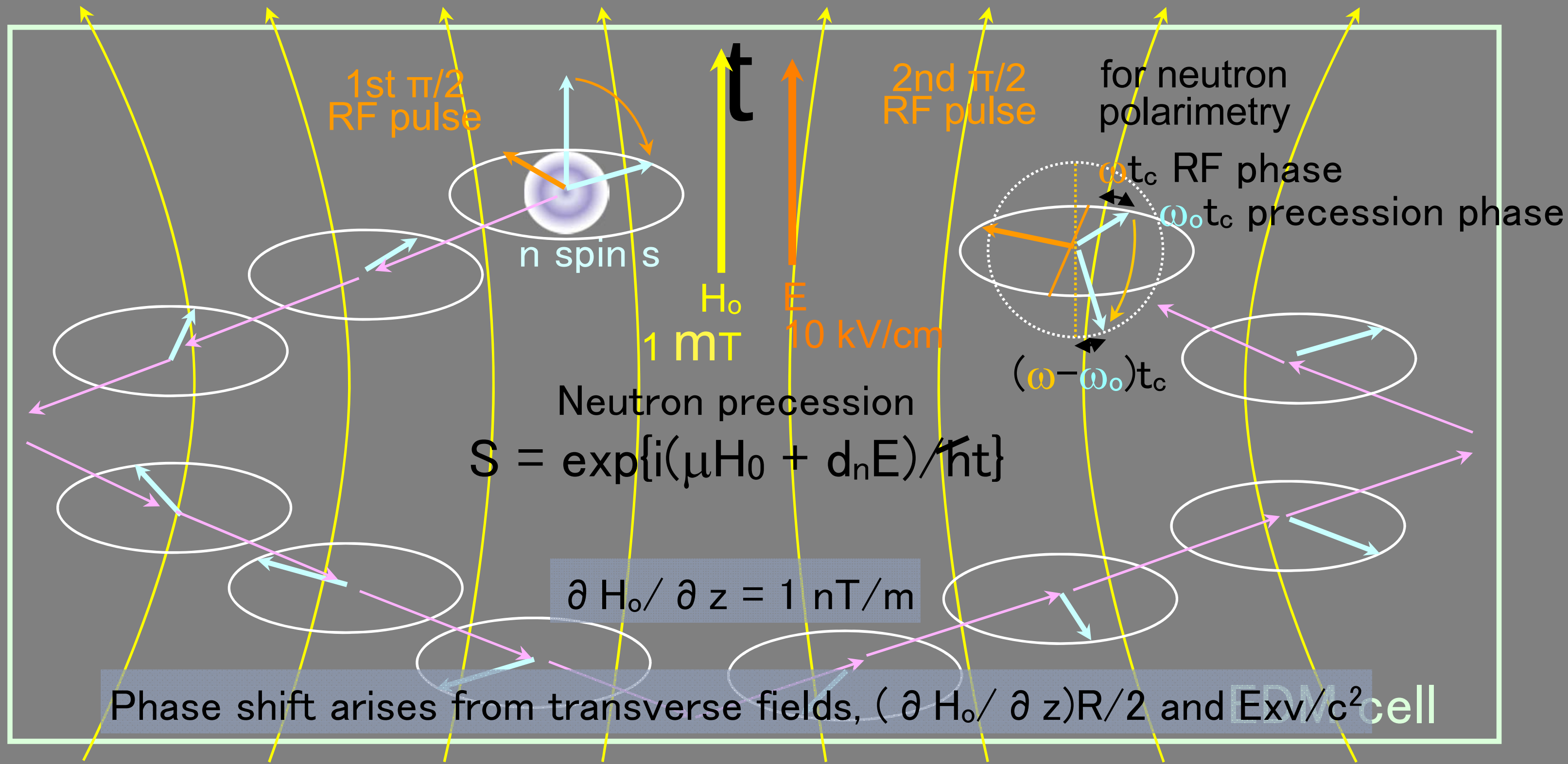

open
close
UCN guide
To ⁴He pump
To ³He pump
3 m
UCN valve
SRD2
4He cryostat
3He cryostat
35 K
Liq. He
1.25 m
phonon
UCN
He-II
19 K D₂O
300 K D₂O
Graphite
n
Spallation target
p
UCN detector
annular disk
1-cm diam
Decrease the
aperture

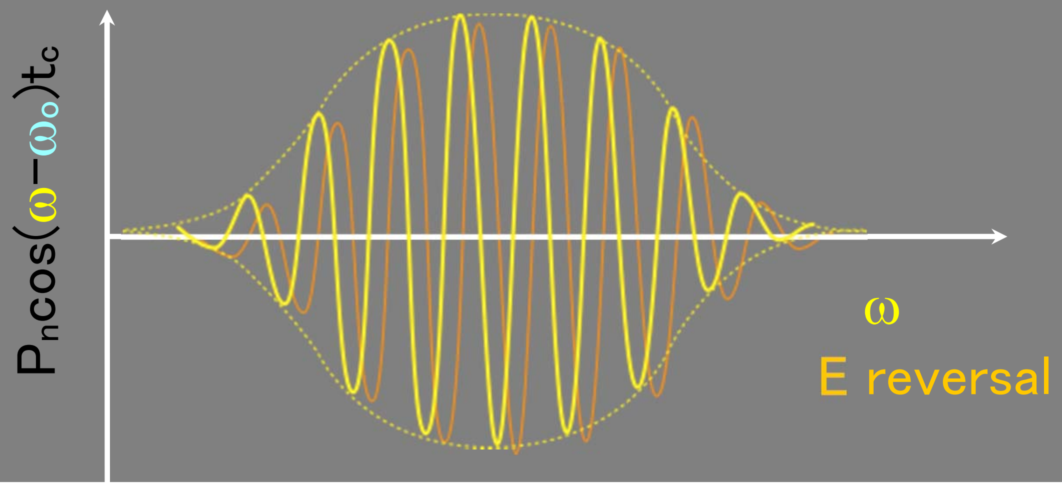

open
close
UCN valve
UCN detector
UCN guide
3 m
To ⁴He pump
To ³He pump
SRD22
4He cryostat
3He cryostat
35 K
1.25 m
Liq. He
phonon
UCN
He-II
19 K D2O
300 K D2O
Graphite
n
Spallation target
p
annular disk
1-cm diam
Decrease the
aperture

Delay mode with a 200 nA proton beam
With the annular disk, April 2008



measuremen





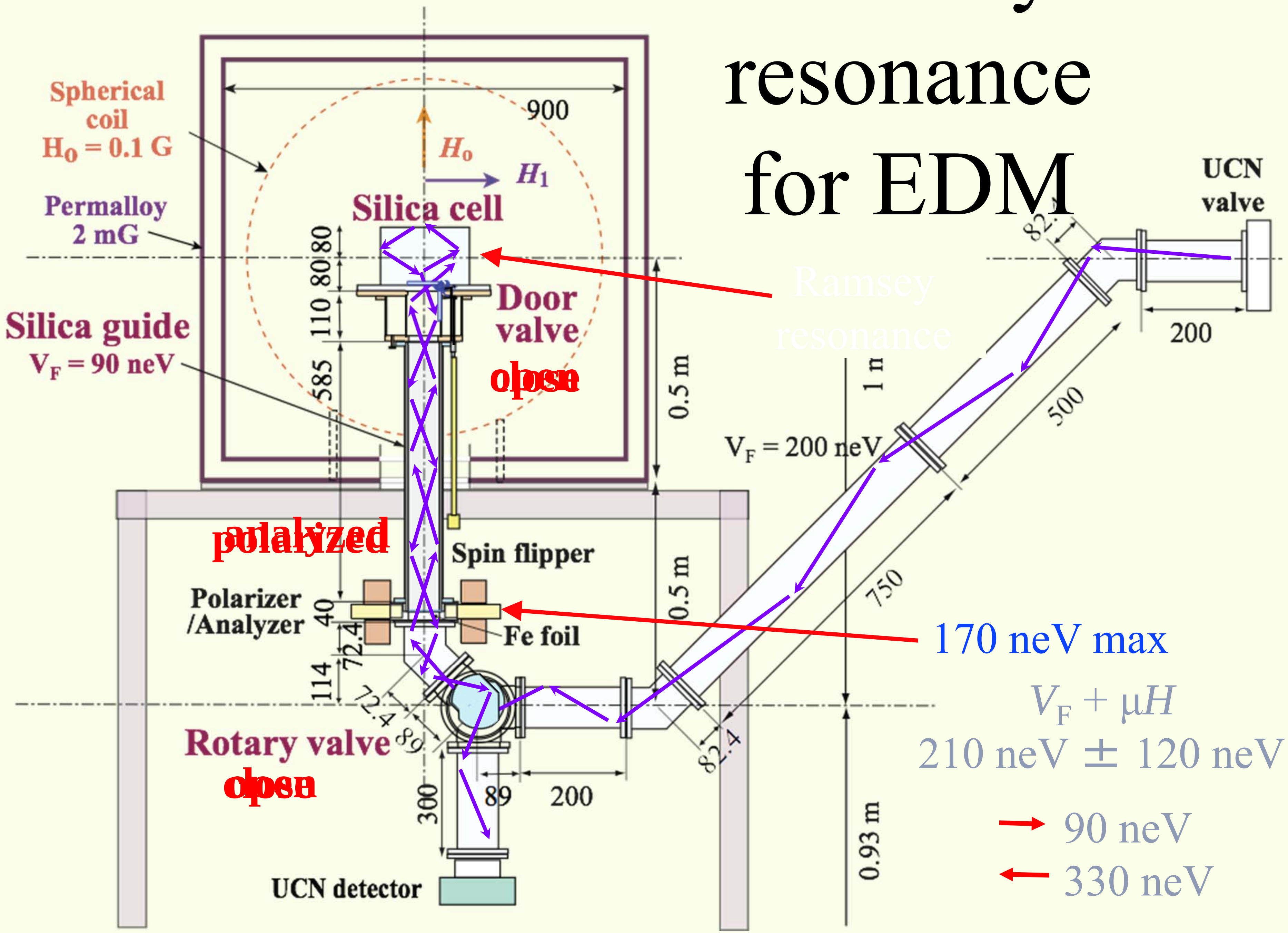
P_n: UCN polarization

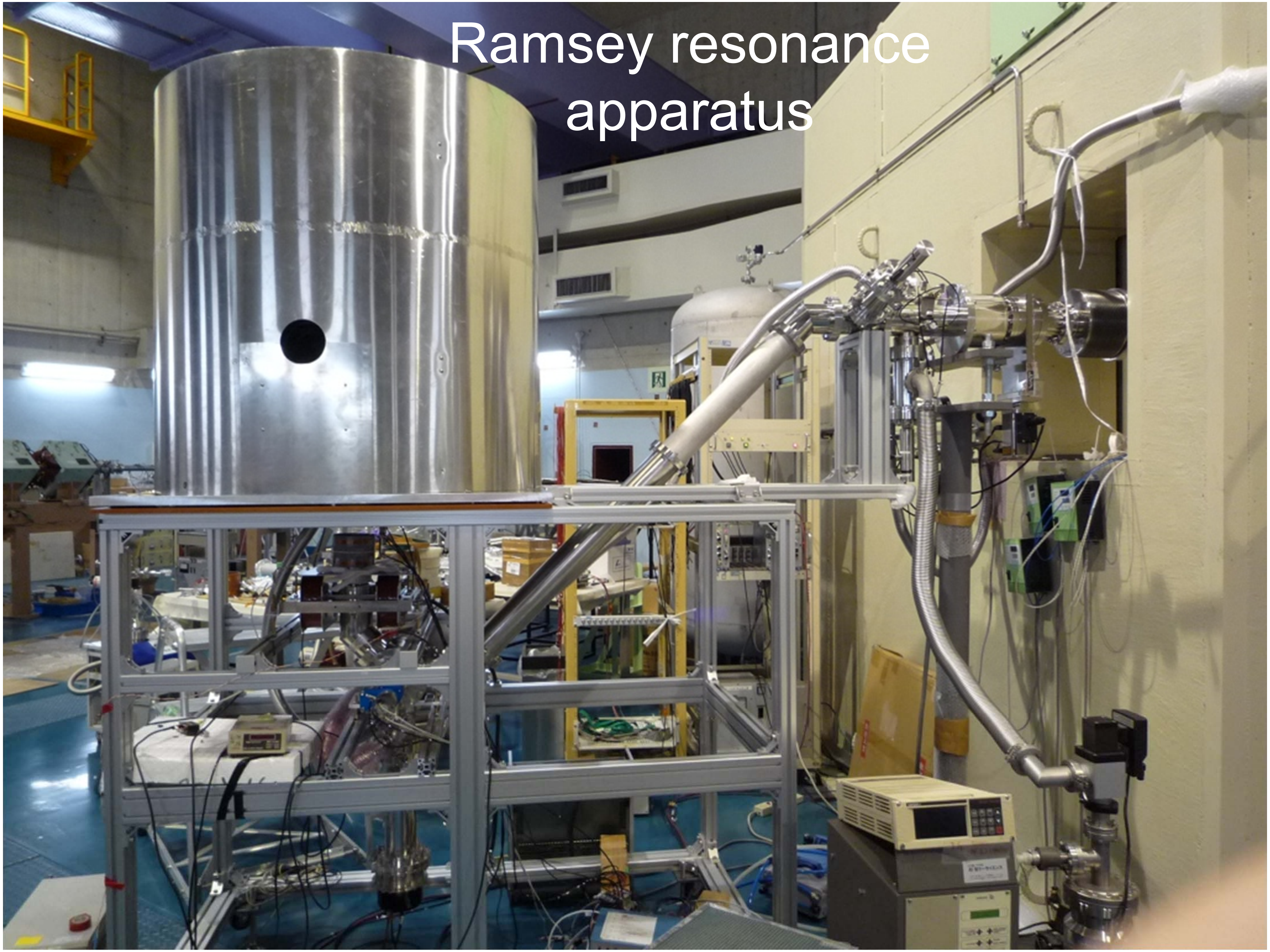
ω_o: $2\mu_n H_o \pm 2d_n E$

t_c: precession time

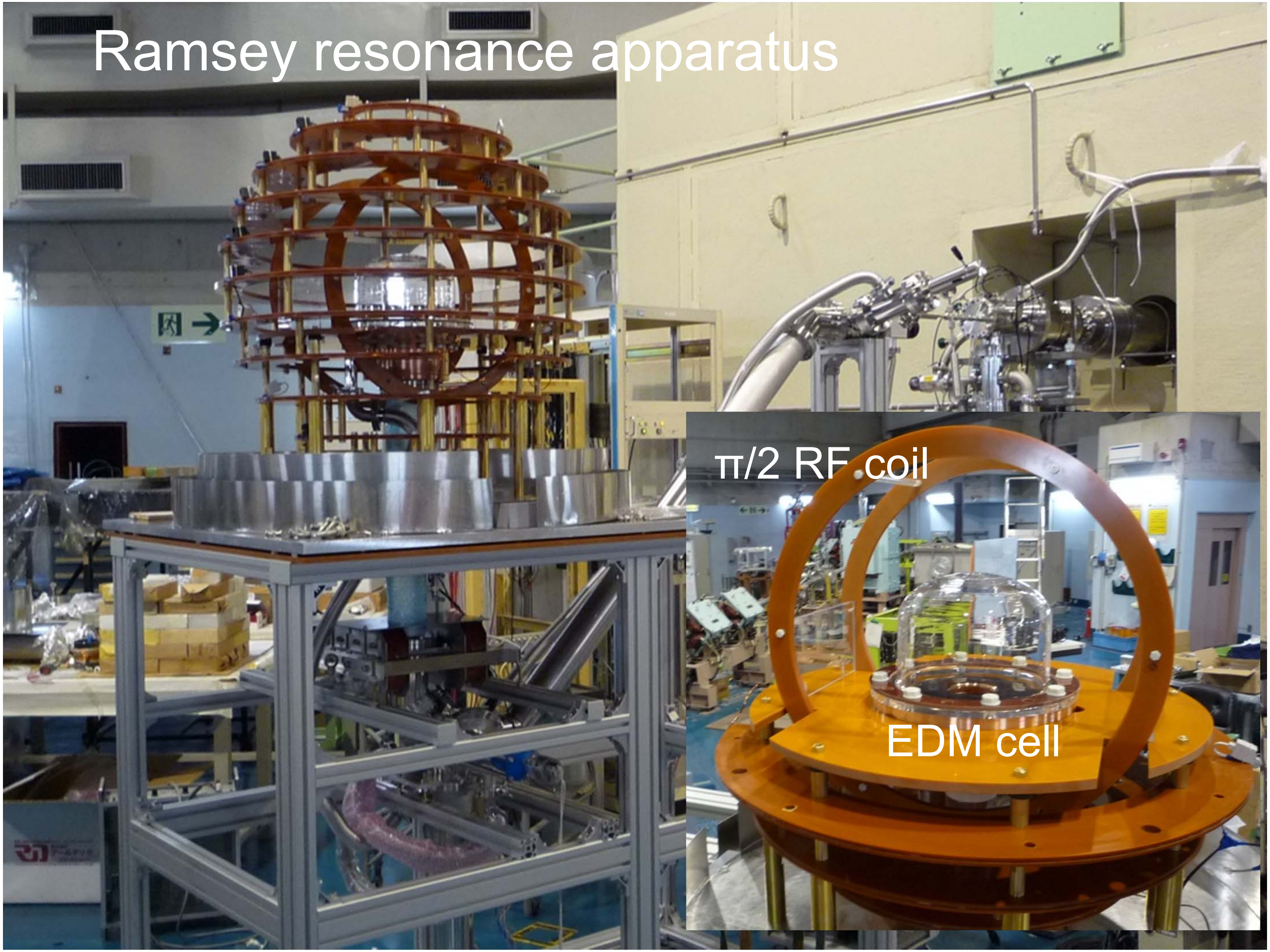
$\delta d_{sta} = \hbar/\{2P_nEt_c\sqrt{N}\}$

Ramsey resonance for EDM

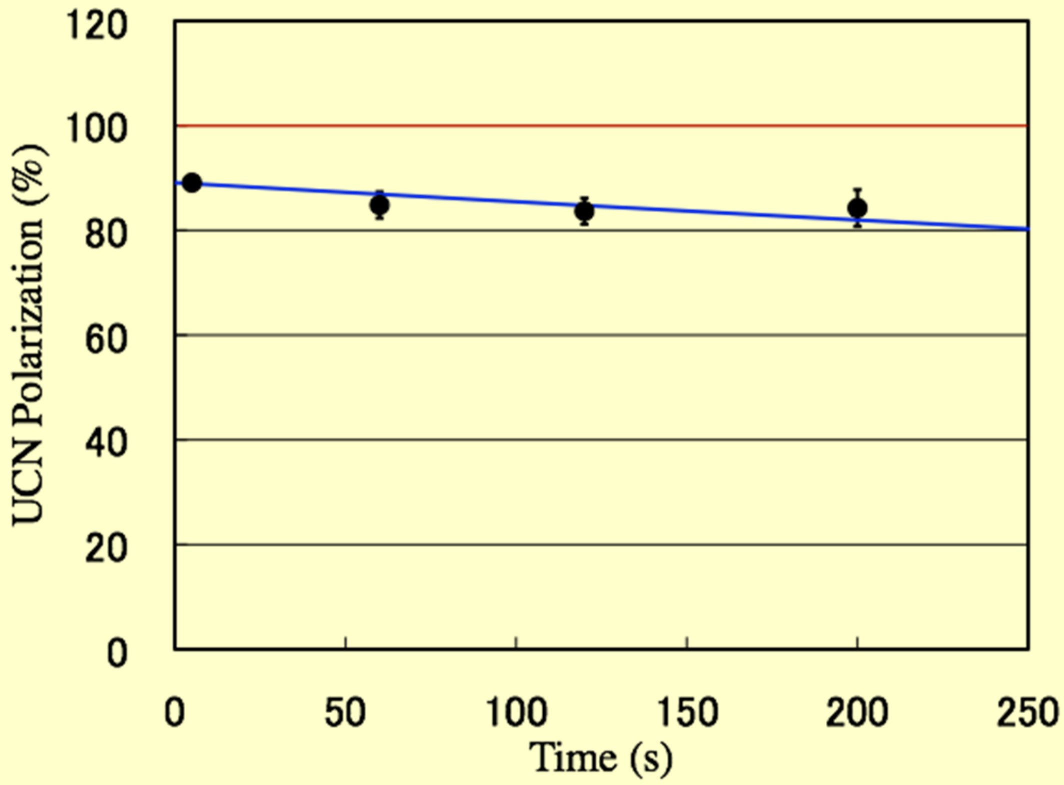



Ramsey resonance
apparatus

Ramsey resonance apparatus



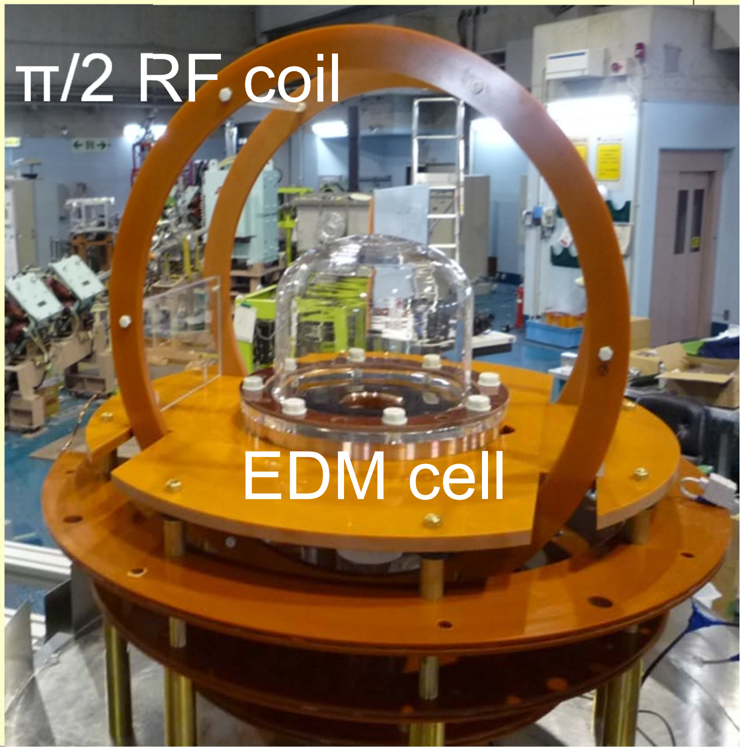
Relaxation of UCN Polarization in the Ramsey Cell



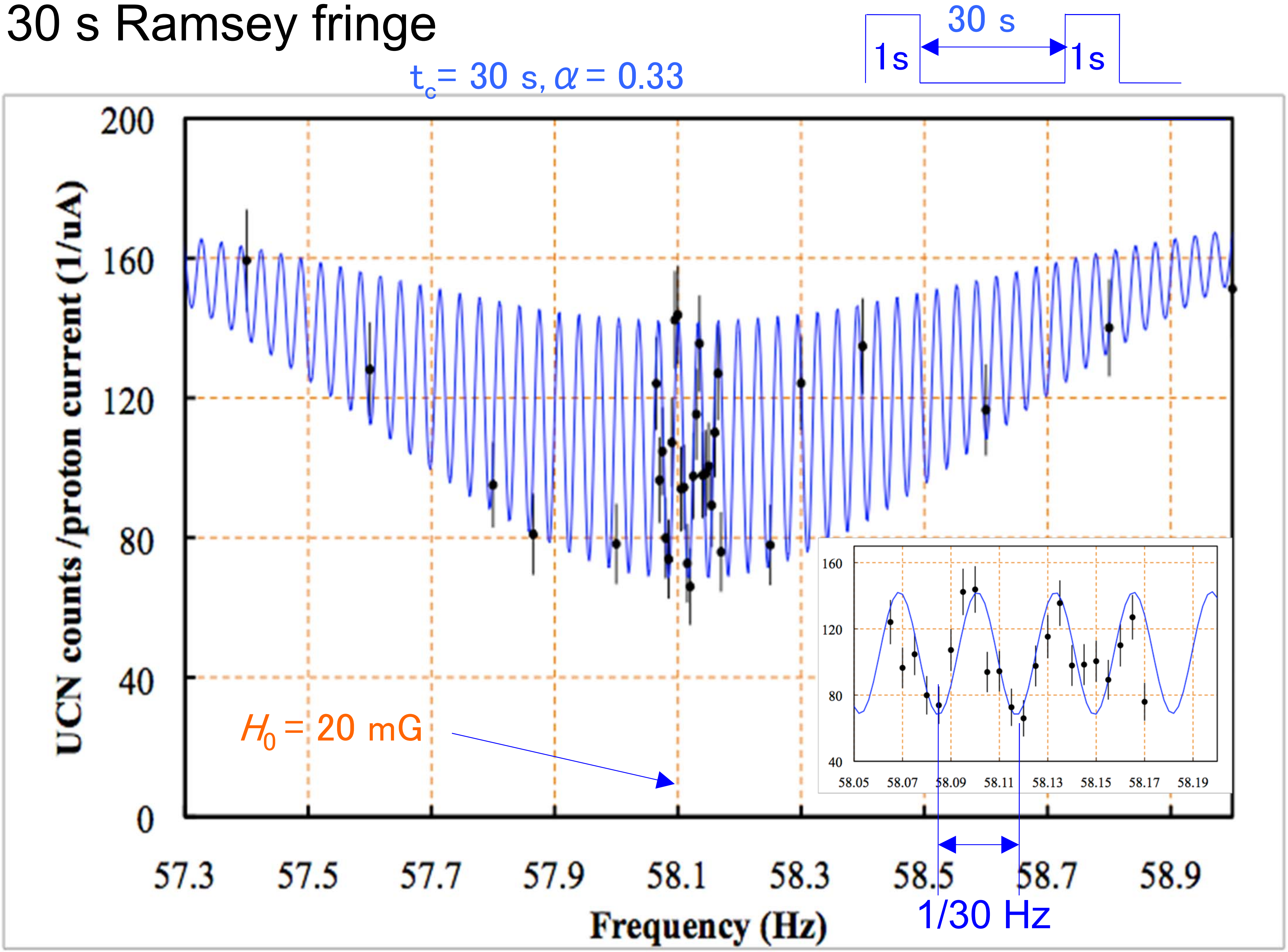
Silica + DLC

P_0 = 89.1(1.2) %

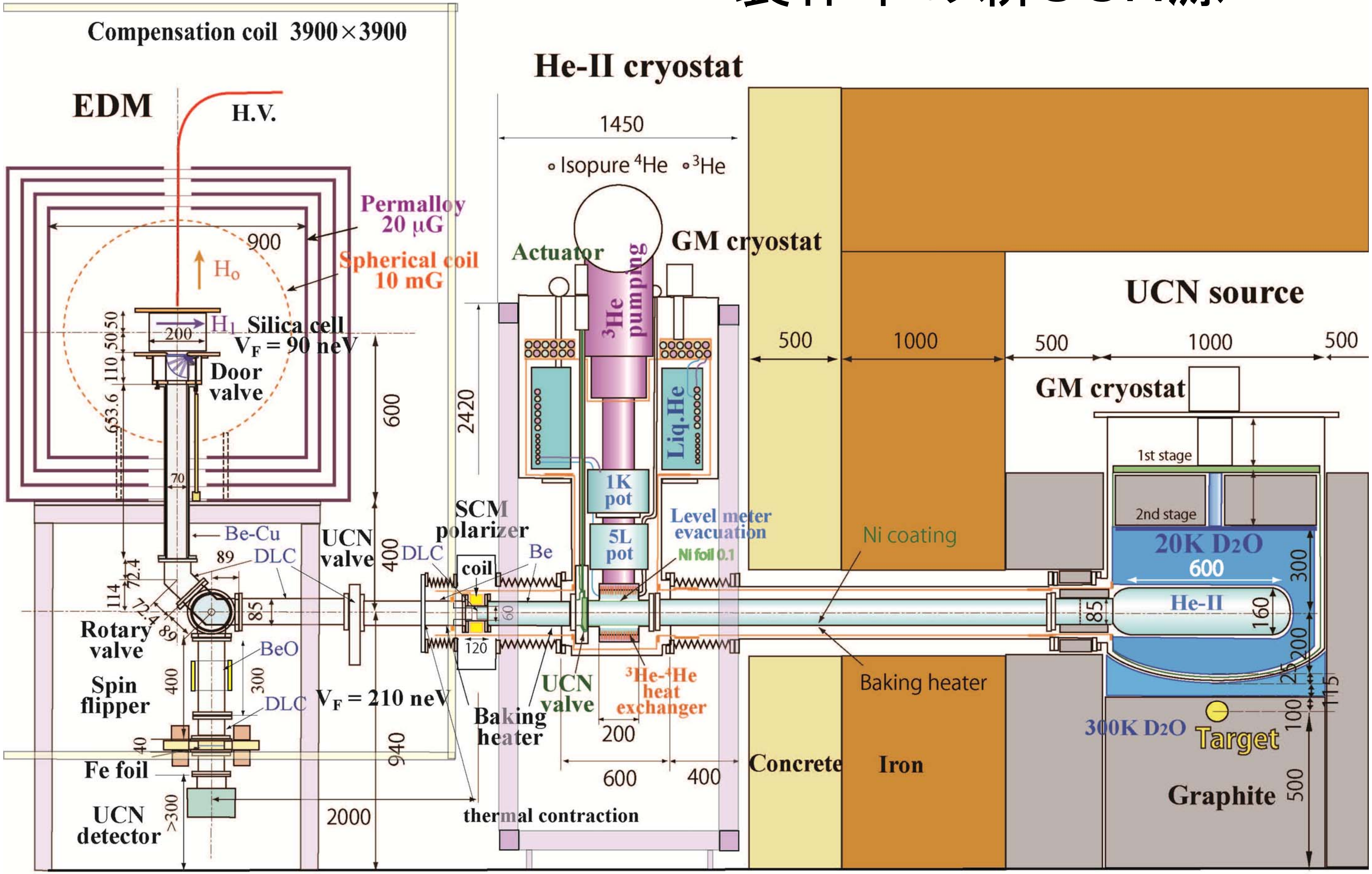
$T_1 = 2400^{+1300}_{-700}$ s



30 s Ramsey fringe

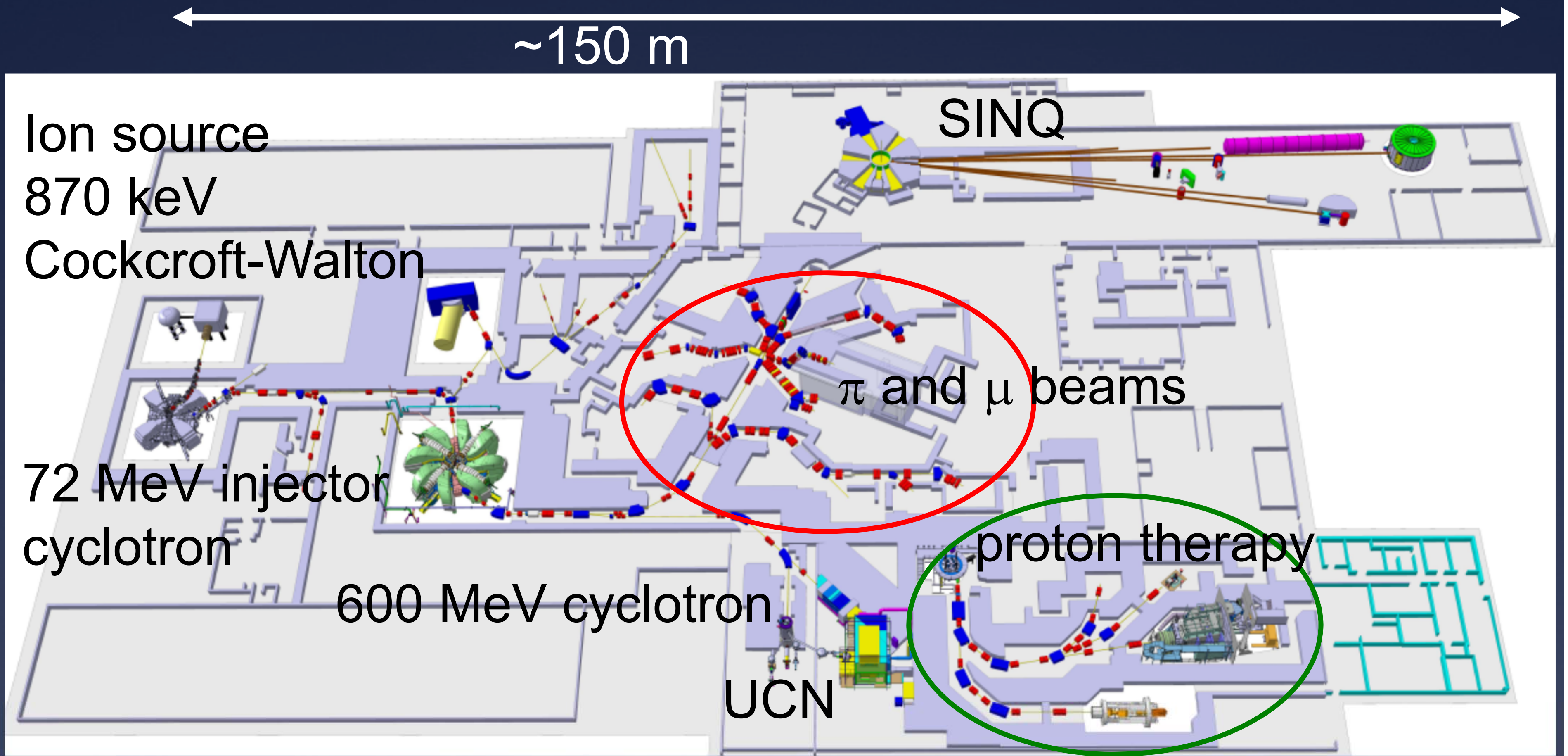


製作中の新UCN源



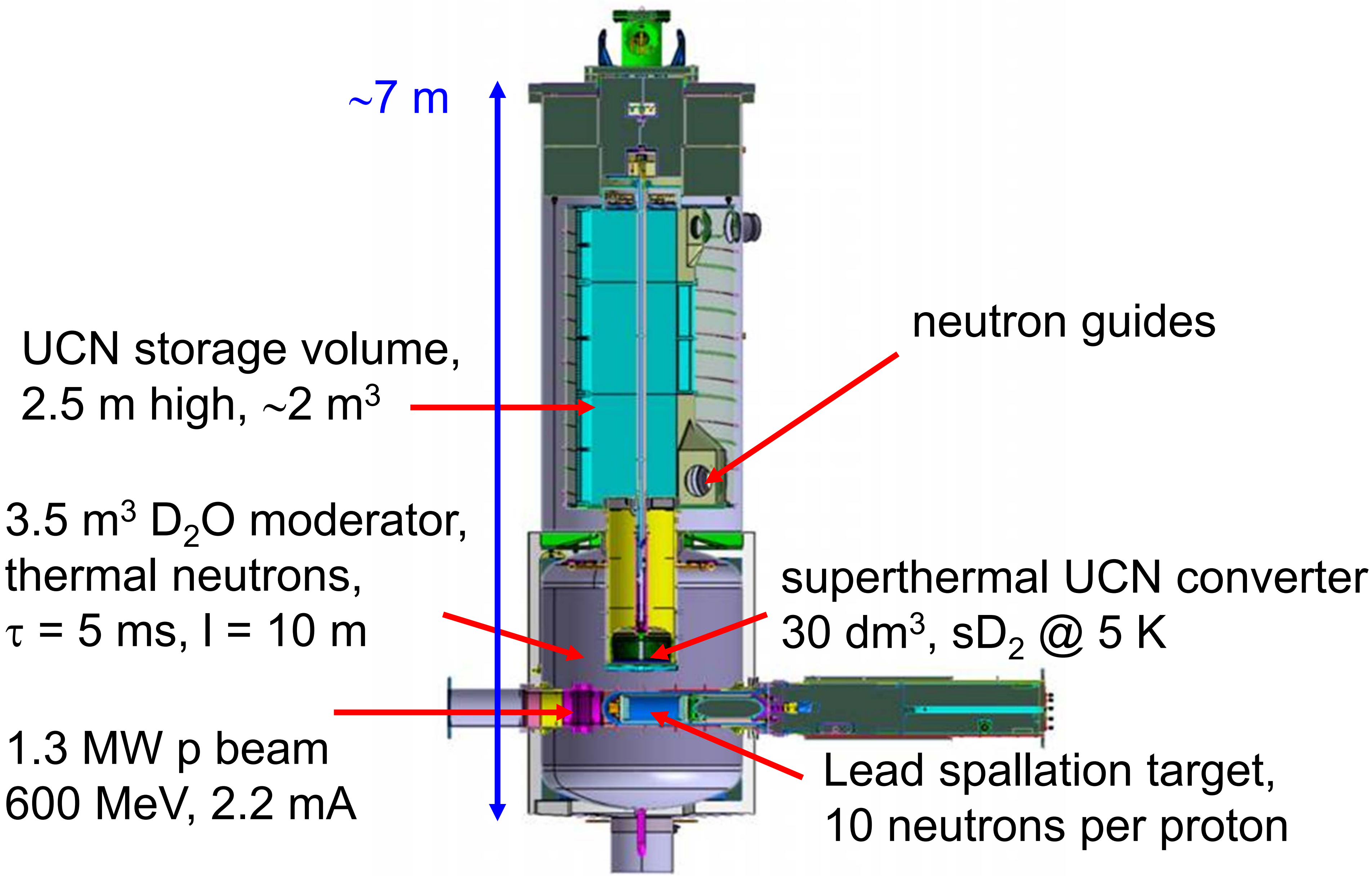
Compensation coil 3900×3900
EDM
H.V.
Permalloy 20 μG
Spherical coil 10 mG
900
H₀
H₁
Silica cell
V_F = 90 neV
200
Door valve
600
Be-Cu
DLC
89
UCN valve
Rotary valve
BeO
Spin flipper
V_F = 210 neV
Fe foil
UCN detector
2000
940
400
SCM polarizer
coil
Be
120
Baking heater
thermal contraction
He-II cryostat
1450
Isopure ⁴He
³He
Actuator
³He pumping
GM cryostat
2420
Liq.He
1K pot
5L pot
Level meter evacuation
Ni foil 0.1
UCN valve
³He-⁴He heat exchanger
200
600
400
Ni coating
Baking heater
500
1000
Concrete
Iron
UCN source
500
1000
500
GM cryostat
1st stage
2nd stage
20K D₂O
600
300
He-II
85
160
200
25
100
300K D₂O
Target
Graphite
500

Proton accelerator facility @ PSI

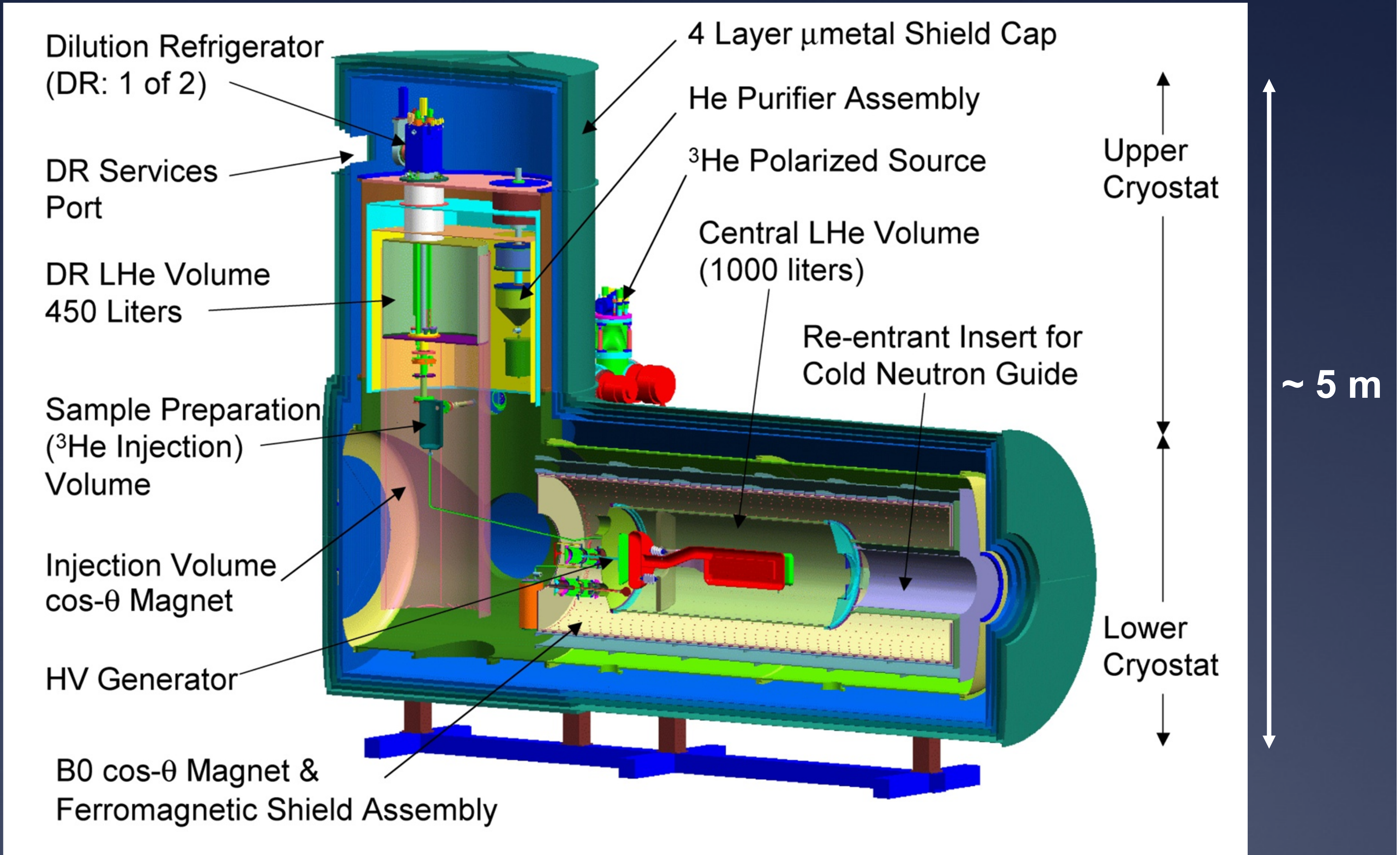


Ring cyclotron: 600 MeV, 2.2 mA →1.3 MW

PSI UCN source



UCN at SNS


Dilution Refrigerator
(DR: 1 of 2)
DR Services
Port
DR LHe Volume
450 Liters
Sample Preparation
(^{3}He Injection)
Volume
Injection Volume
cos-θ Magnet
HV Generator
B0 cos-θ Magnet &
Ferromagnetic Shield Assembly
4 Layer μmetal Shield Cap
He Purifier Assembly
^{3}He Polarized Source
Central LHe Volume
(1000 liters)
Re-entrant Insert for
Cold Neutron Guide
Upper
Cryostat
Lower
Cryostat
~ 5 m

ご静聴ありがとうございました

Thank you for your attention

Comparison with the theoretical prediction

Production rate of present exp.

4 UCN/cm^3/s (E_c = 210 neV)

5.2 UCN/cm^3/s (E_c: 210→250 neV)

↔ 0.9 UCN/cm^3/s at ILL 250neV Phys. Lett. A 308(2003)67

Production rate predicted

4 - 8 UCN/cm^3/s at 400W, 250neV

$(1/8) \times (2 - 4) \times 10^{-9}\ \Phi_n$ /cm^3/s, $\Phi_n(T_n = 80\text{ K})$

[$(2 - 4) \times 10^{-9}\ \Phi_n$ /cm^3/s, $\Phi_n(T_n = 20\text{ K})$]

$\Phi_n = 1.5 \times 10^{10}$ (n/cm^2/s)

by MCNPX Monte Carlo

UCN source improvement

Date	I_p	τ_s	$T_{He\text{-}II}$	He-II film perimeter	^{3}He, H contamination
2002	200 nA	14 s	1.2 K		Normal ^{4}He
June 2006	1 μA		0.9 K	8.5 cm	Normal ^{4}He
November2006	1 μA	34 s	0.8 K		Normal ^{4}He
July 2007	1 μA	39 s	0.8 K		Pure ^{4}He
April 2008	1 μA	47 s	0.8 K	5 cm	Pure ^{4}He Fomblin
July 2009	1 μA	45 s (75 s*)	0.8 K		Pure ^{4}He Alkali degreasing

^{3}He cryostat

Suppress He-II film flow

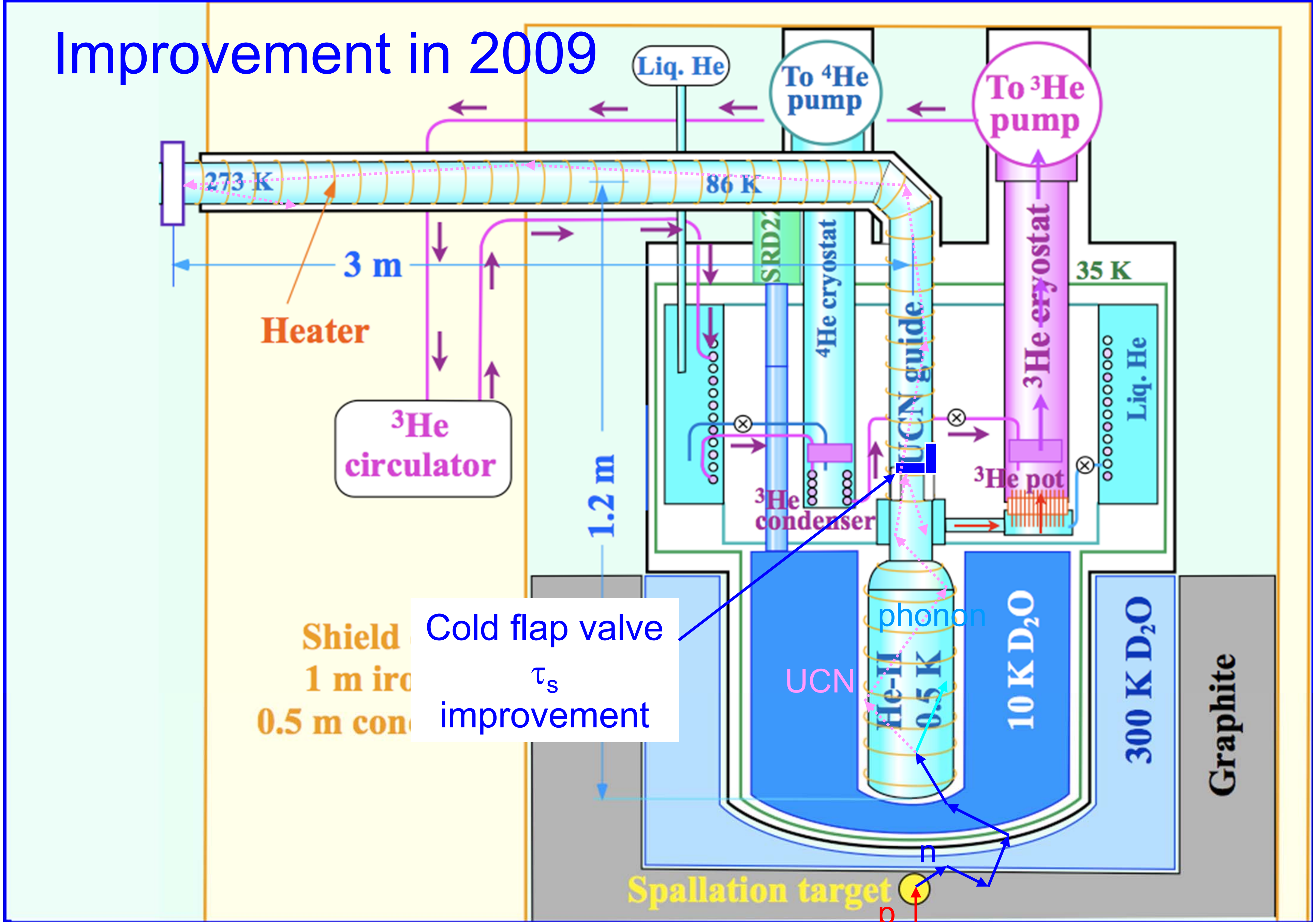
Remove ^{3}He

Remove Hydrogen

Remove Hydrogen

(* Experiment cell)

Improvement in 2009



Cooling power for a 100 times higher UCN production

7.5 W γ heating in the horizontal He-II (Experiment)
4.5 W γ heating γ heating in the vertical He-II (MCNPX Monte Carlo)
at a proton beam power of 20 kW

7.5 W x ¼ (duty factor) ~ 2 W
with longer time constant of temperature raising,
larger heat capacity of He-II

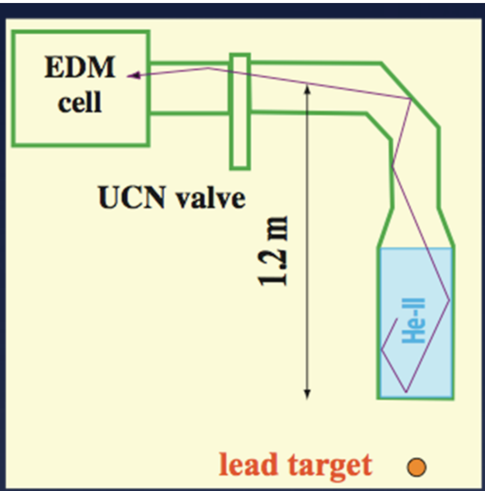
Cooling power

$$Q \times P_{He} \times dV/dt \;/\; \{R \times T\}$$

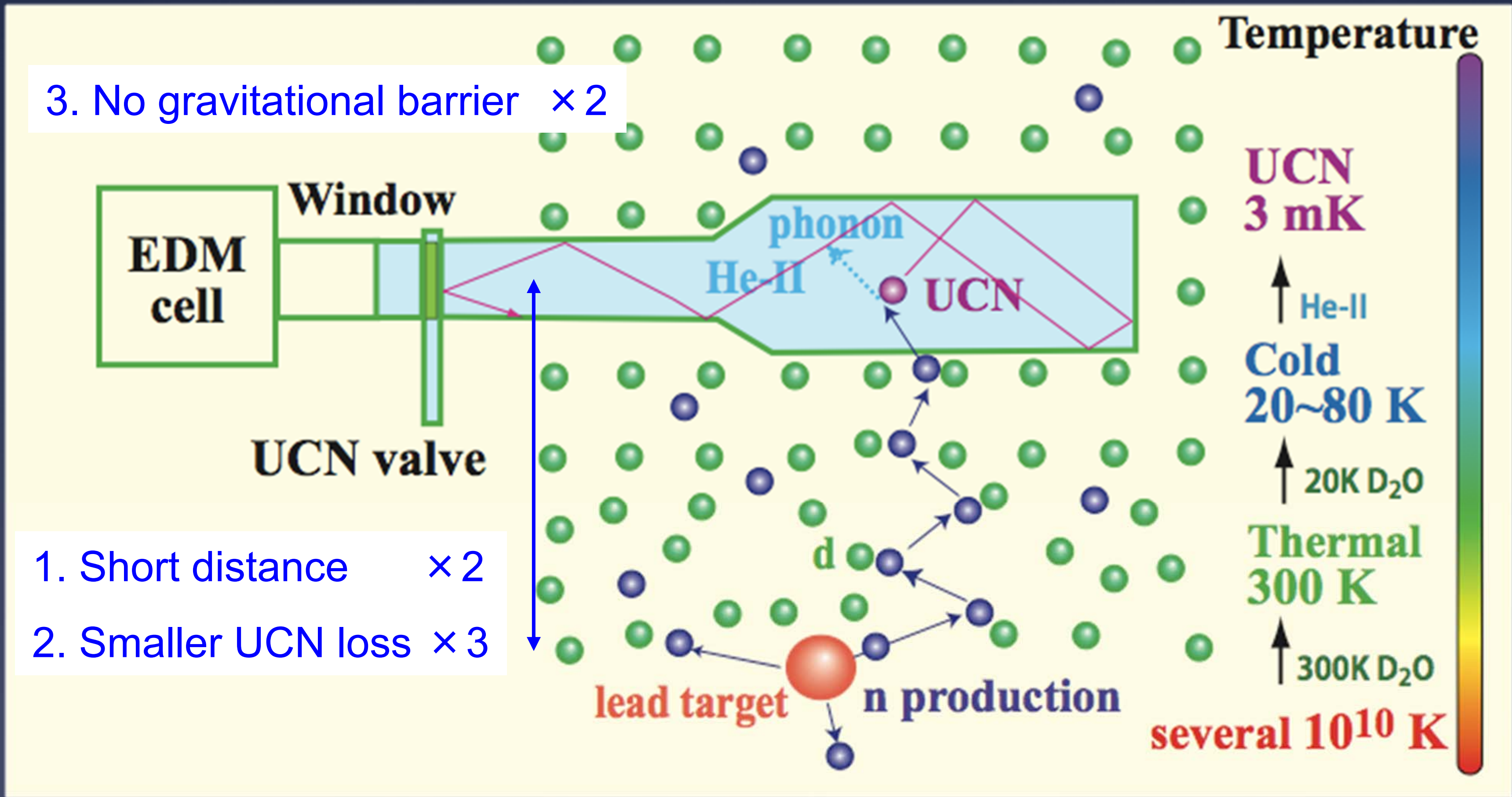
Q	×	P_{He}	×	dV/dt	/	{ R	×	T }
latent heat of vaporization		vapor pressure at 0.8 K		pumping power		gas constant		pump temperature

34.5 J/mol × 3 Torr × 1 × 10^4 m^3/h / {8.3 × 10^{-5} m^3bar/(mol·K) × 300 K} = 17 W

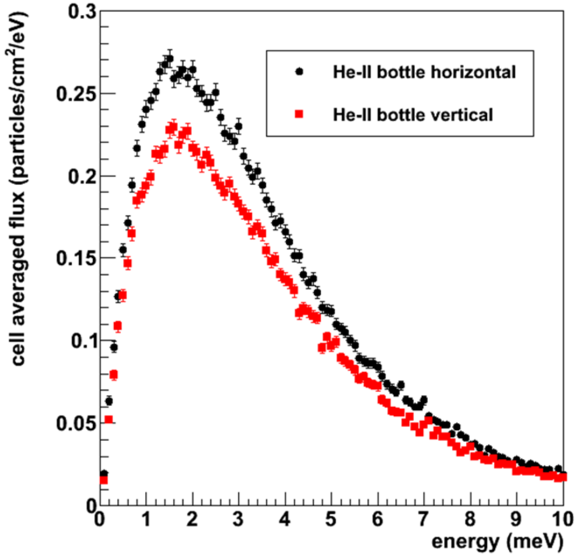
A new 20 kW UCN source

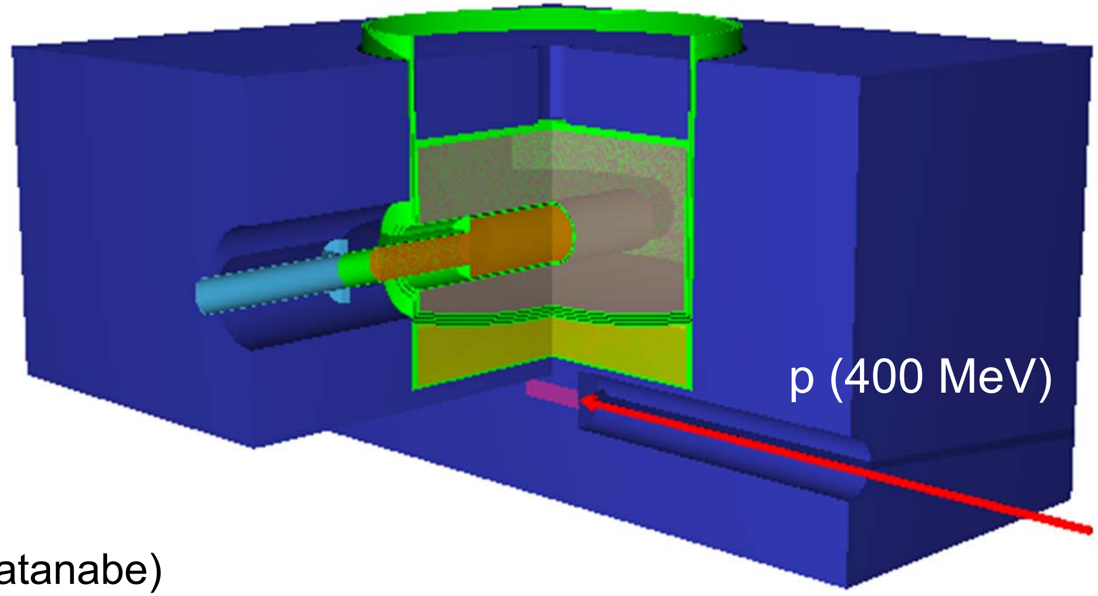


proton beam ×10 (Japan) ×50 (Japan, Canada)
vertical to horizontal ×12 (Japan)
15×120 = 1800 UCN/cm^3

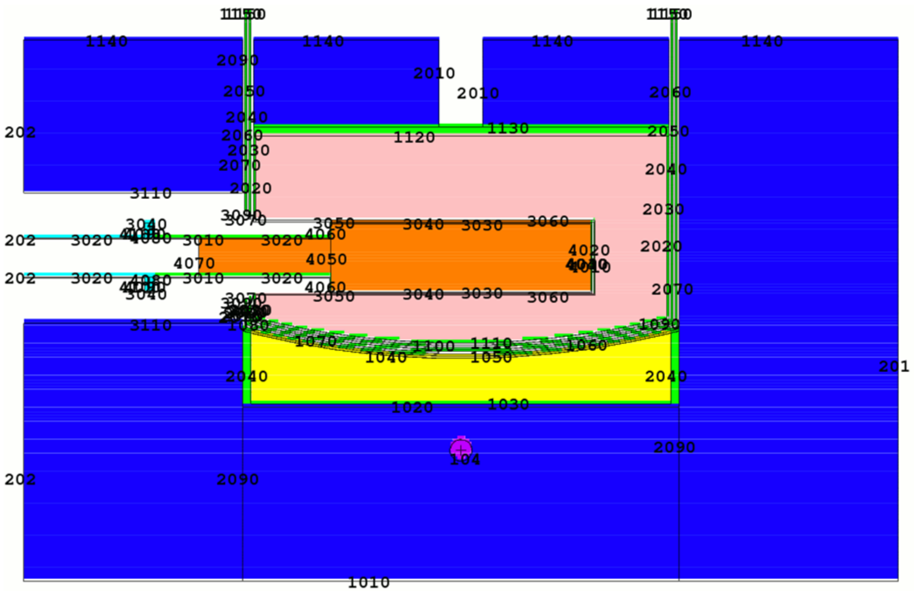


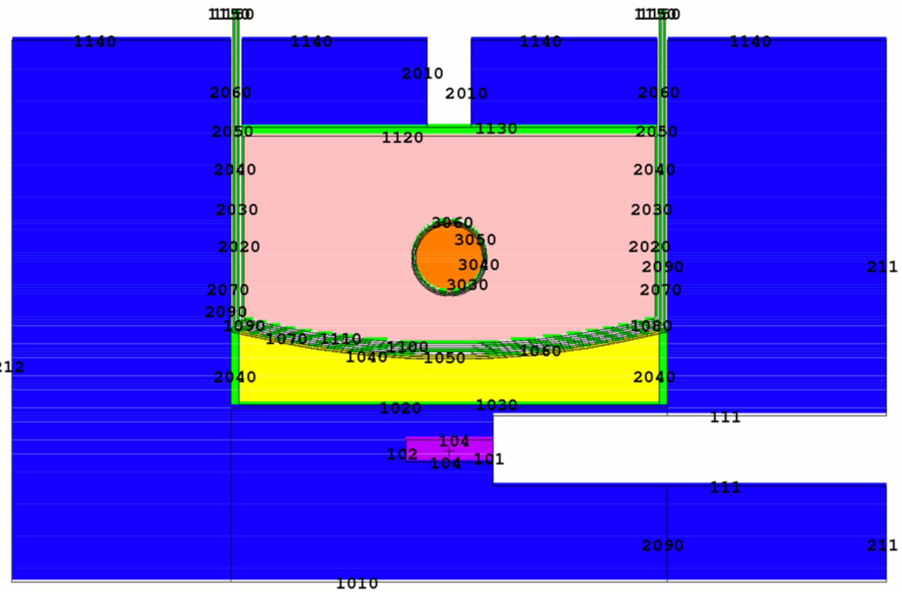
MC calculation by MCNPX





(by Y. Watanabe)





TRIUMF

International Spallation Ultracold Neutron Source

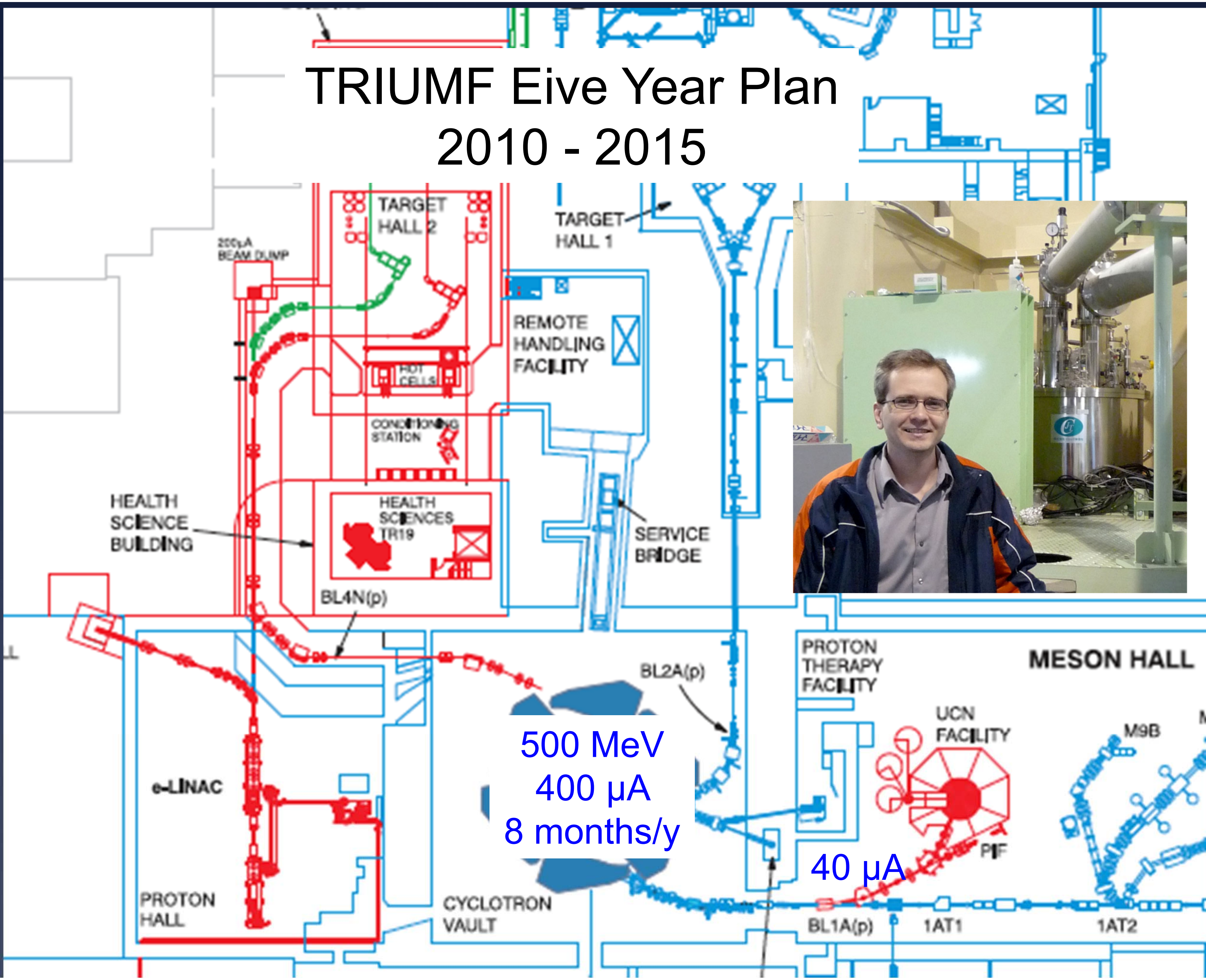
Spokespeople: Y. Masuda (KEK), J.W. Martin (Winnipeg)

Collaborators: J.D. Bowman, J. Birchall, L. Buchmann, L. Clarke, C. Davis, B.W. Filippone, M. Gericke, R. Golub, K. Hatanaka, M. Hayden, T.M. Ito, S. Jeong, I. Kato, S. Komamiya, E. Korobkina, E. Korkmaz, L. Lee, K. Matsuta, A. Micherdzinska, W.D. Ramsay, S.A. Page, B. Plaster, I. Tanihata, W.T.H. van Oers, Y. Watanabe, S. Yamashita, T. Yoshioka

(KEK, Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, Tokyo, UNBC, Osaka, Kentucky)

We propose to construct the world's highest density source of ultracold neutrons and use it to conduct fundamental and applied physics research using neutrons.

TRIUMF Eive Year Plan
2010 - 2015



TRIUMF kicker concept

2013UCN production rate × 5

ρ = 9000 UCN/cm^3 at E_c = 90 neV

(42000 250)

for

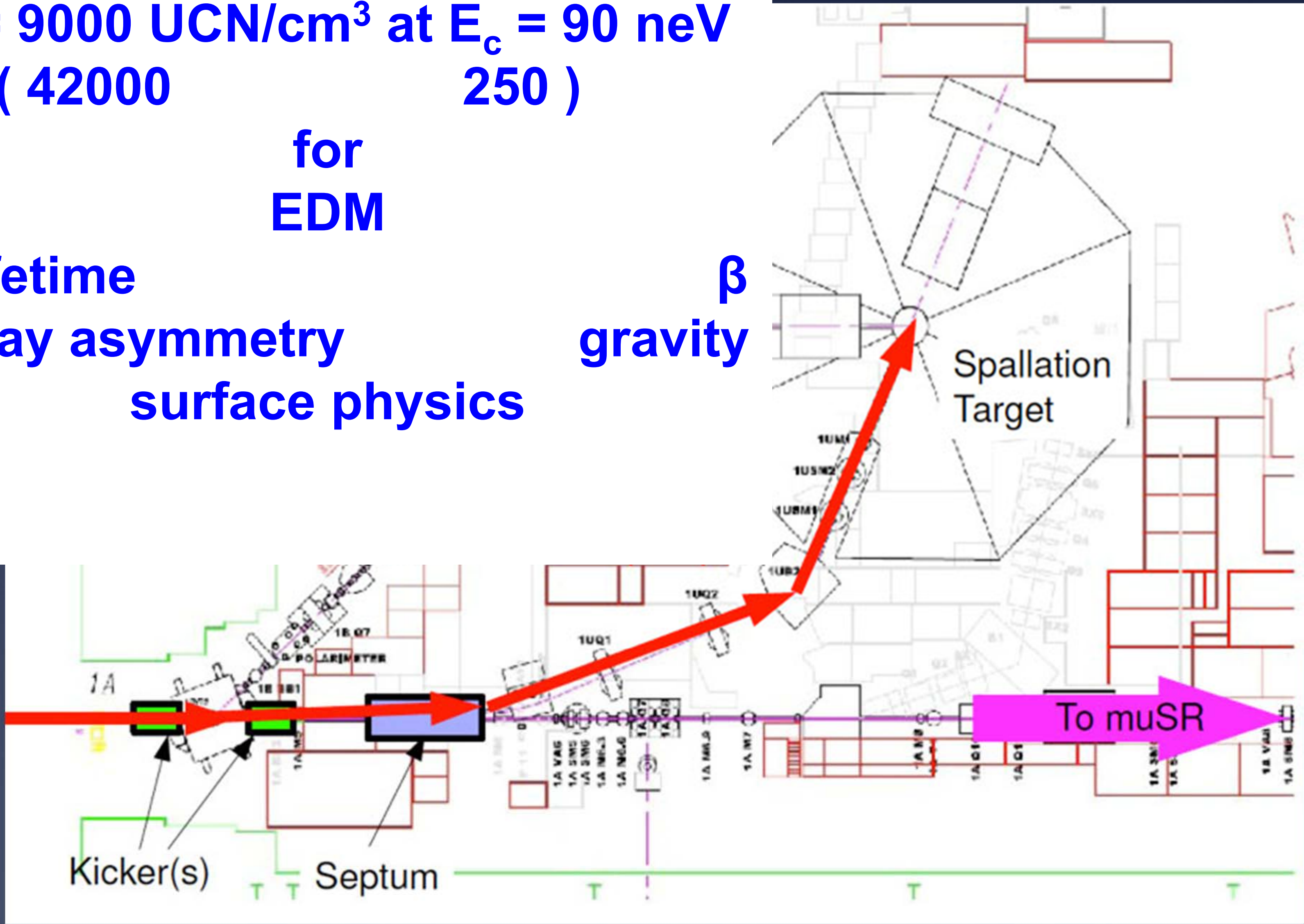
EDM

n lifetime β

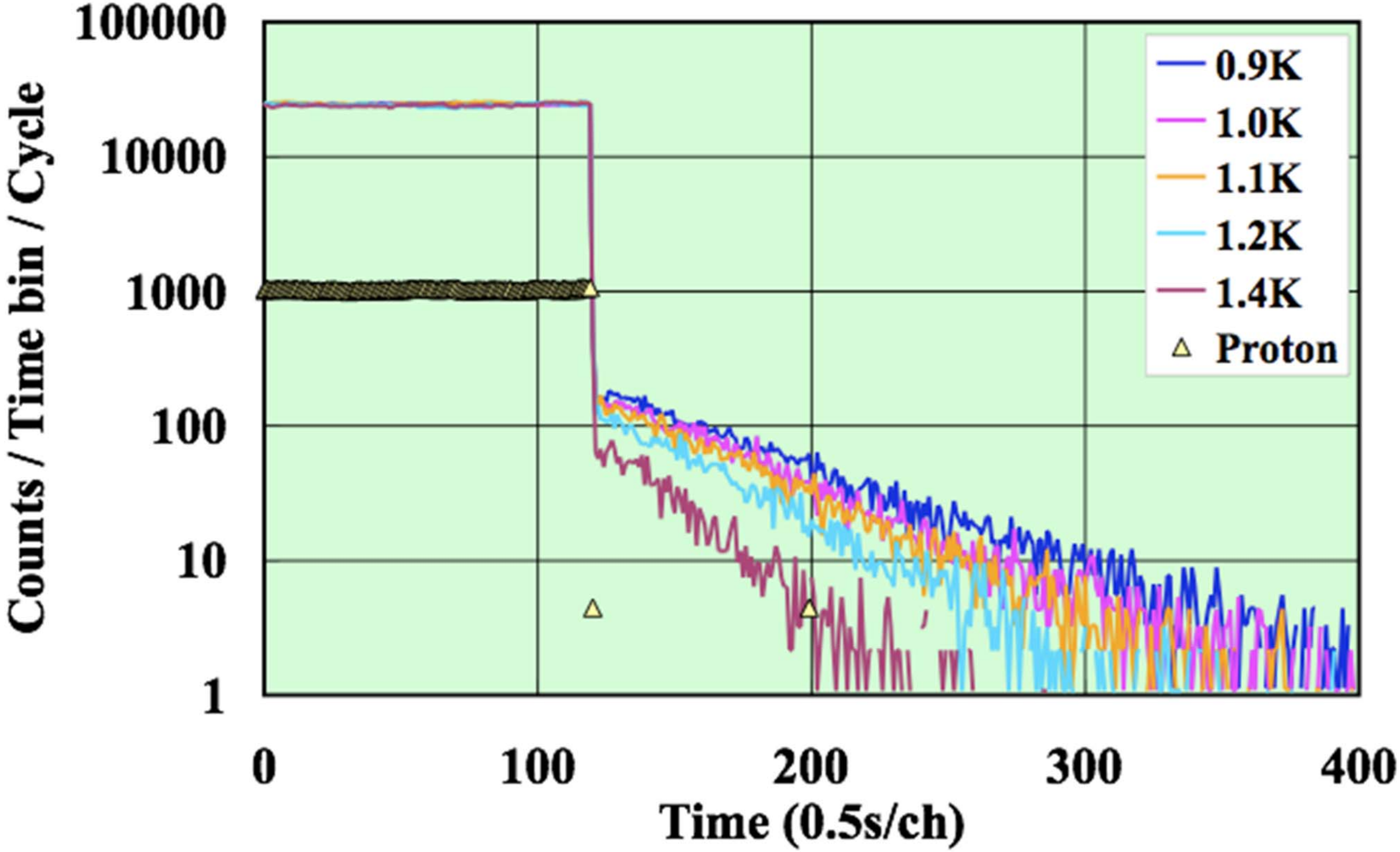
decay asymmetry gravity

surface physics

8 months/year !



With a proton-pulse of 60 s, 1 μA



World's UCN projects, $\rho_{UCN} = P_{UCN} \times \tau_s \times \varepsilon_{ext} \times$(dilution factor)

	source type	E_c neV	P_{UCN} /cm³/s	τ_s s	ε_{ext}	ρ_{UCN} /cm³ source/exp.
Ours	spallation He-II	210	0.4×10^4 (10L)	150	~1	3×10^5 (20L) /5×10^4
ILL	n beam He-II	250	10	150	~1	**/1000
SNS	n beam He-II	134	0.3 (7L)	500	1	**/150
PNPI	reactor He-II					
LANL	spallation SD2	250	4.4×10^4 (240cm³)	1.6	1.3×10^3/ 4.4×10^4*	145 (3.6L) /120
PSI	spallation SD2	250	2.9×10^5 (27L*)	6	0.1	2000 (2m³) /1000
NCSU	reactor SD2	335	2.7×10^4 (1L)	**	**	1300/**
Munich	reactor SD2	250	**	**	**	1×10^4/**