Instruments for fundamental science

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Outline

1. The impossible particle and its properties
2. Search for a neutron electric dipole moment
3. Neutron beta-decay instruments
4. Cold-neutron precision polarimetry
5. Concepts of ultracold-neutron production

The neutron before Chadwick

The neutron before Chadwick

“Such an atom would posses striking properties. Its outer field would vanish [...] and therefore it should easily penetrate matter. The existence of such an atom is presumably difficult to observe with a spectrograph, and it could not be stored in a closed vessel.“

(„Nuclear Constitution of Atoms“, Proc. Royal Soc. 1920)

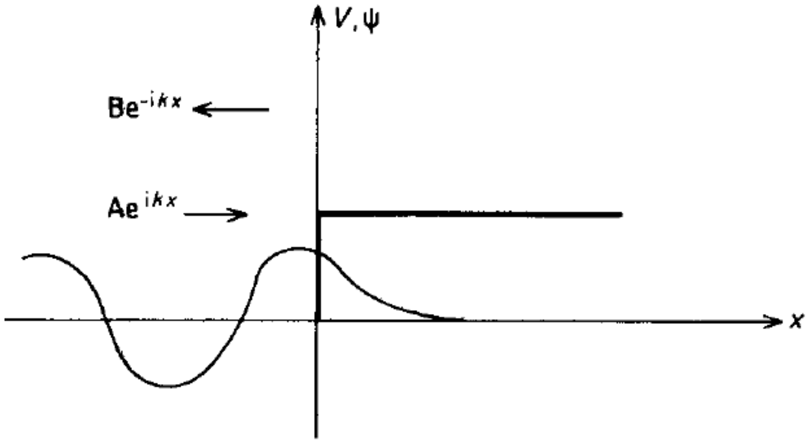
How to store it nevertheless?

Mirror reflection under any angle of incidence

→ ***UCN can be trapped in “neutron bottles”***

Trapping potential #1:

neutron optical potential *V* + i*W*



Origin:

- neutron scattering by nuclei
- interference of incident and scattered waves
- refractive index:

$$n = \frac{k'}{k} = \sqrt{1 - \frac{V}{E}}$$

$$V = \frac{2\pi\hbar^2}{m} N a$$

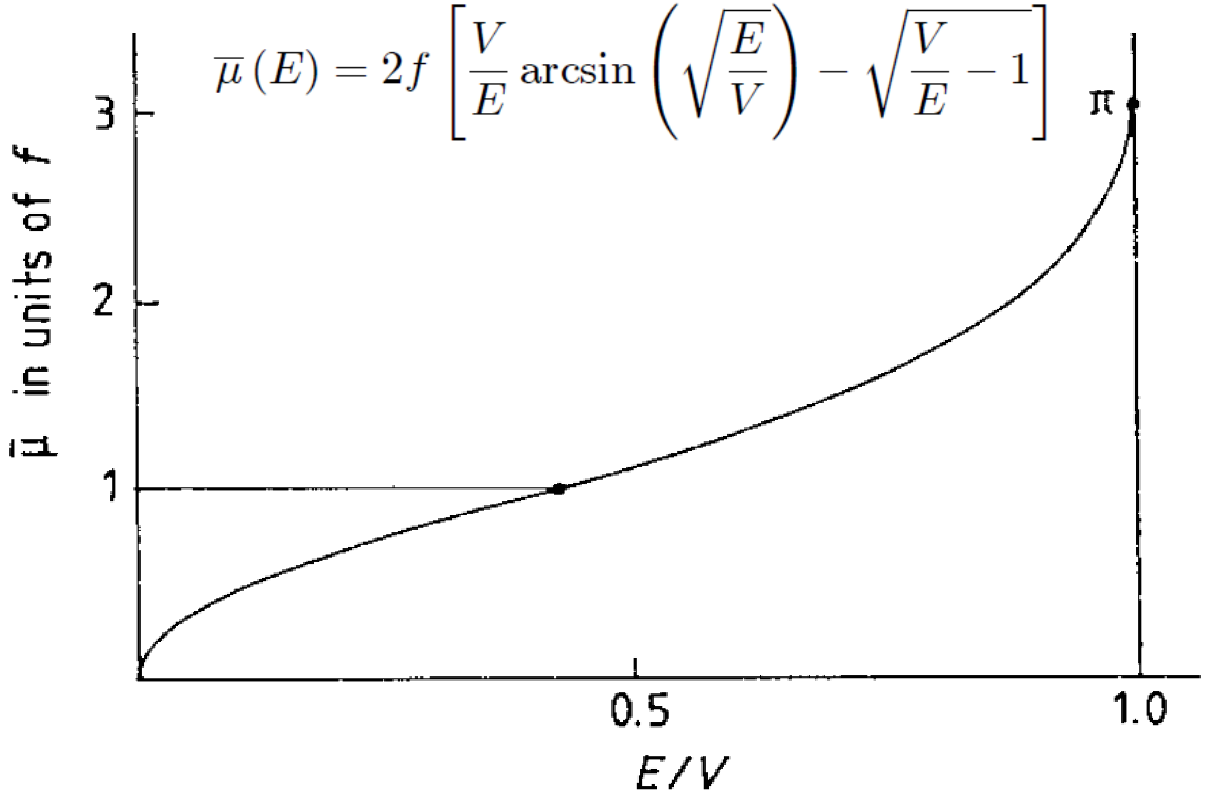
Typical values for *V*:

Be: 252 neV,   Al: 54 neV,   Ti: -49 neV

W is due to capture and inelastic scattering
→ losses of trapped UCN ensemble

- barn capture cross section materials: $f = W/V \sim 10^{-4}$
- best value obtained for mbarn material: 2×10^{-6}

Loss per wall collision for trapped UCN gas:

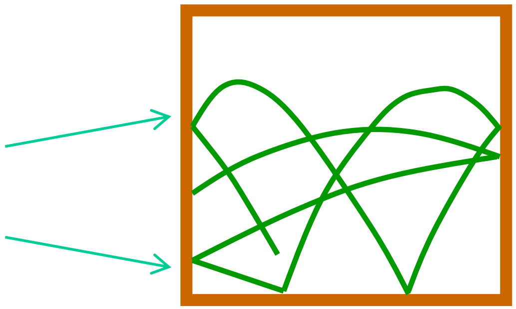


$$\overline{\mu}\,(E) = 2f\left[\frac{V}{E}\arcsin\left(\sqrt{\frac{E}{V}}\right) - \sqrt{\frac{V}{E}-1}\right]$$

Trapping potential #2:

neutron gravity ***mgz*** for Δz = 1 m: ΔE = 100 neV

Losses at height *z* $\propto \frac{\epsilon_0 - mgz}{\epsilon_0}\overline{\mu}\,(\epsilon_0 - mgz)$

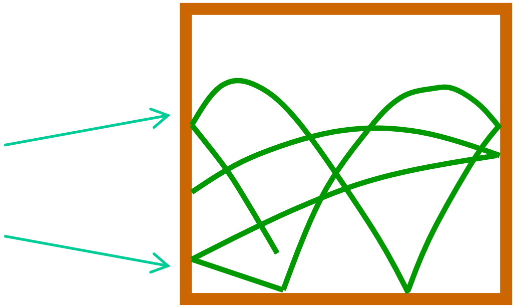


lower losses here
than there

Trapping potential #2:

neutron gravity ***mgz***   for Δz = 1 m: ΔE = 100 neV

Losses at height z $\propto \frac{\epsilon_0 - mgz}{\epsilon_0}\overline{\mu}\left(\epsilon_0 - mgz\right)$



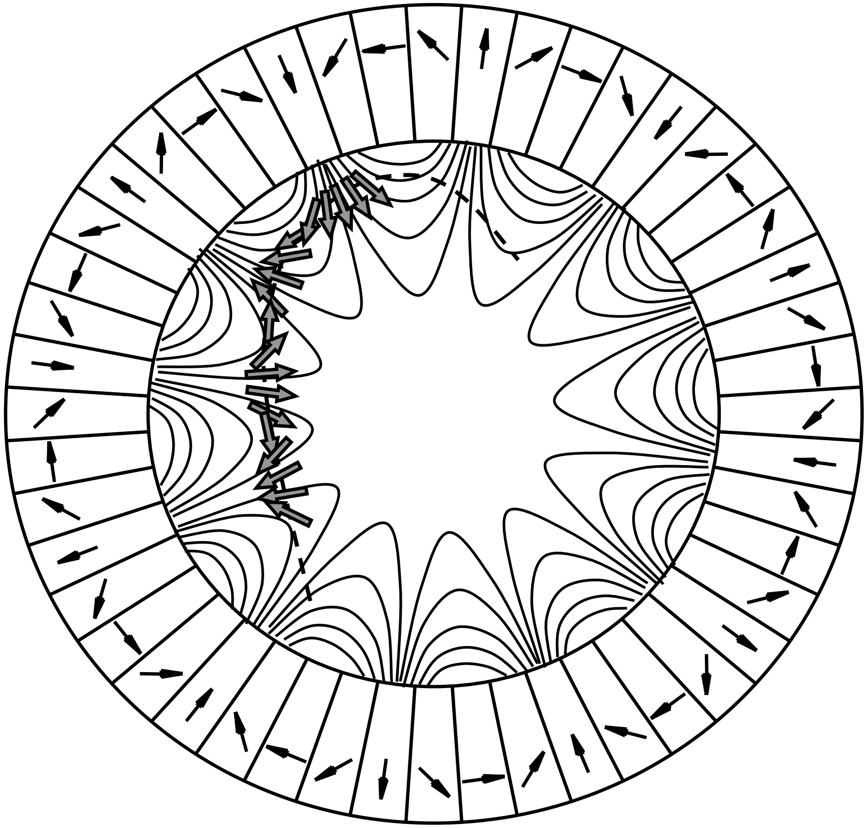
lower losses here
than there

as good for trapping
(if bottle is tall enough):

Trapping potential #3:

magnetic interaction $\pm\mu B$

for ΔB = 1 T: ΔE = ±60 neV



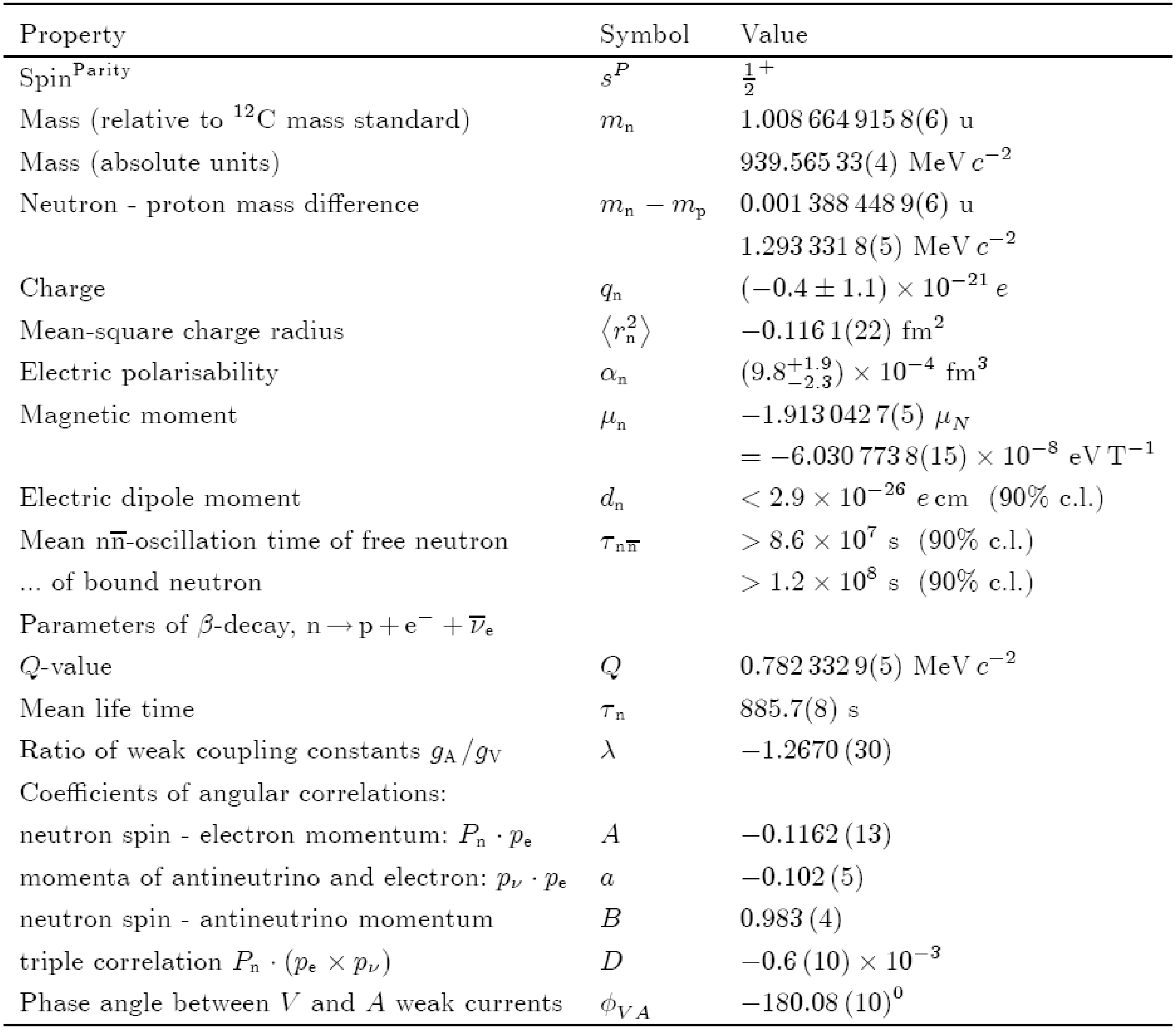
Adiabatic spin transport if

$$\frac{1}{|\boldsymbol{B}|}\cdot\left|\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right| \ll \frac{\boldsymbol{\mu}\cdot\boldsymbol{B}}{\hbar} = \omega_\mathrm{L}$$

→ mT fields sufficient in typical situations

Magnetic gradient fields suppress losses due to wall collisions

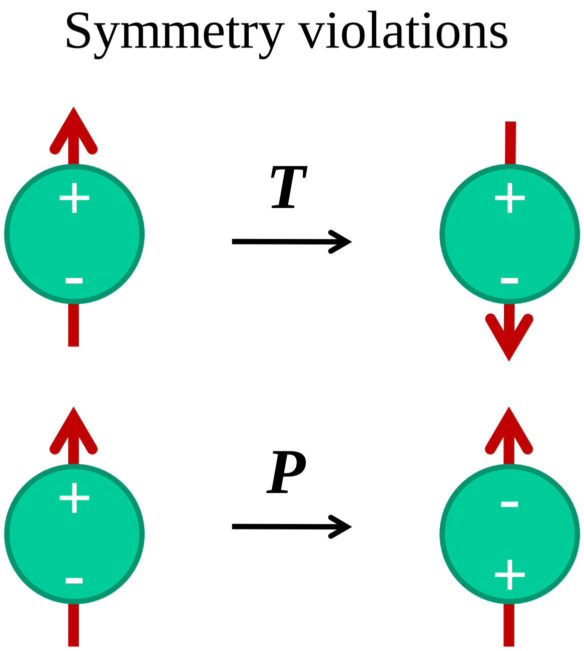
Neutron properties:

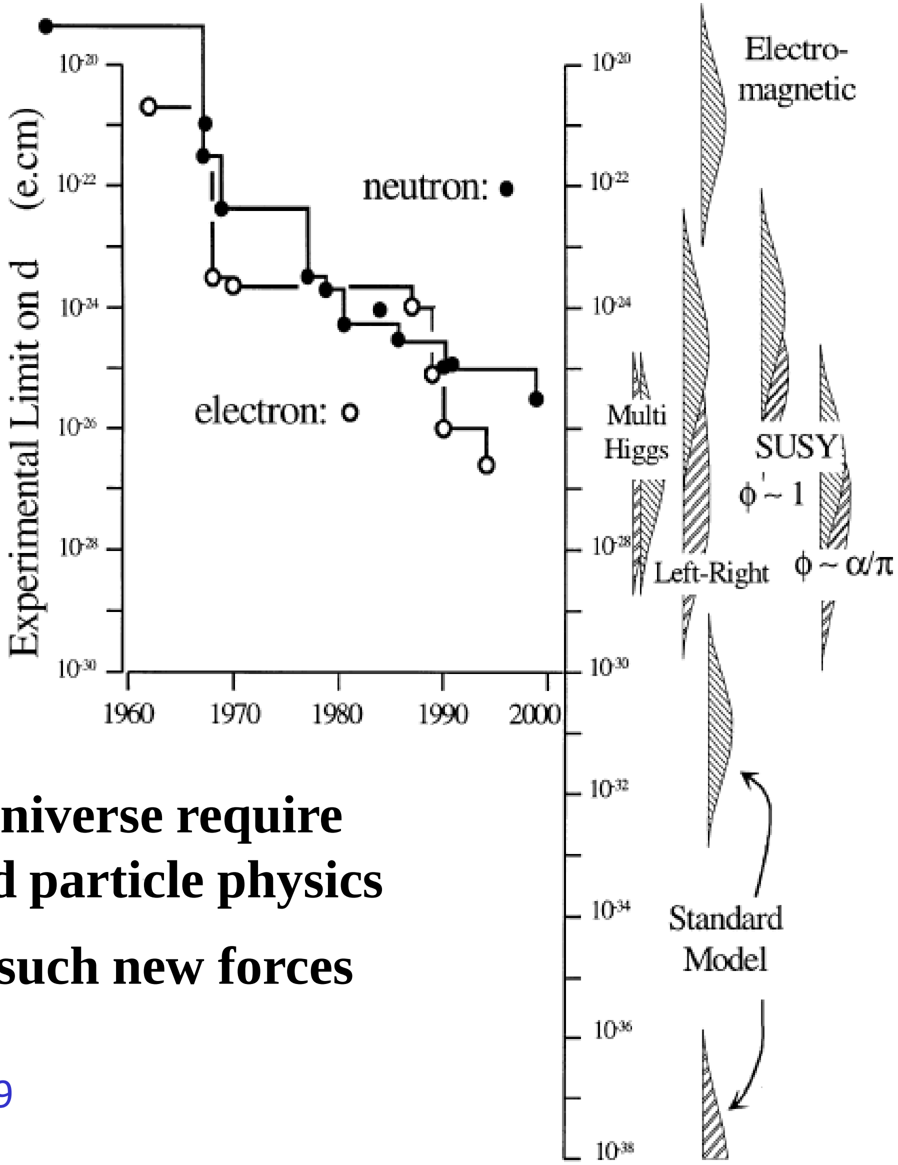


Property	Symbol	Value
Spin$^{\text{Parity}}$	s^P	$\frac{1}{2}^+$
Mass (relative to ^{12}C mass standard)	m_n	$1.008\,664\,915\,8(6)$ u
Mass (absolute units)		$939.565\,33(4)$ MeV c^{-2}
Neutron - proton mass difference	$m_\text{n} - m_\text{p}$	$0.001\,388\,448\,9(6)$ u
		$1.293\,331\,8(5)$ MeV c^{-2}
Charge	q_n	$(-0.4 \pm 1.1) \times 10^{-21}\ e$
Mean-square charge radius	$\langle r_\text{n}^2 \rangle$	$-0.116\,1(22)$ fm^2
Electric polarisability	α_n	$(9.8^{+1.9}_{-2.3}) \times 10^{-4}$ fm^3
Magnetic moment	μ_n	$-1.913\,042\,7(5)\ \mu_N$
		$= -6.030\,773\,8(15) \times 10^{-8}$ eV T^{-1}
Electric dipole moment	d_n	$< 2.9 \times 10^{-26}\ e\,\text{cm}$ (90% c.l.)
Mean n$\overline{\text{n}}$-oscillation time of free neutron	$\tau_{\text{n}\overline{\text{n}}}$	$> 8.6 \times 10^7$ s (90% c.l.)
... of bound neutron		$> 1.2 \times 10^8$ s (90% c.l.)
Parameters of β-decay, $\text{n} \rightarrow \text{p} + \text{e}^- + \overline{\nu}_\text{e}$		
Q-value	Q	$0.782\,332\,9(5)$ MeV c^{-2}
Mean life time	τ_n	$885.7(8)$ s
Ratio of weak coupling constants g_A/g_V	λ	$-1.2670\,(30)$
Coefficients of angular correlations:		
neutron spin - electron momentum: $P_\text{n} \cdot p_\text{e}$	A	$-0.1162\,(13)$
momenta of antineutrino and electron: $p_\nu \cdot p_\text{e}$	a	$-0.102\,(5)$
neutron spin - antineutrino momentum	B	$0.983\,(4)$
triple correlation $P_\text{n} \cdot (p_\text{e} \times p_\nu)$	D	$-0.6\,(10) \times 10^{-3}$
Phase angle between V and A weak currents	ϕ_{VA}	$-180.08\,(10)^0$

precison is crucial for applications!

Search for a neutron electric dipole moment





- 6×10^{-10} **nucleons per photon in our Universe require CP violating forces beyond standard particle physics**
- **neutron EDM is a sensitive probe to such new forces**

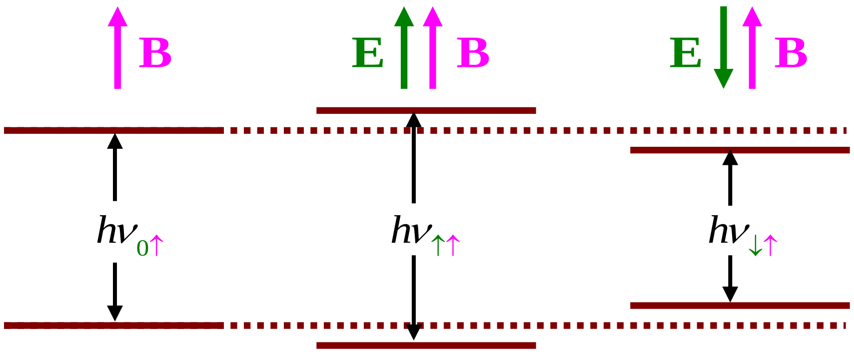
M. Pospelov, A. Ritz, Annals Phys. **318** (2005) 119

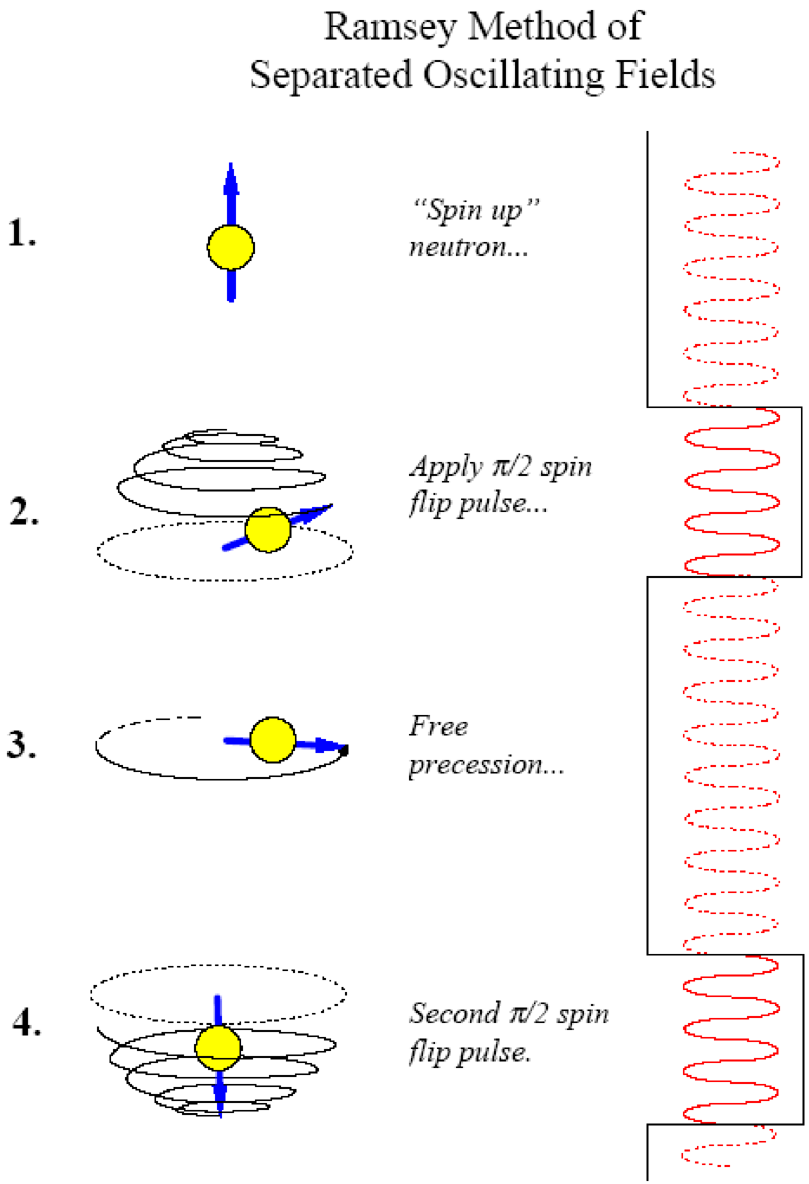
How can we measure it?

compare spin precession frequencies for

E parallel to **B**: $$\nu_{\uparrow\uparrow} = \frac{2}{h}\left(\boldsymbol{\mu}\cdot\mathbf{B} + \mathbf{d}_n\cdot\mathbf{E}\right)$$

E anti-parallel to **B**: $$\nu_{\downarrow\uparrow} = \frac{2}{h}\left(\boldsymbol{\mu}\cdot\mathbf{B} - \mathbf{d}_n\cdot\mathbf{E}\right)$$



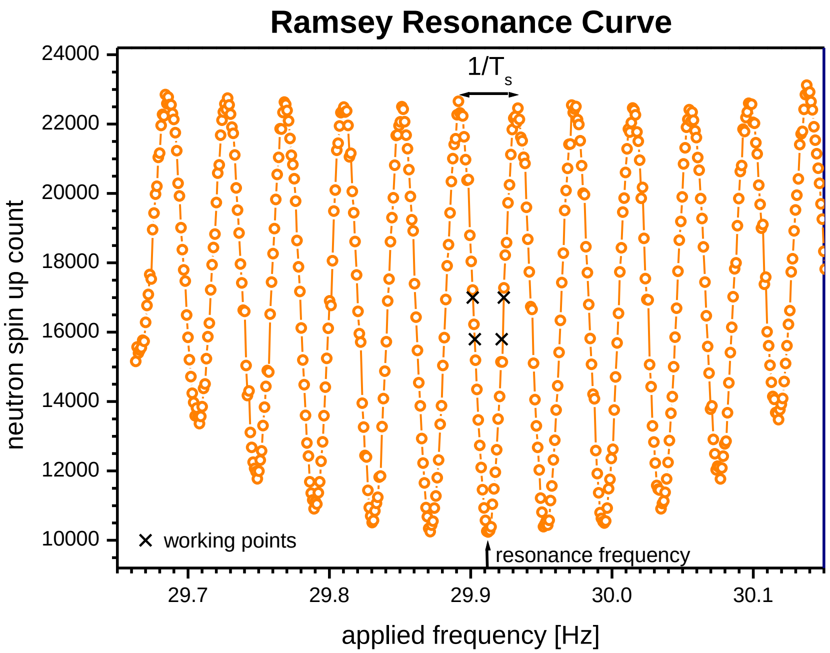

Ramsey Method of Separated Oscillating Fields

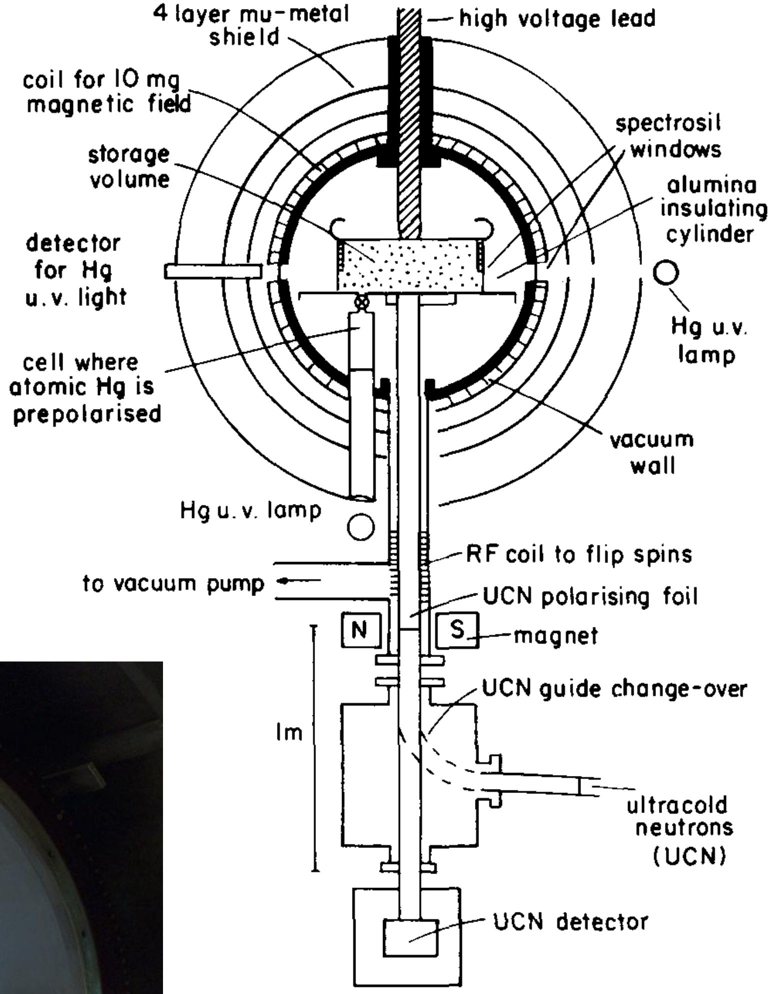
1. *"Spin up" neutron...*

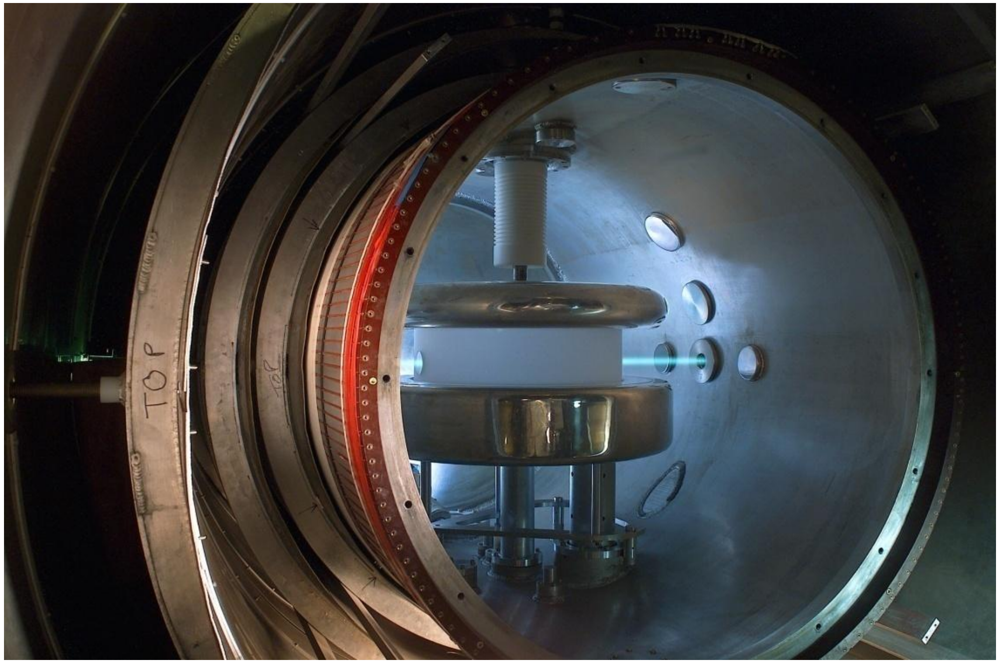
2. *Apply π/2 spin flip pulse...*

3. *Free precession...*

4. *Second π/2 spin flip pulse.*



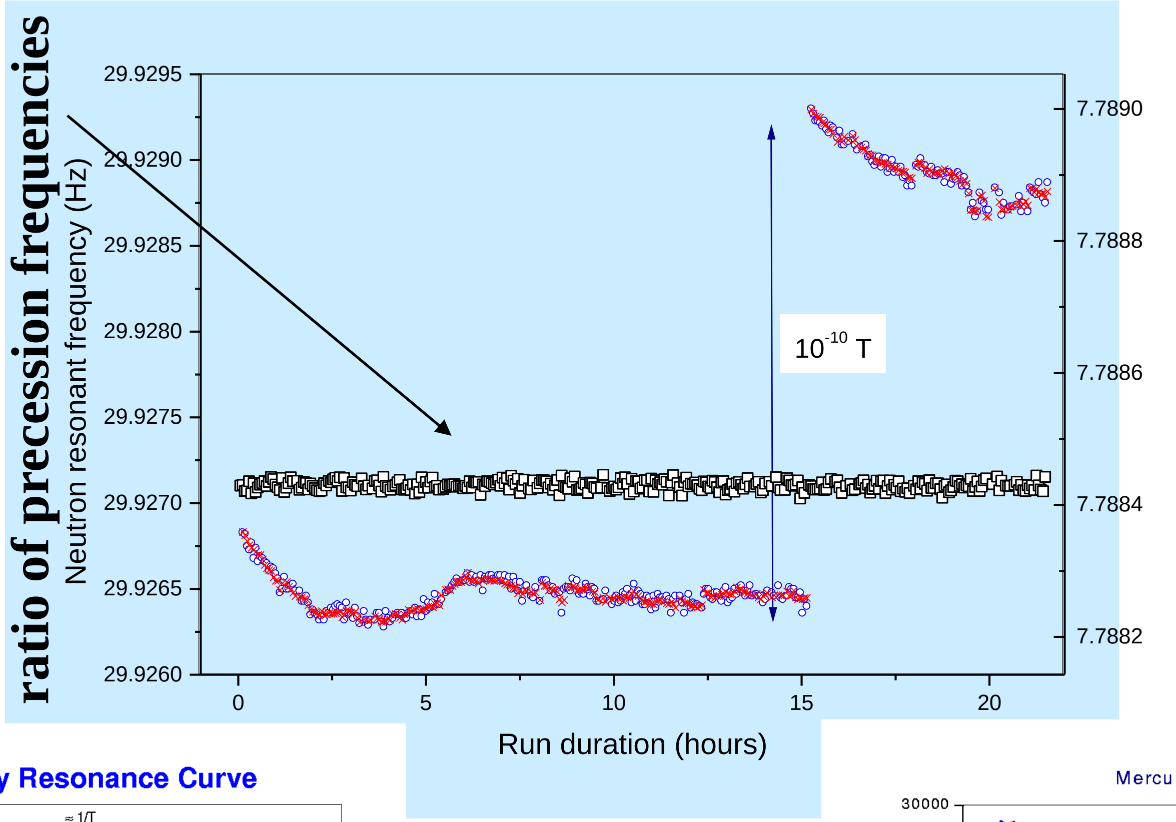




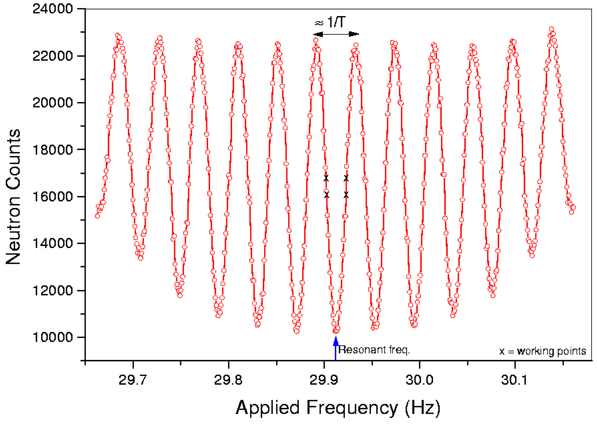
$$\sigma\left(d_{\mathrm{n}}\right) = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

Rutherford, Sussex, ILL

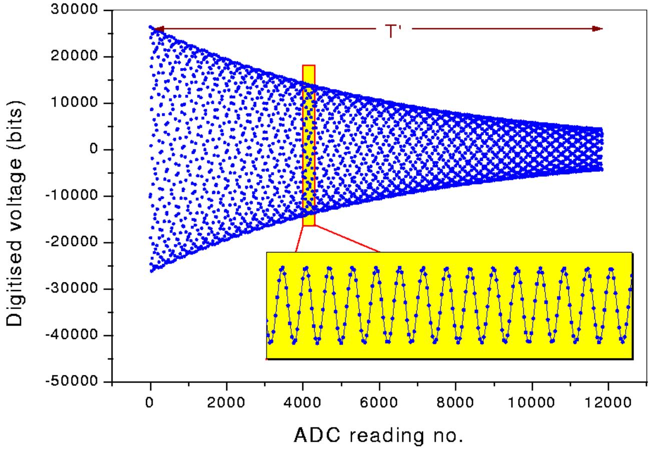
^{199}Hg co-magnetometer for correction of magnetic field drifts



Ramsey Resonance Curve



Mercury spin precession

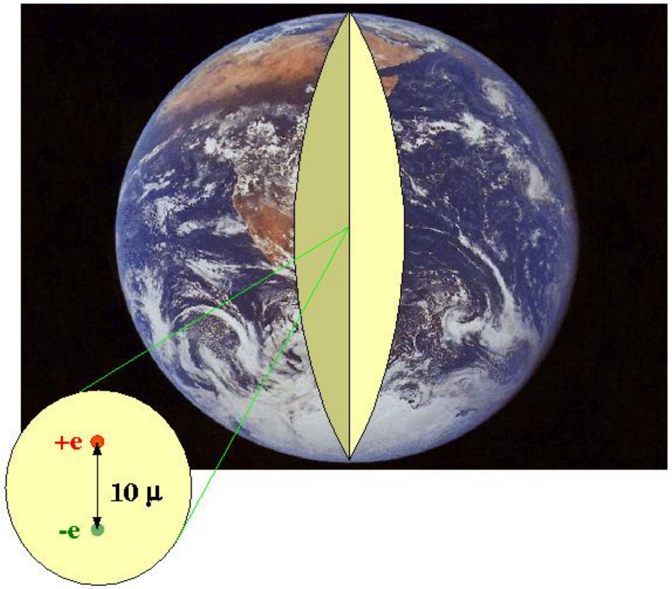


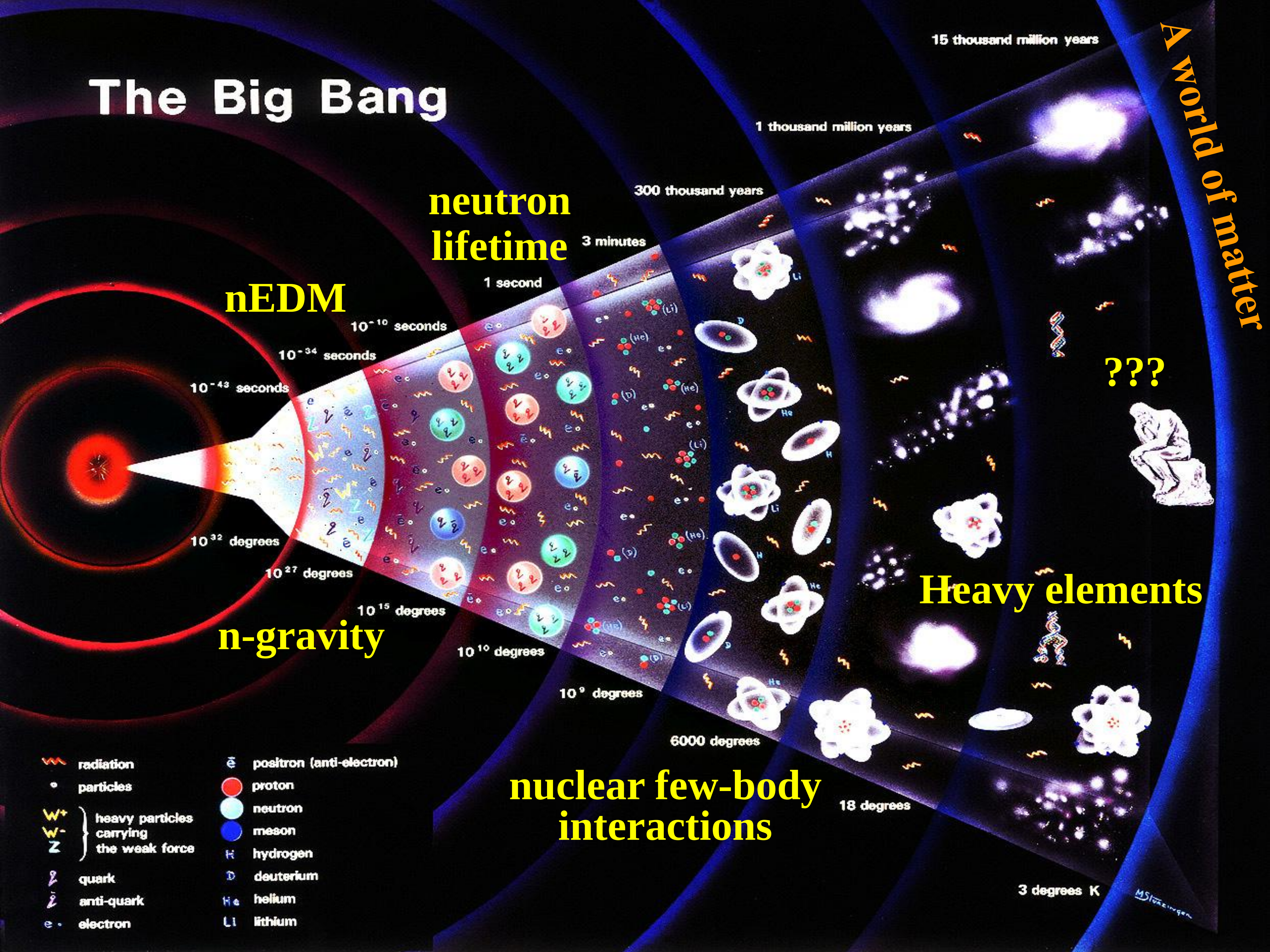
Best result so far (RAL / Sussex / ILL)

$|d_n| < 2.9 \times 10^{-26}$ **e cm** (90% CL)

C.A. Baker et al., PRL **63** (2006) 131801

- **10^{-22} eV spin-dependent interaction**
- **one spin precession per half year**





neutron lifetime

nEDM

n-gravity

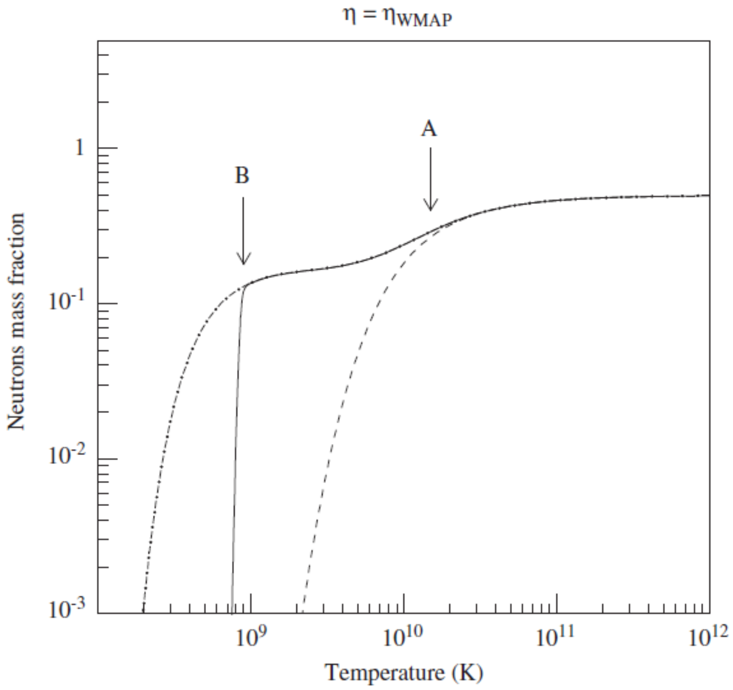
nuclear few-body interactions

Heavy elements

???

A world of matter

Big bang nucleosynthesis and the neutron lifetime



10^{-6} s (100 MeV) quarks & gluons form nucleons

$n + e^{+} \leftrightarrow p + \nu, \quad n + \nu \leftrightarrow p + e, \quad n \rightarrow p + e + \nu$

$$\frac{[\mathrm{n}]}{[\mathrm{p}]} = \exp\left(-\frac{\Delta m c^2}{kT}\right)$$

1 s (1 MeV) neutrinos decouple ⇒ neutrons decay

$n \rightarrow p + e + \nu, \quad p + n \leftarrow d + \gamma$

3 min (0.1 MeV) deuterons become stable

$p(n,\gamma)d, \quad d(d,n)^{3}He, \quad d(d,p)^{3}H, \quad {}^{3}He(n,\gamma)^{4}He \ldots$

after 30 min **primordial abundances of light elements:**

^{1}H	75%
^{4}He	25%
^{2}H	30ppm
^{3}He	13ppm
^{7}Li	4×10^{-10}

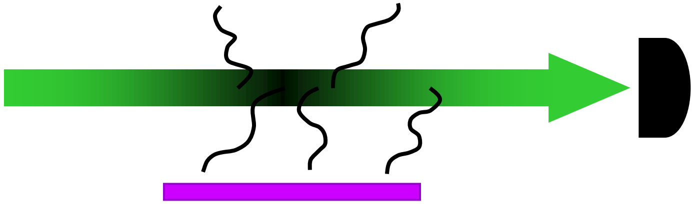
A. Coc, NIM A 611 (2009) 224
R.E. Lopez, M.S. Turner, PR D 59 (1999) 103502
Steven Weinberg: The first three minutes

How can we measure the neutron lifetime?

- **In-beam experiments:**
  - measure radioactivity of a neutron beam:

$$\boxed{\frac{dN}{dt} = -\frac{N}{\tau_n} = -\frac{\rho V}{\tau_n}}$$

$E_n \approx$ **a few meV**

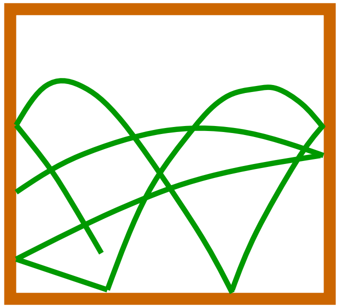


- requires absolute determinations of $\frac{dN}{dt}$, ρ and V

- **UCN trapping experiments:**
  - measure decrease of neutron number directly:

$$\boxed{N(t) = N(0)\exp\left(-\frac{t}{\tau}\right)}$$

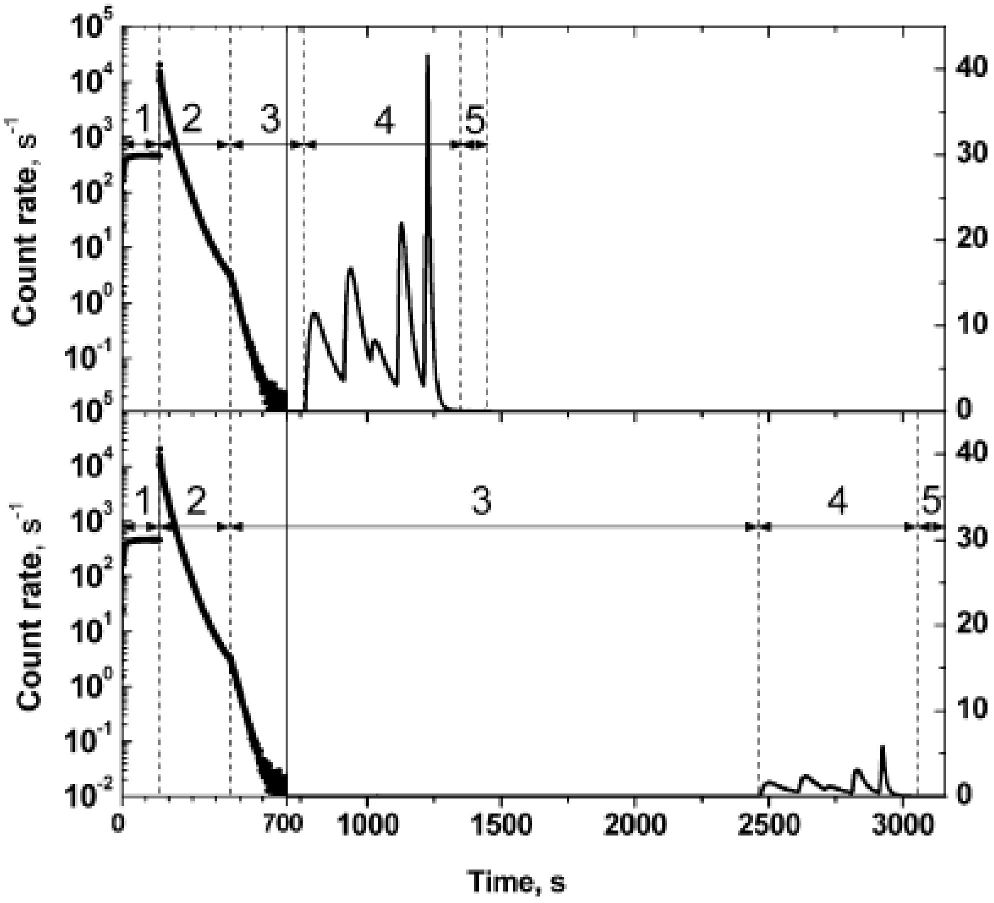
$E_n <$ **250 neV**

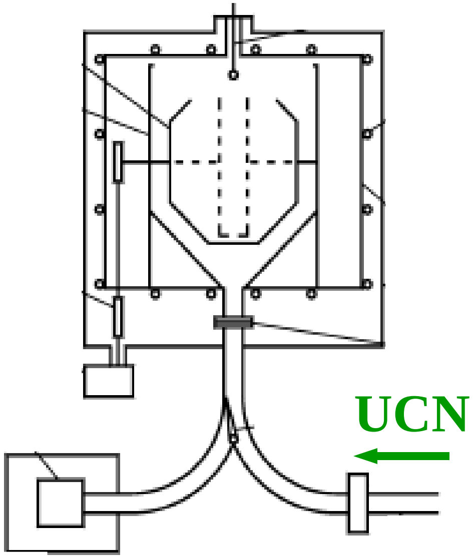


- No absolute determinations, but: $\tau^{-1} = \tau_{\mathrm{n}}^{-1} + \tau_{\mathrm{loss}}^{-1}$

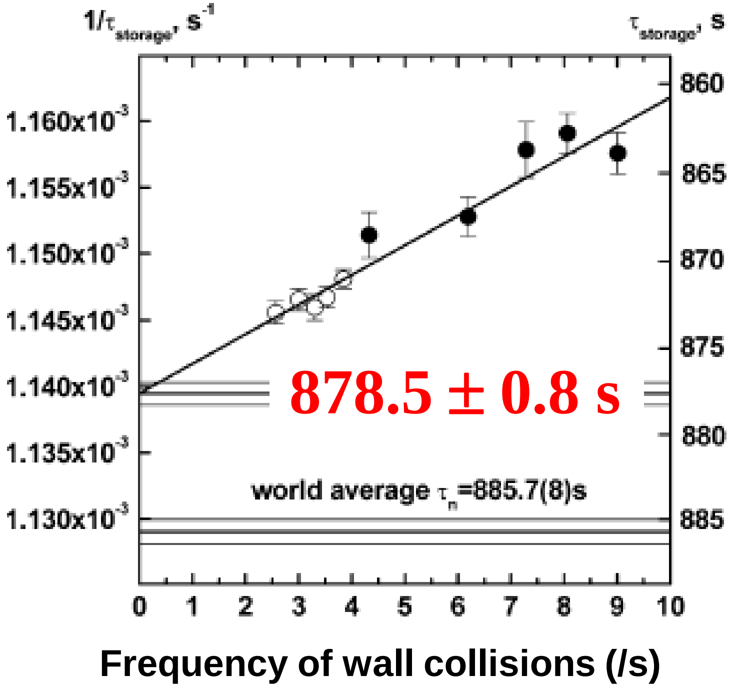
Neutron lifetime experiment with low-*T* „fomblin“ oil coated walls

A. Serebrov et al., Phys. Lett. B 605 (2005) 72

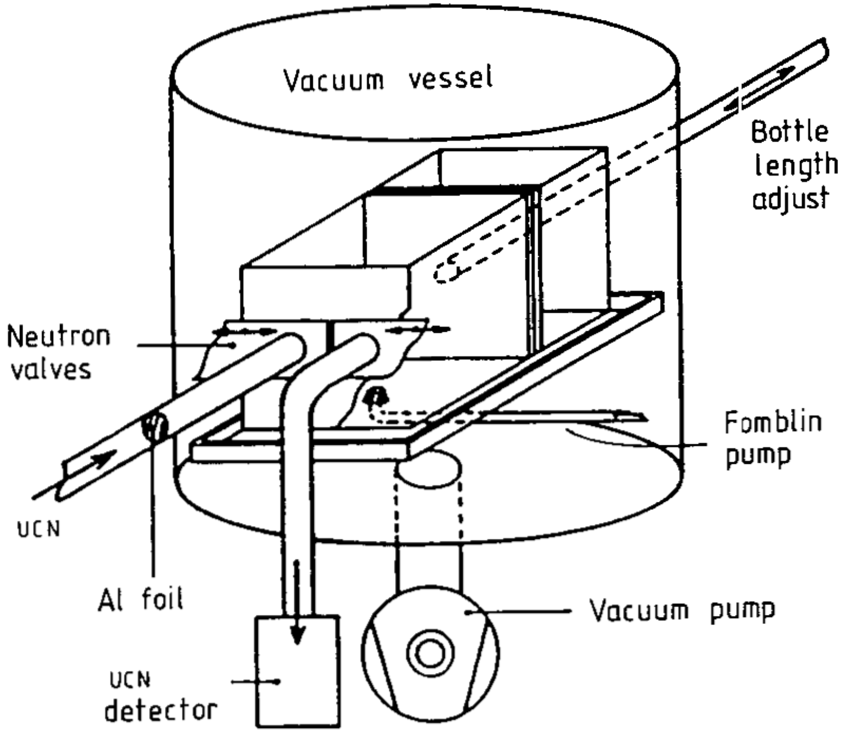




$$\tau_{\text{storage}}^{-1} = \tau_{\text{n}}^{-1} + \tau_{\text{loss}}^{-1}$$



The liquid-wall trap of Walter Mampe



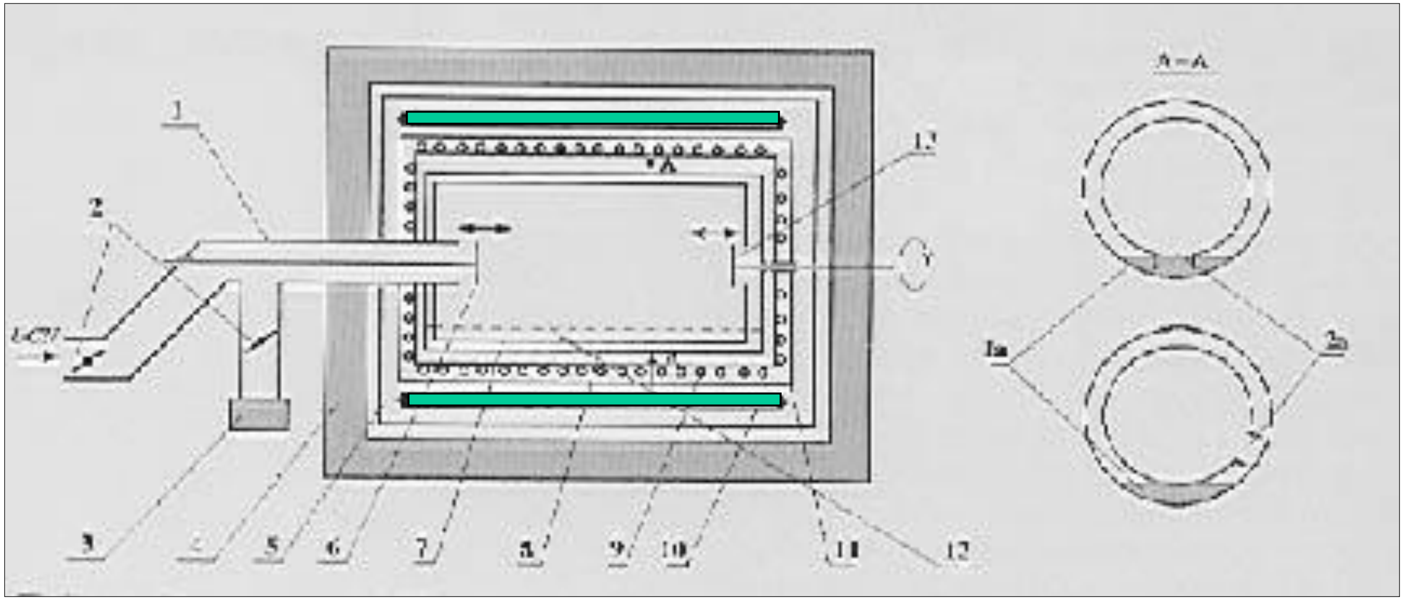
- Liquid surfaces (fomblin oil)
- Modulation of losses via well-defined variation of the ratio surface/volume
- Extrapolation: volume → ∞
- Result:

$\tau_n = 887.6 \pm 3$ s W. Mampe et al., Phys. Rev. Lett 63 (1989) 593

- Result of MAMBO II:

880.7 ± 1.8 s A. Pichlmaier et al. Phys. Lett. B 693 (2010) 221

Experiment with detection of upscattered neutrons

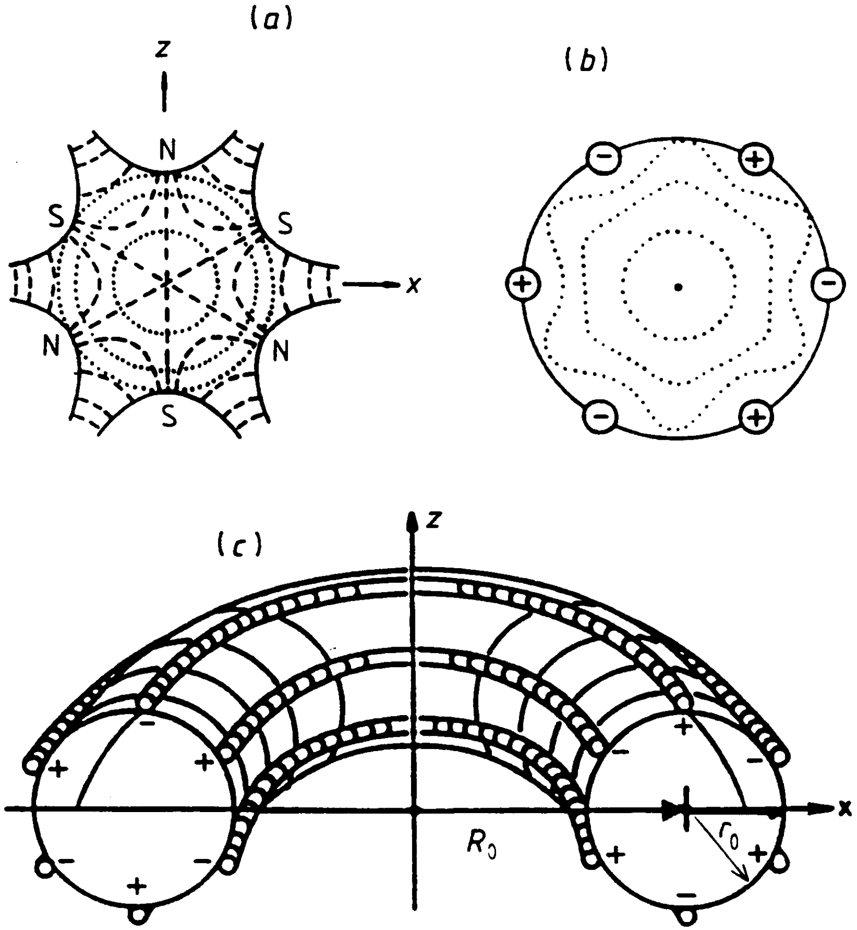


- Liquid surfaces (fomblin oil)
- Result:

$\tau_n = 885.4 \pm 0.9_{stat} \pm 0.4_{syst}$ s   Arzumanov et al., Phys. Lett. B 483 (2000) 15

$881.6 \pm 0.8_{stat} \pm 1.9_{syst}$ s   Arzumanov et al. JETP Lett. 95 (2012) 224

NESTOR: magnetically trapped VCN (20 m/s)



τ_n = 877.0 ± 10 s

W. Paul et al., Z. Phys. C 45 (1989) 25

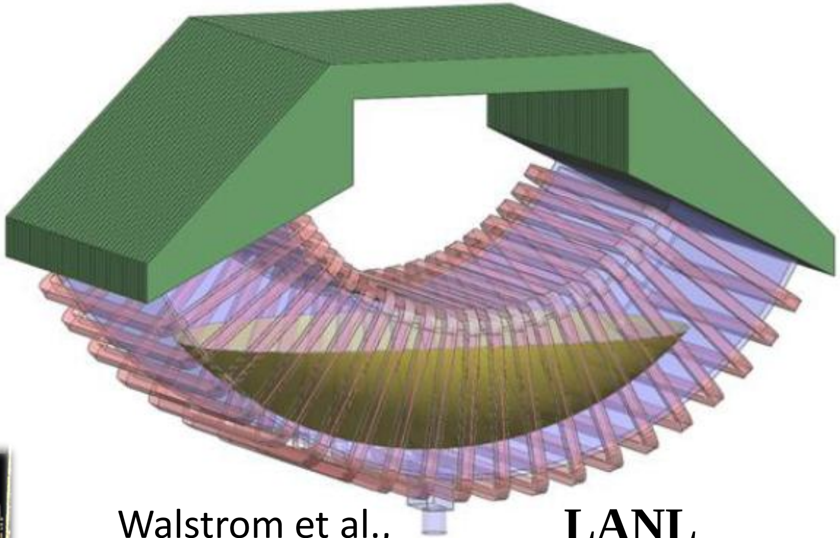
Present magnetic trap projects

UCNτ (electron detection)

Penelope
(proton detection)

TU Munich

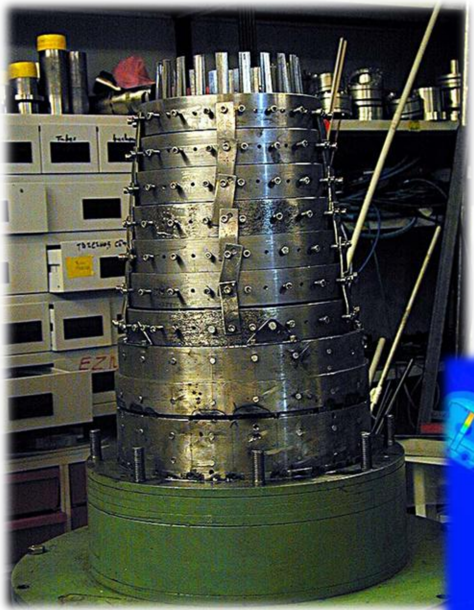
perm. mag. trap
("fill and empty")



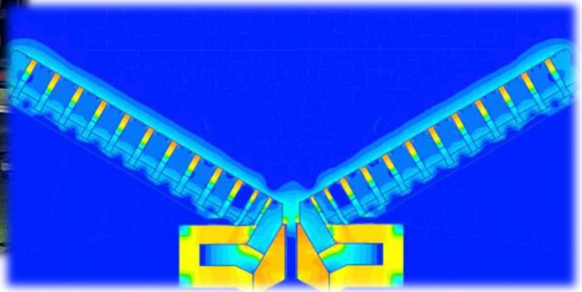
Walstrom et al.,
NIM A 599 (2009) 82

LANL

R. Picker et al.,
J. Res. NIST 110 (2005) 357



PNPI / LPC / ILL



V. Ezhov et al. J. Res. NIST 110 (2005) 345

Benefit/challenge comparison of two magnetic trapping strategies

$$\boxed{N(t) = N(t_0)\exp\left(-\frac{t}{\tau_\mathrm{n}}\right)}$$

“fill and empty”

detection of UCN

– need to determine $N(t_0)$

– fast coil ramping required

⊕ high SNR

⊕ Low sensitivity to time-dependent backgrounds

⊕ Monitoring of depolarisation and leakage of marginally trapped neutrons

“counting the deads”

detection of decay β’s or p’s

⊕ get decay curve in one shot

⊕ needs only slow coil ramping

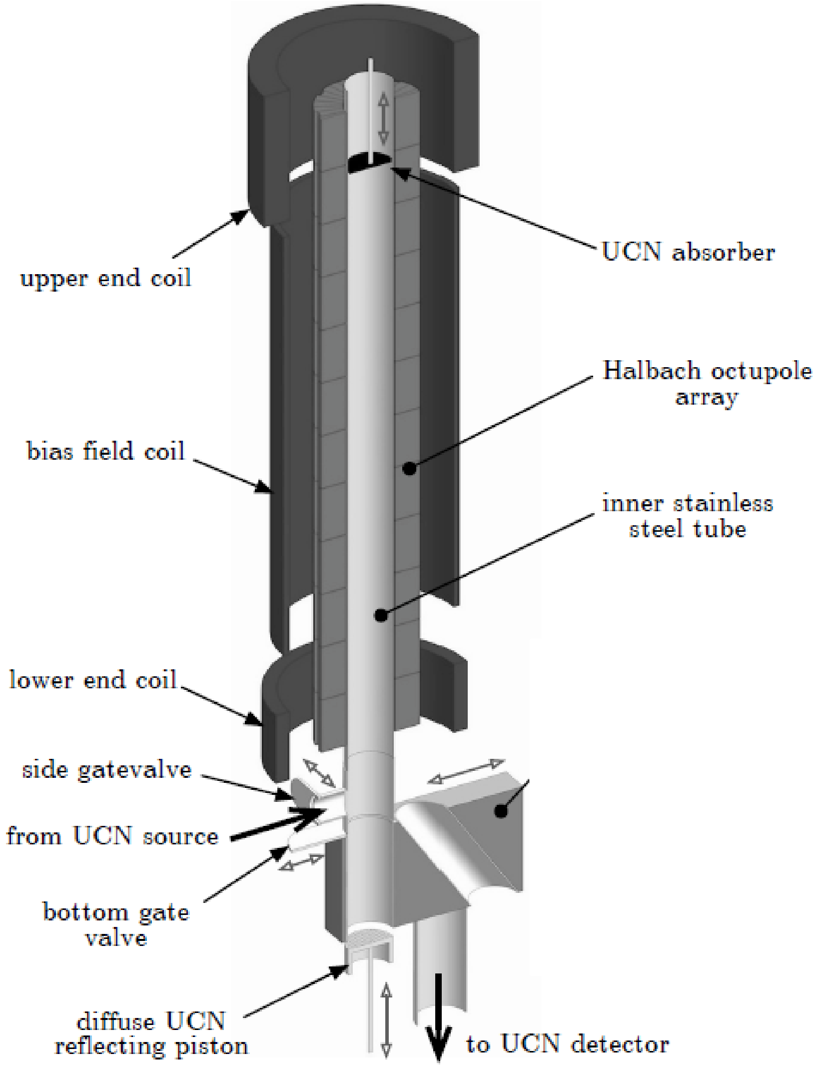
– SNR for β-detection

– stability issue for p-detection

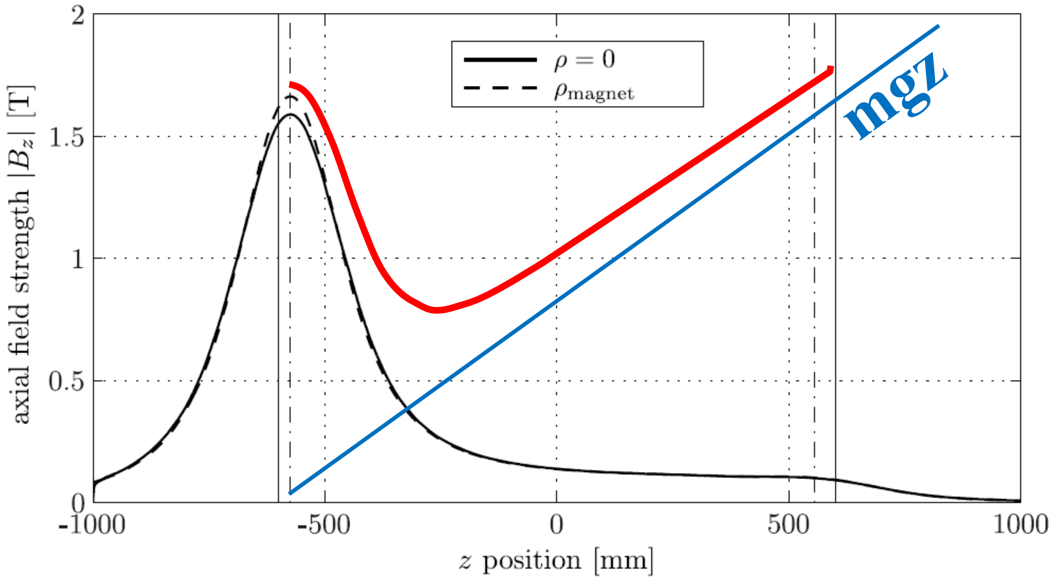
– susceptible to time-dependent backgrounds and variations of neutron density distributions

HOPE – Halbach OctuPole neutron lifetime Experiment

Ph.D. theses:
K. Leung, F. Rosenau, F. Lafont

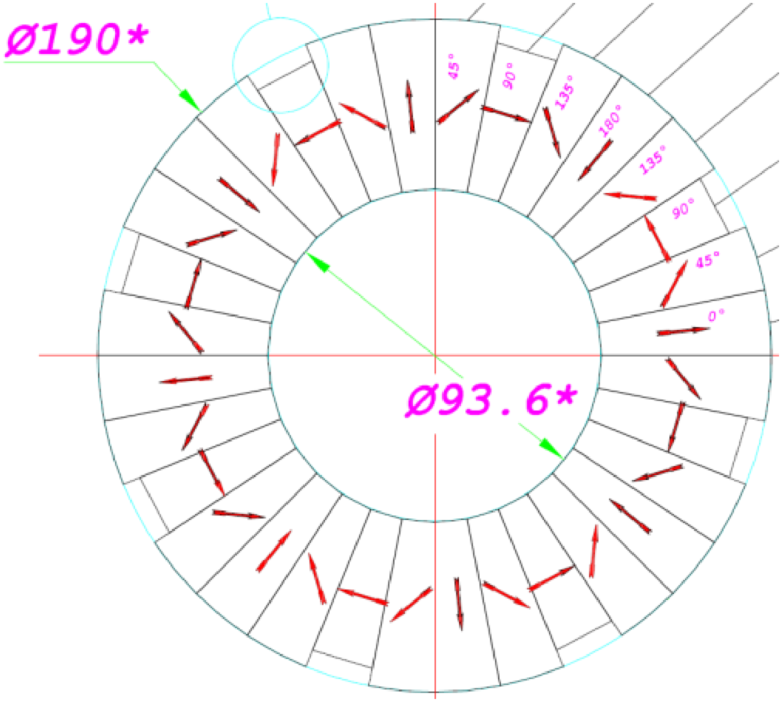


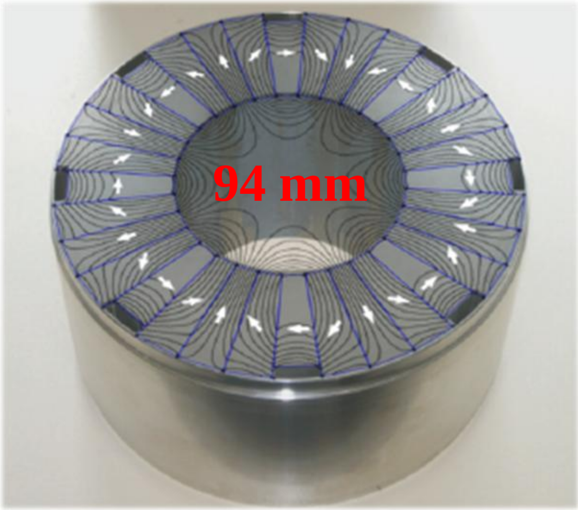
- magneto-gravitational trap
- $V_{\mathrm{eff}} \approx 2$ l
- trap depth 40 – 45 neV
- high-density UCN source
- counting the dead & survivors

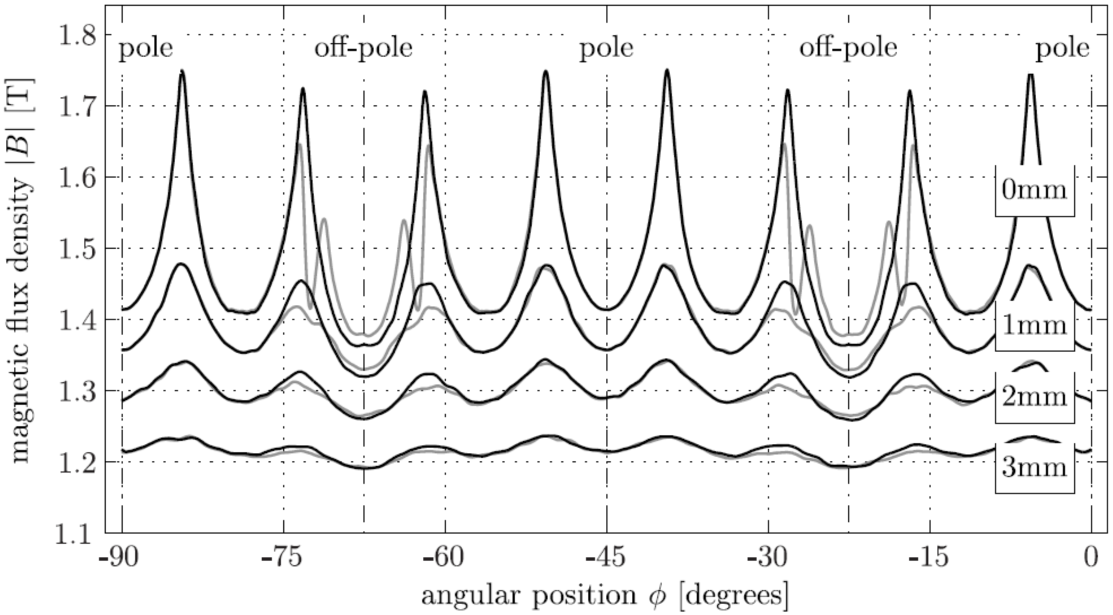


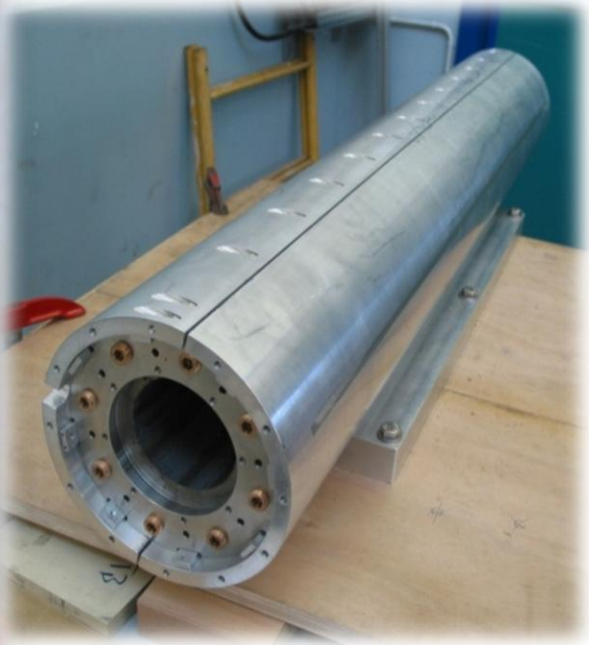
Halbach octupole

- $B(r) = B_R(r/R)^3$
- 32 magnet slices
- NdFeB magnets: $B_R = 1.35$ T





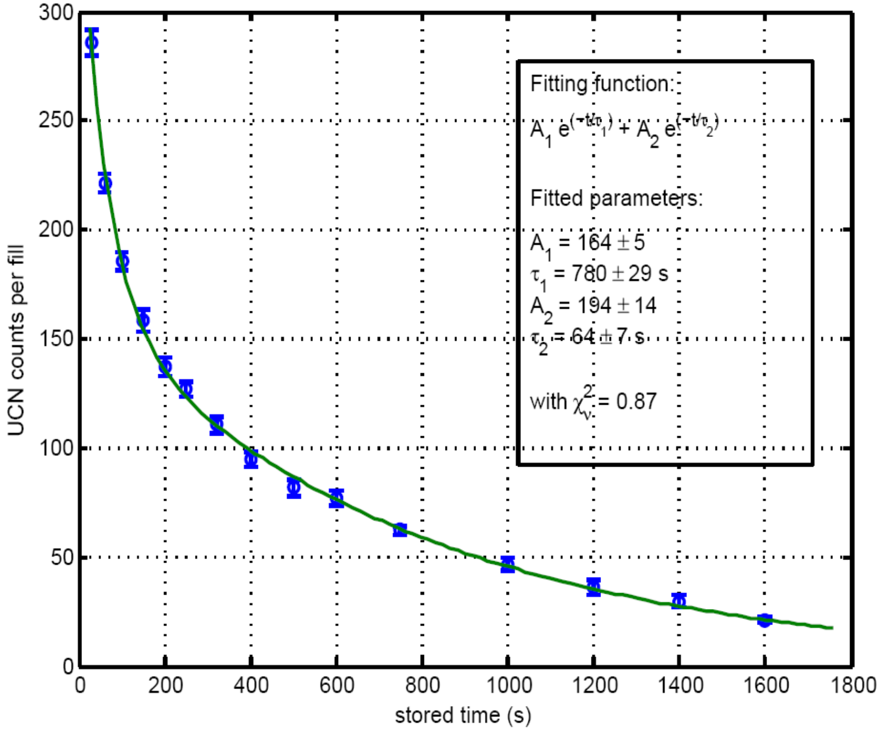




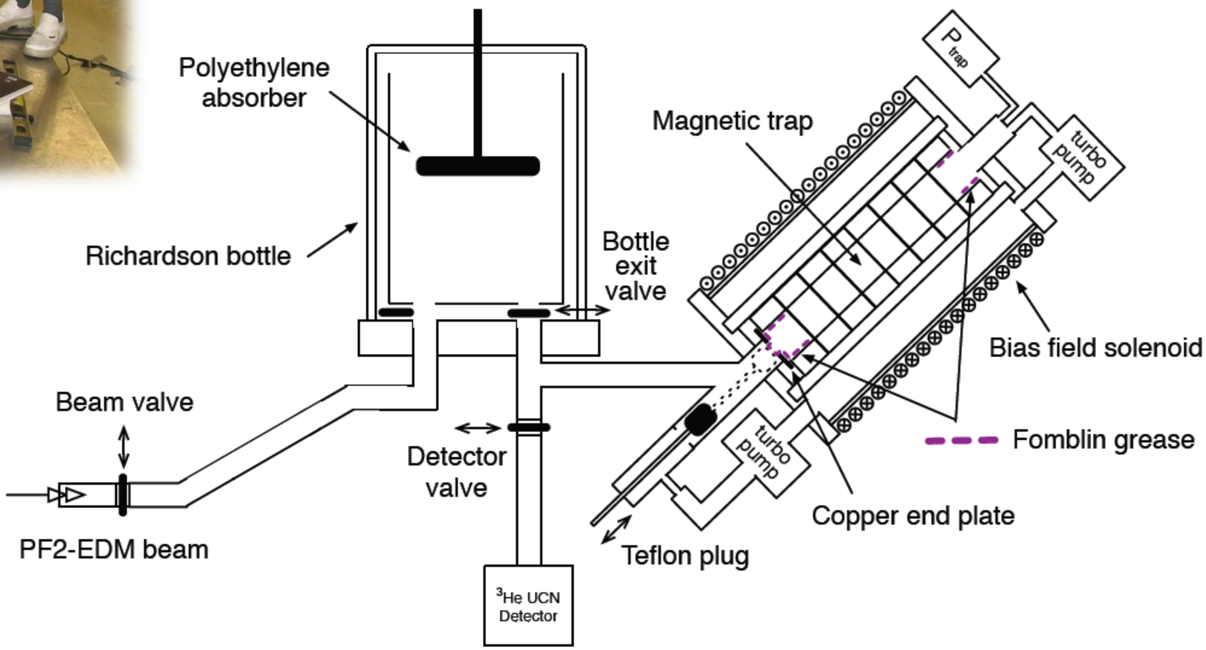
12 octupoles + hands & forces = magnetic trap

First UCN trapping at PF2

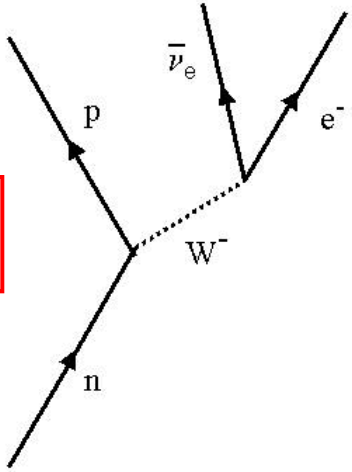
Ph.D. thesis Kent Leung



Storage time achieved: **780 s**
(trap closed by teflon plug)



Neutron β decay in a broader context



in Standard model:

$$\boxed{n \to p + e^- + \bar{\nu}_e \quad (+782\ \text{keV})}$$

„V-A“ structure with

known Fermi- and Gamow-Teller matrix elements

precise determination of g_A and g_V from two independent n-decay observables

$$\tau_n^{-1} \propto g_V^2 \left(1 + 3\lambda^2\right) \qquad \lambda = g_A / g_V$$

from β asymmetry
(PERKEO and other expts.)

$\Rightarrow$ **semileptonic weak cross sections**

$$n + e^+ \leftrightarrow p + \bar{\nu}_e \qquad n + \nu_e \leftrightarrow p + e \qquad p + p \to d + e^+ + \nu_e \ \ldots$$

$\Rightarrow$ **precision test of CKM unitarity:**

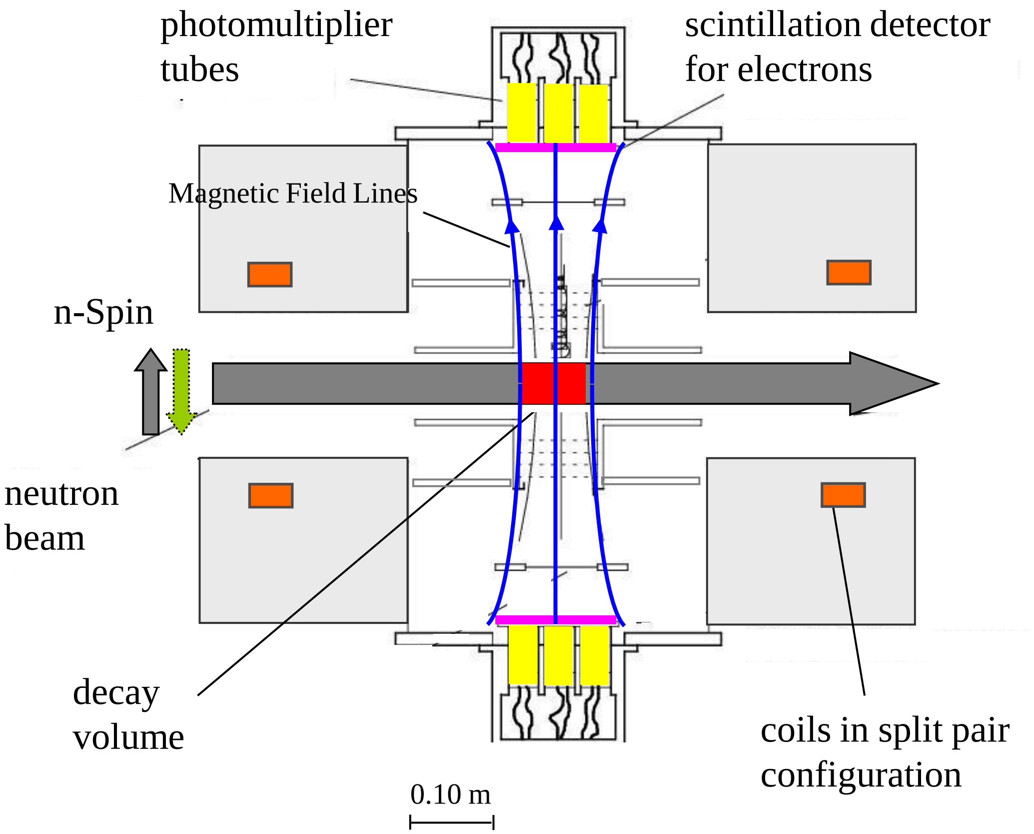
$$g_V = G_F V_{ud} \qquad |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

+ various other tests of the standard model of particle physics

Example: Neutron decay spectrometer PERKEO II

measured decay asymmetries of polarised neutrons:

$$\vec{P}_n \cdot \vec{p}_{electron} \;, \qquad \vec{P}_n \cdot \vec{p}_{neutrino} \;, \qquad \vec{P}_n \cdot \vec{p}_{proton}$$



magnetic field (1.1 T):

- perpendicular to n–beam
- parallel alignment of n–spin
- separation into hemispheres
  - ⇒ integration over hemispheres
  - ⇒ 2 x 2 π detector
- guide e^-, p onto detectors
  - ⇒ detect electron backscatter events

Slide courtesy B. Maerkisch

Its successor instrument: PERKEO III

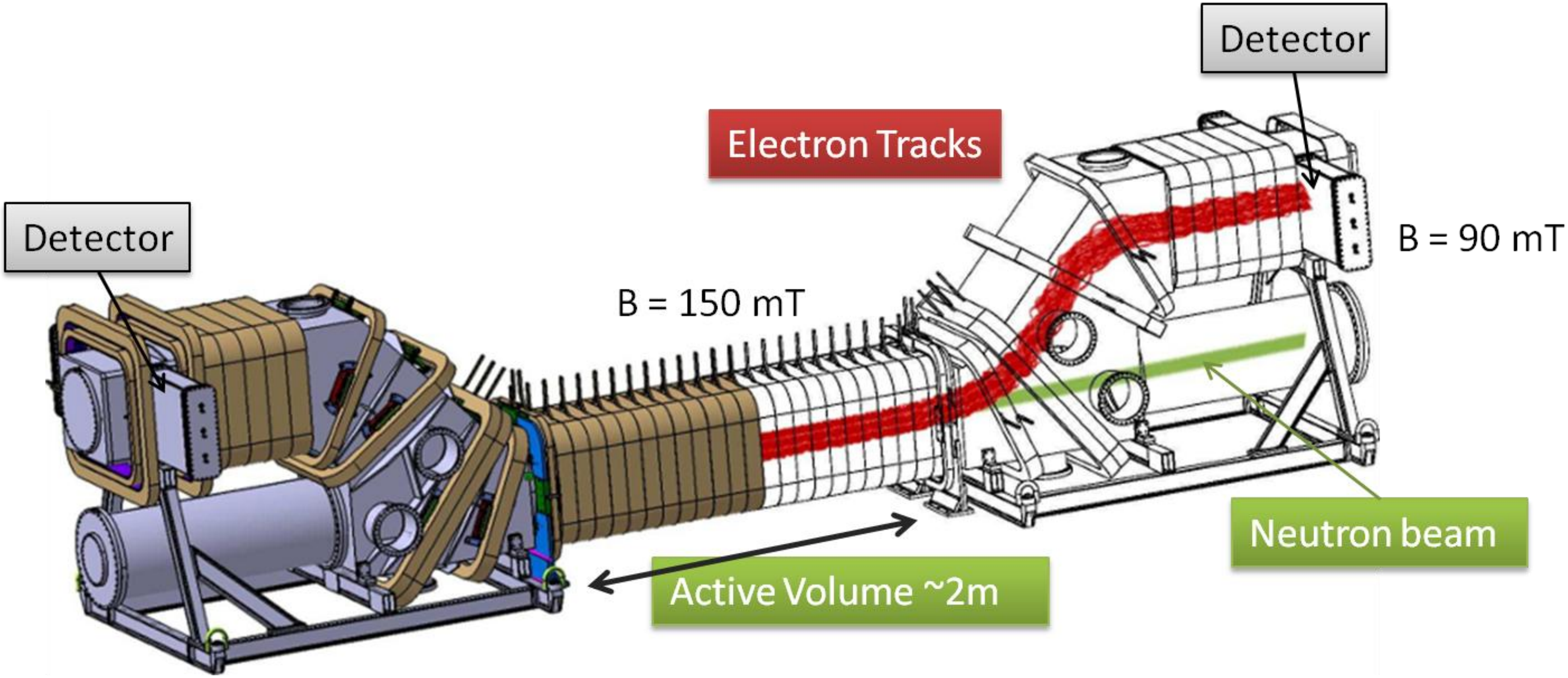
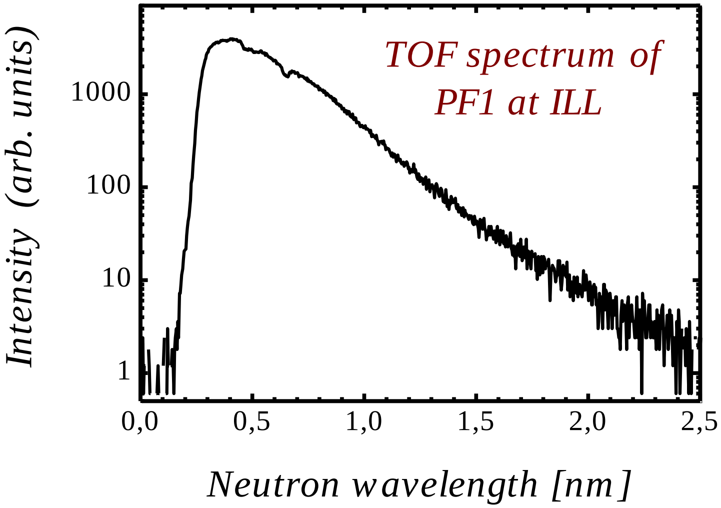


Figure by B. Maerkisch

Typical polarised-n-decay in-beam experiment setup

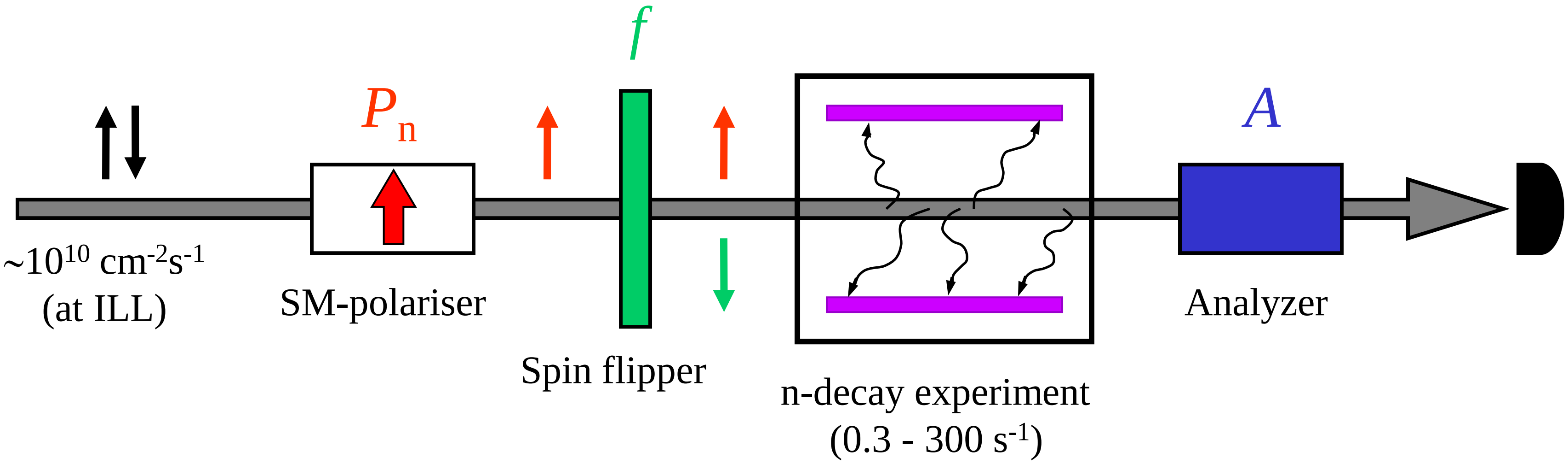
need polarisation of white beam with high precision



- white neutron beam (meV)
- Neutron beam polarisation:

  $95\% < P_n \le 99.7\%$
- Required accuracy for A and f :

  $\le 0.1\%$



~10^{10} cm^{-2}s^{-1}
(at ILL)

SM-polariser

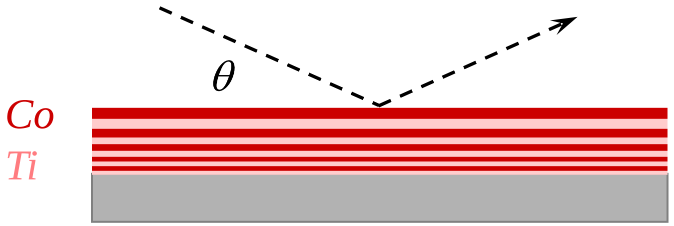
Spin flipper

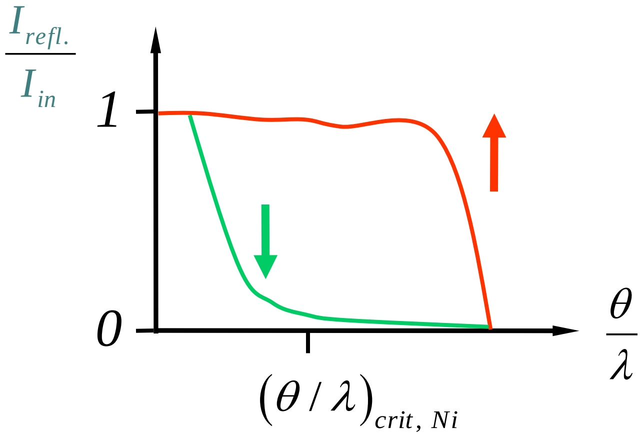
n-decay experiment
(0.3 - 300 s^{-1})

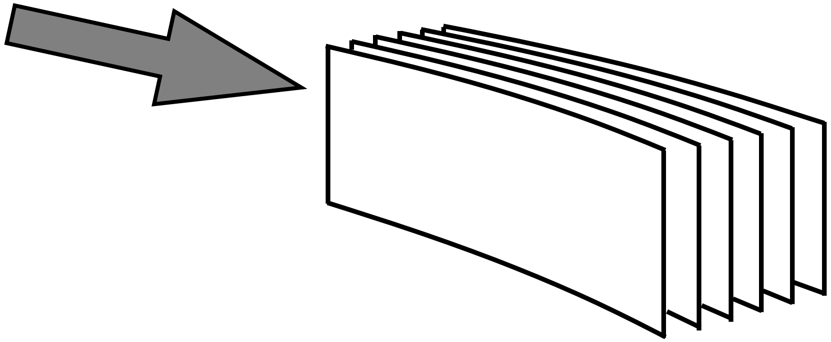
Analyzer

Standard method of neutron beam polarisation:

Supermirrors





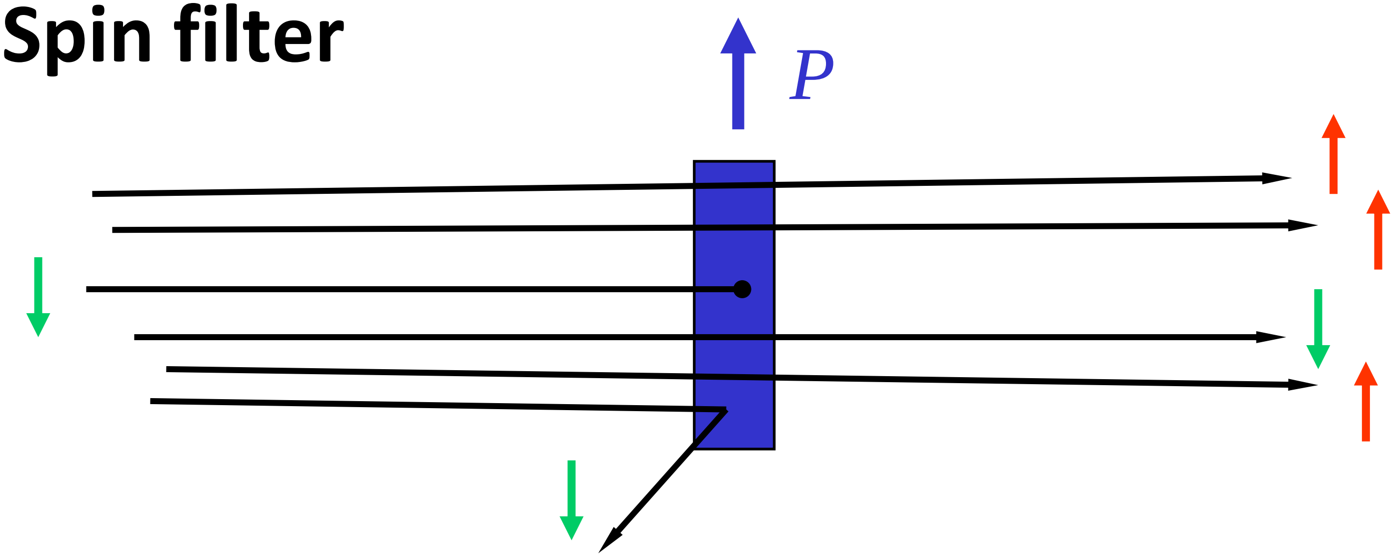


$$P_n(x, y, \Omega, \lambda)$$

$$I(x, y, \Omega, \lambda)$$

O. Schärpf, Physica B 156&157 (1989) 639

Spin filter



Cross section: $\sigma_{\pm} = \sigma_0 \pm P\sigma_p$

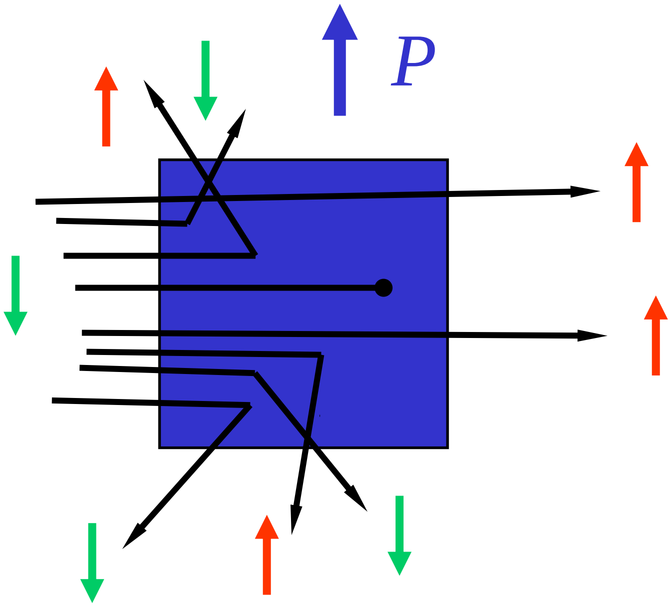
Transmission: $T_{\pm} = \exp\left(-\sigma_{\pm} N d\right)$

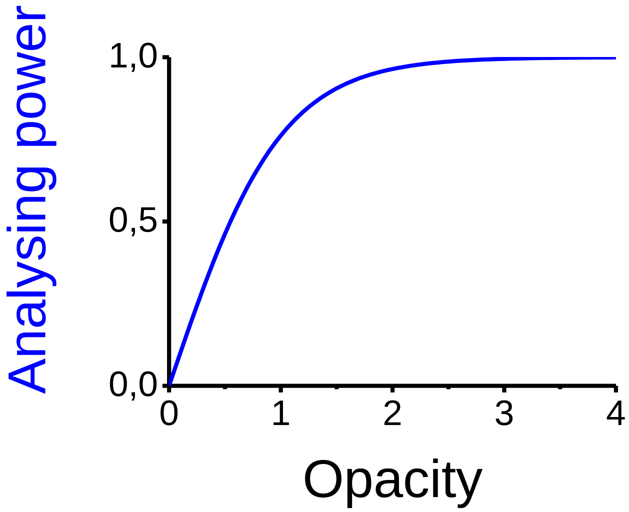
Analys. power: $A = \tanh\left(\sigma_p P N d\right)$

Opacity: $\kappa = \sigma_p P N d$

No dependence of T and A on geometrical parameters!

Opaque spin filter





$$\text{"}\textit{ideal}\ \text{analyser"}\ (A \rightarrow 1):$$

$$e.g.: \quad A = 0.999 \quad \Rightarrow \quad \kappa = 3.8$$

$$\frac{\delta\kappa}{\kappa} = 0.03 \quad \Rightarrow \quad \frac{\delta A}{A} = 2.3 \times 10^{-4}$$

$\Rightarrow$ *no precise knowledge of filter parameters required!*

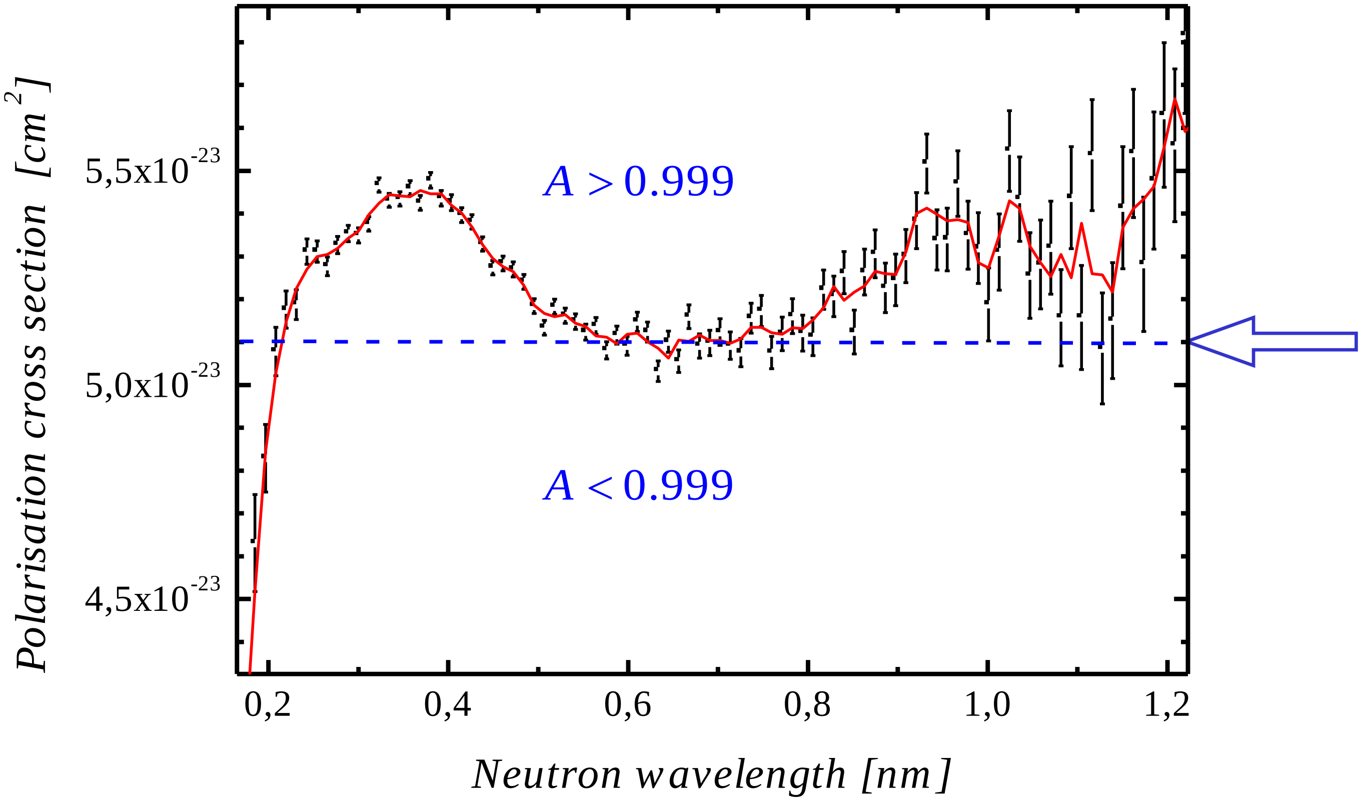
Polarised proton target:

- spin-dep. n-scattering

Polarised ^{3}He filter:

- spin-dep. n-absorption

Polarised proton spin filter

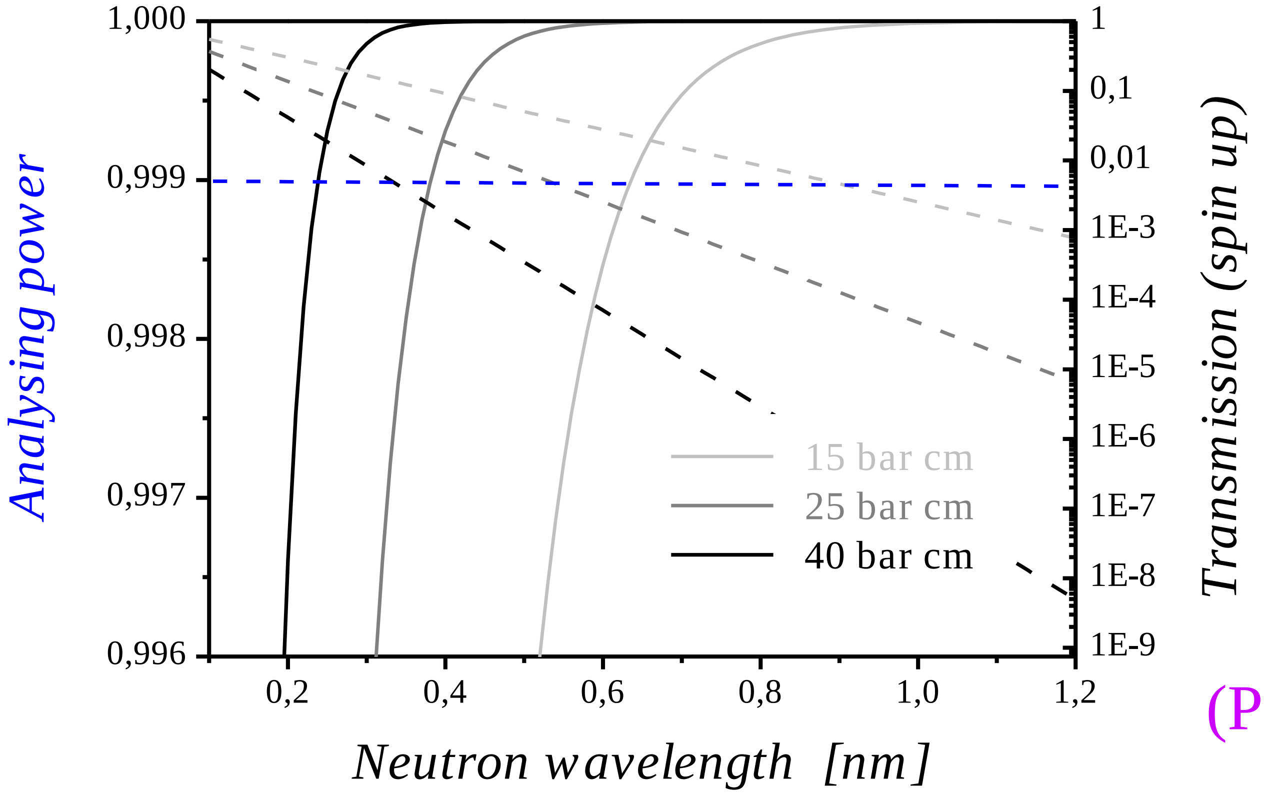


- *P* = 57% (DNP)
- *d* = 19.5 mm

1,2-propanediole, $N = 6.7 \times 10^{22}$ cm^{-3}

Polarised ^{3}He spin filter

- ^{3}He(n,p)T (0$^+$ res.), $\sigma_p \cong \sigma_0$ = 5327(9) barn at 0.18 nm (2200 m/s)
- strongly wavelength-dependent cross section (~λ)

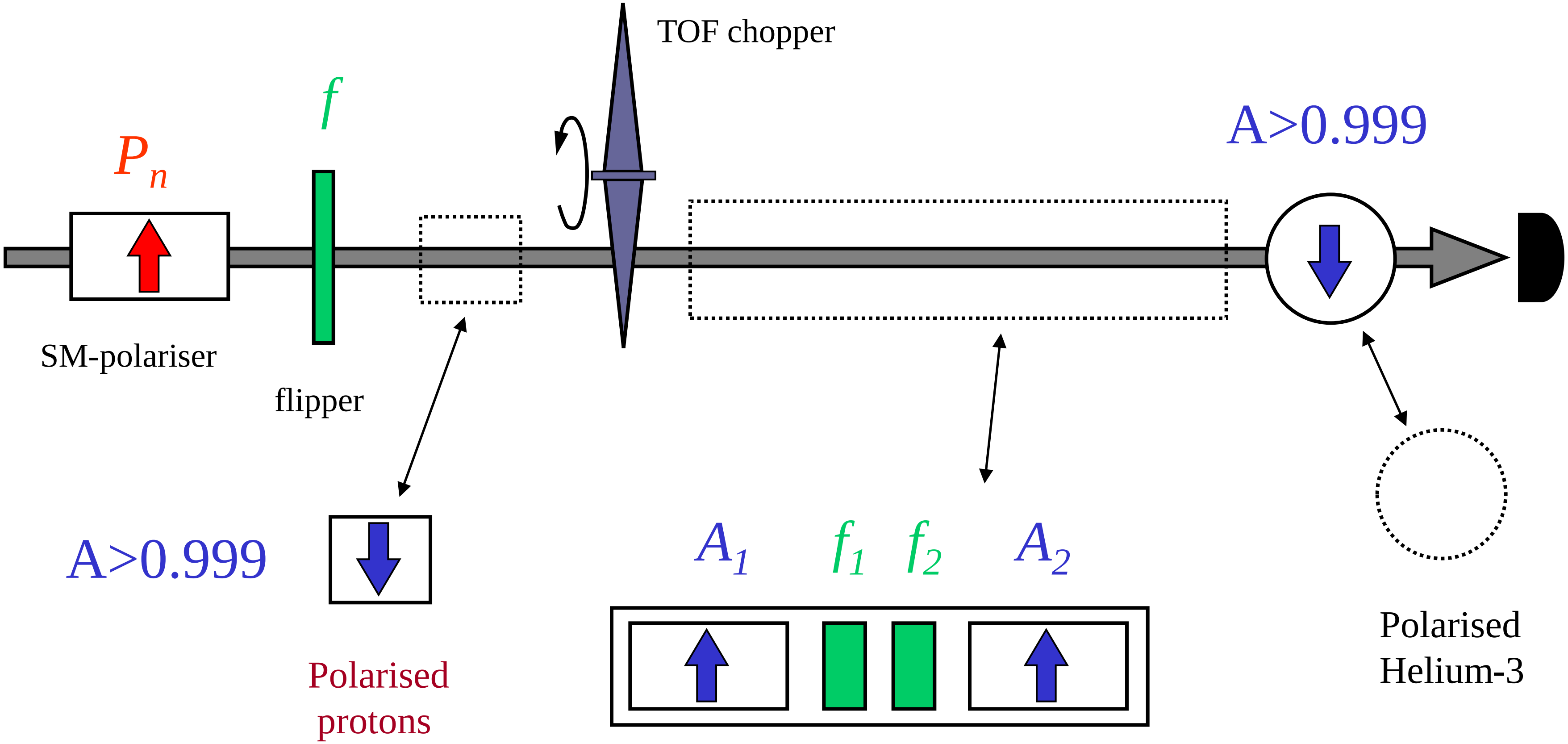


(P_{He}=50%)

☹ need several filter cells to analyse a white beam

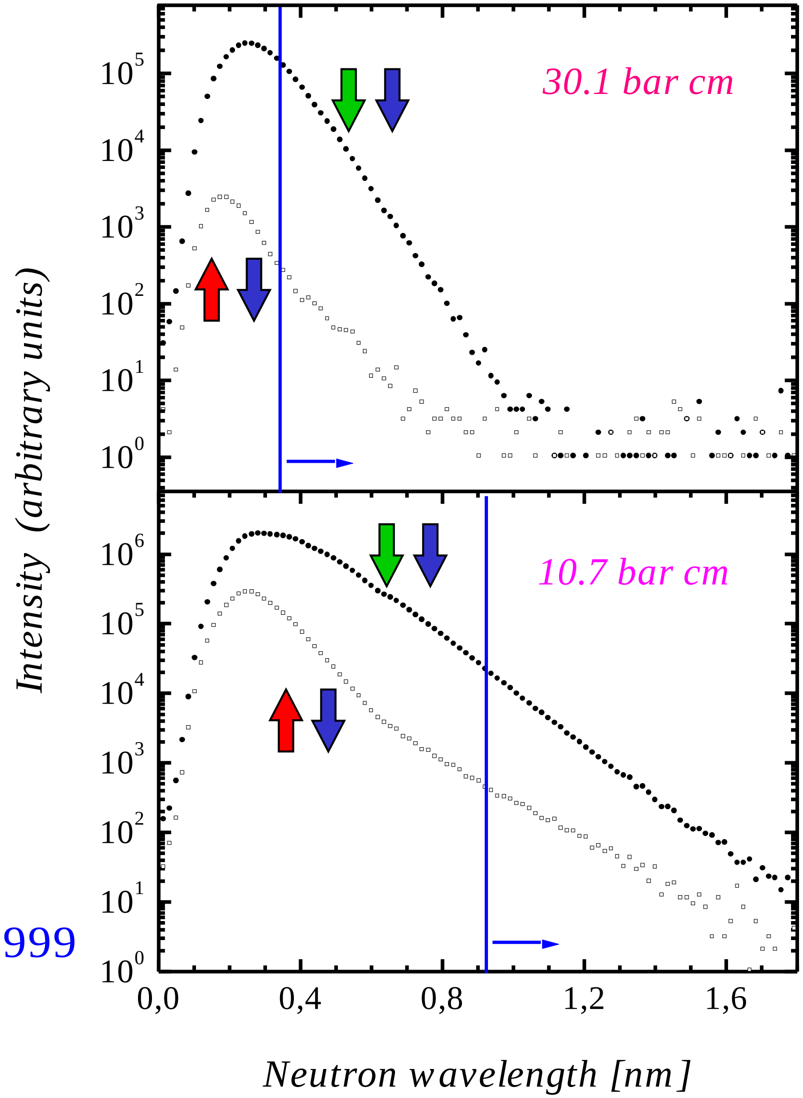
☺ homogeneous analysis over large area

Experimental comparison of three different analysers



prior standard SM method of neutron polarimetry
A. Serebrov et al., NIM A 357 (1995) 503

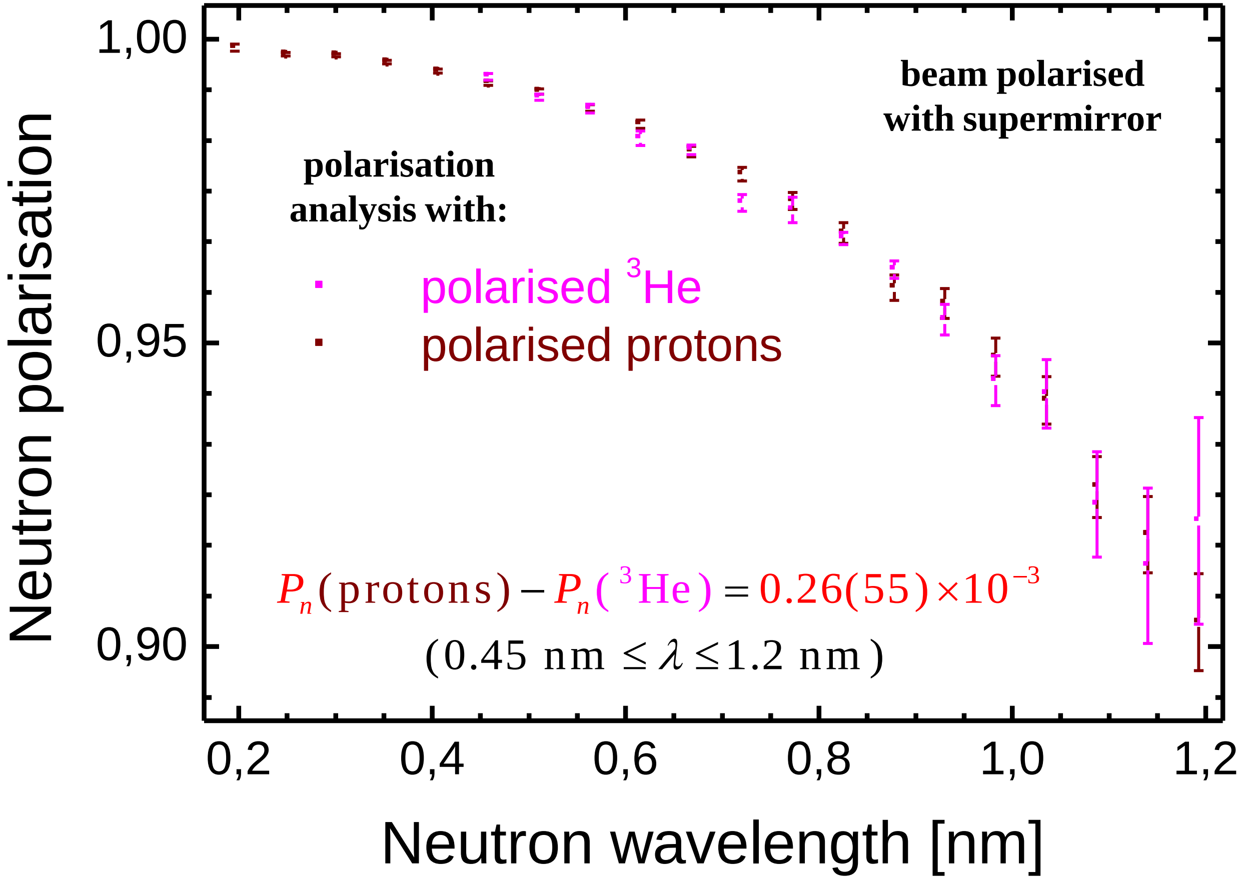
TOF-spectra with ^{3}He analyser



$A < 0.999$

$A > 0.999$

Results (protons – ^{3}He)



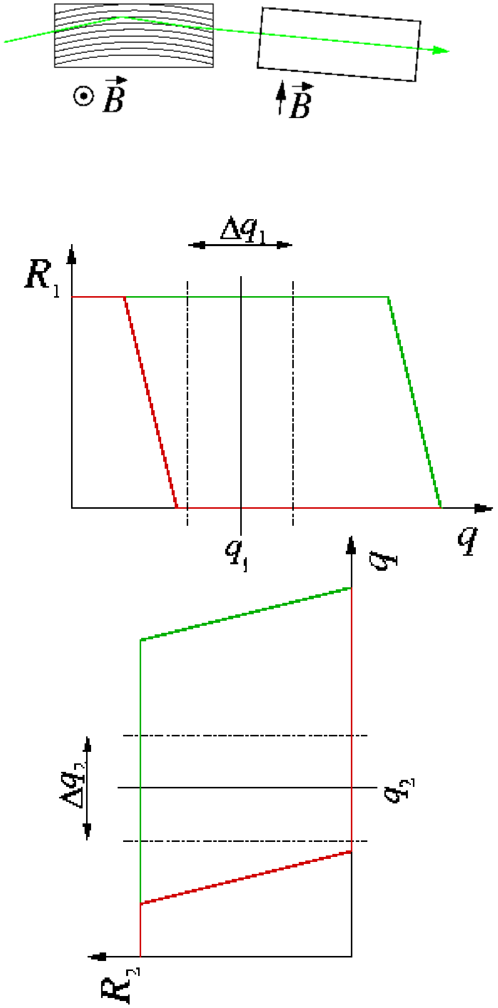
$$P_n(\text{protons}) - P_n(^3\text{He}) = 0.26(55)\times 10^{-3}$$

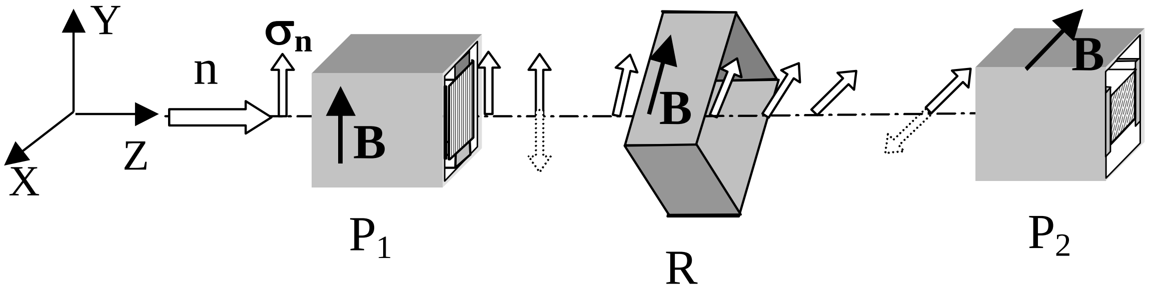
$$(0.45\ \text{nm} \le \lambda \le 1.2\ \text{nm})$$

O. Zimmer, T.M. Müller, P. Hautle, W. Heil, H. Humblot, Phys. Lett. B 455 (1999) 62
O. Zimmer, Phys. Lett. B 461 (1999) 307

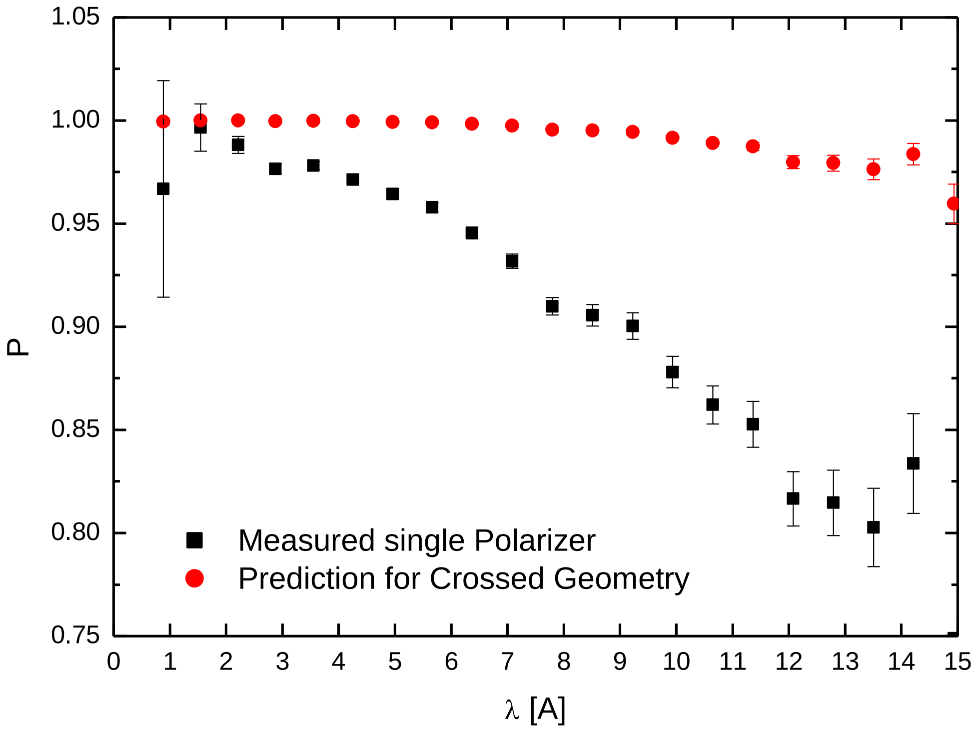
Neutron polarimetry with opaque spin filter more precise than 0.1%.

“Crossed geometry” beam polariser arrangement





M. Kreuz et al., NIM A 547 (2005) 583



Neutron polarisation and polarimetry now better than 0.01%

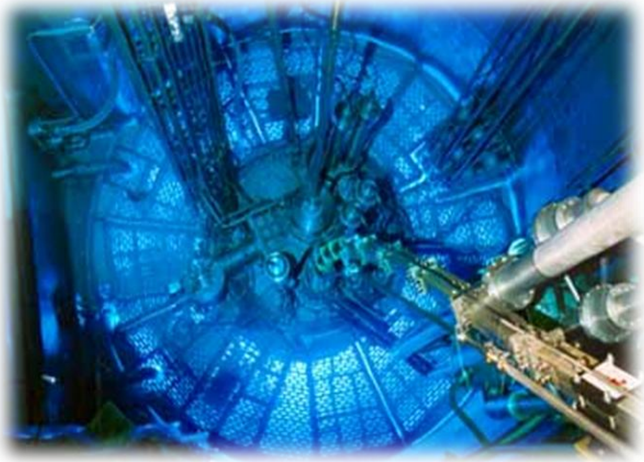
thanks to works of T. Soldner et al. (see Ph.D. thesis Ch. Klauser)

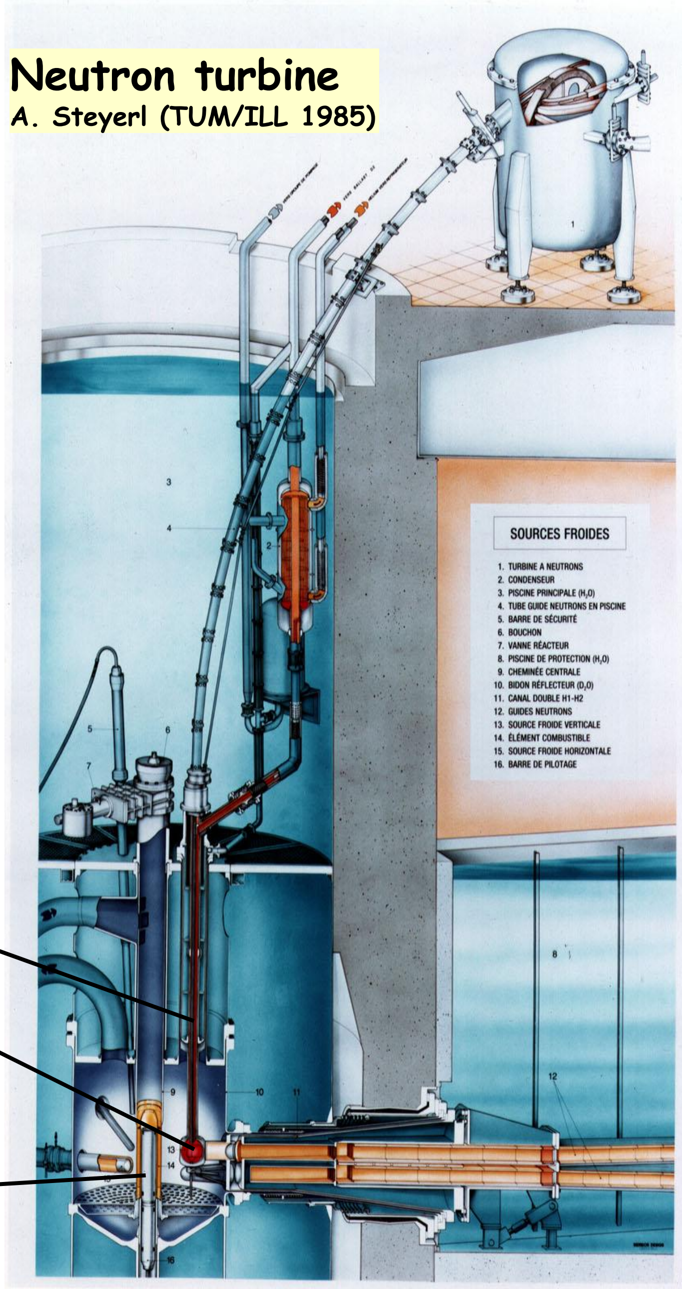
Concepts of UCN production (1): moderation

~30/cm³

- thermal equilibrium of neutron gas with scattering system (moderator)
- cooled moderator (cold source) → more UCN
- in-pile → large UCN production rate
  → large vessels can be filled with UCN

PF2 - the current working horse for UCN physics at ILL





Neutron turbine
A. Steyerl (TUM/ILL 1985)

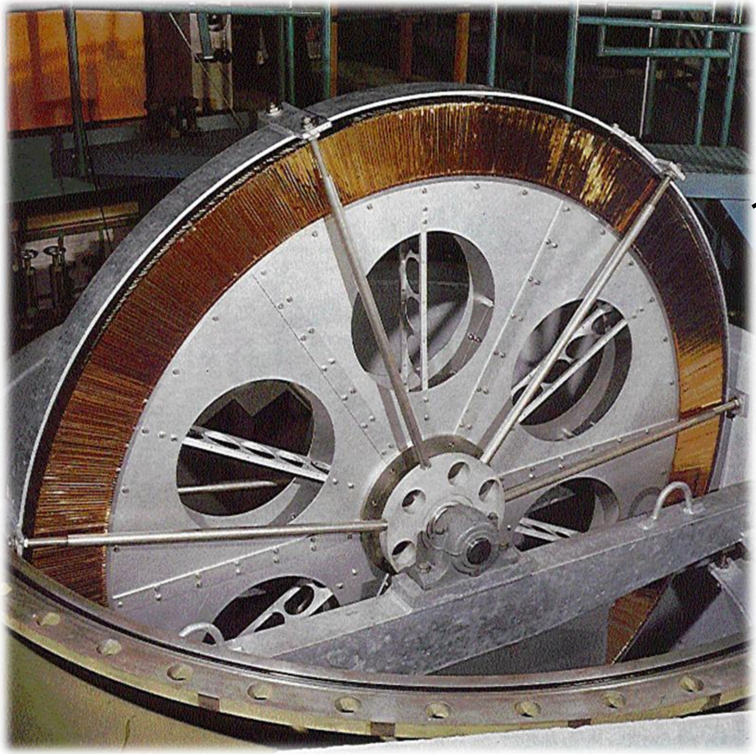
Vertical guide

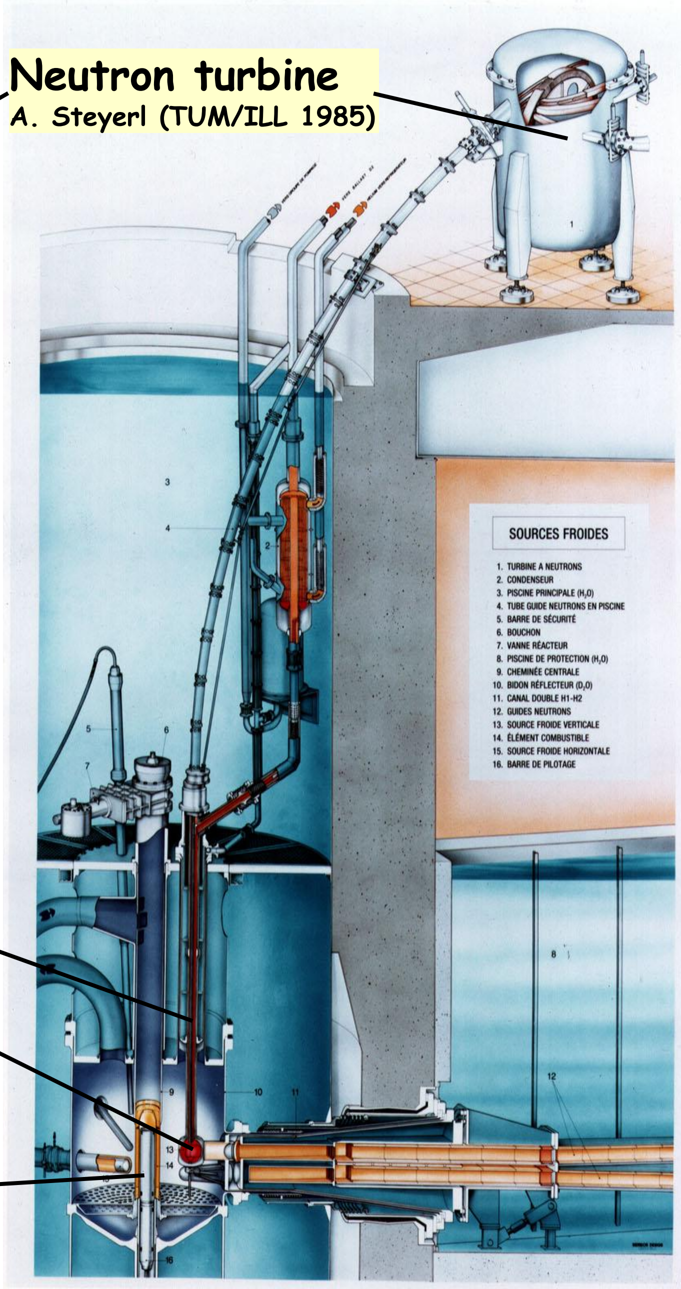
cold source ~1000 UCN cm^{-3}

reactor core

Concepts of UCN production (1): moderation

~30/cm³



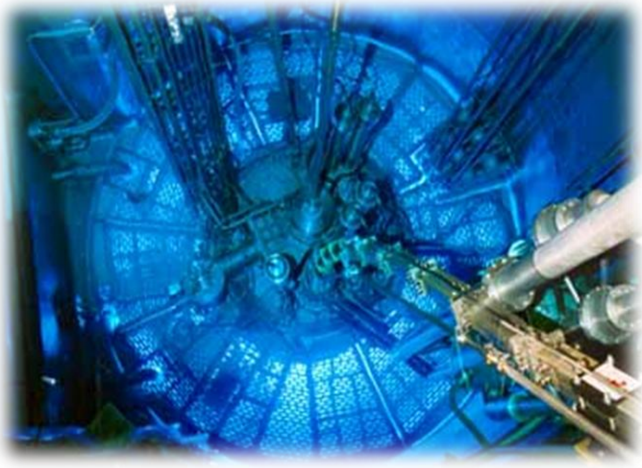


Neutron turbine
A. Steyerl (TUM/ILL 1985)

Vertical guide

cold source
~1000 UCN cm^{-3}

reactor core



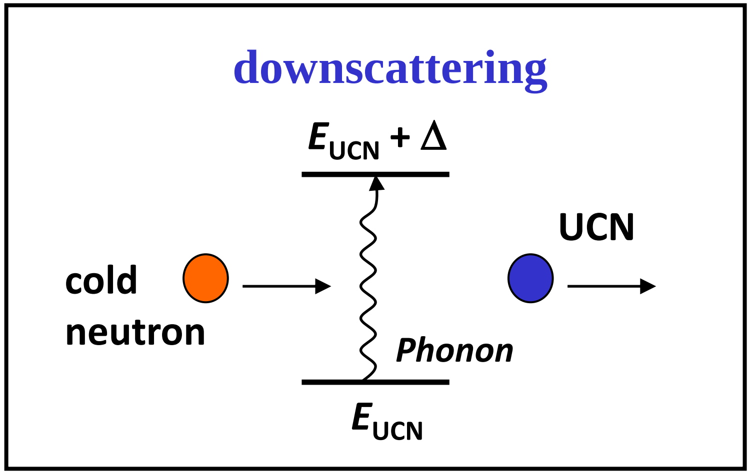
Concepts of UCN production (2): „superthermal“ production

- no thermal equilibrium of neutron gas with scattering system
- Conversion of cold neutrons to UCN by system with energy gap Δ
- up-scattering suppressed by Boltzmann factor
  $\rightarrow$ “accumulation” of neutrons as UCN

$$\sigma_{\mathrm{up}} = \frac{E_{\mathrm{UCN}} + \Delta}{E_{\mathrm{UCN}}} \cdot e^{-\Delta / k_{\mathrm{B}} T} \cdot \sigma_{\mathrm{down}}$$

$\rightarrow$ for **$\Delta \gg k_B T \gg E_{\mathrm{UCN}}$**

$$\sigma_{\mathrm{up}} \ll \sigma_{\mathrm{down}}$$



downscattering

- two converter materials:

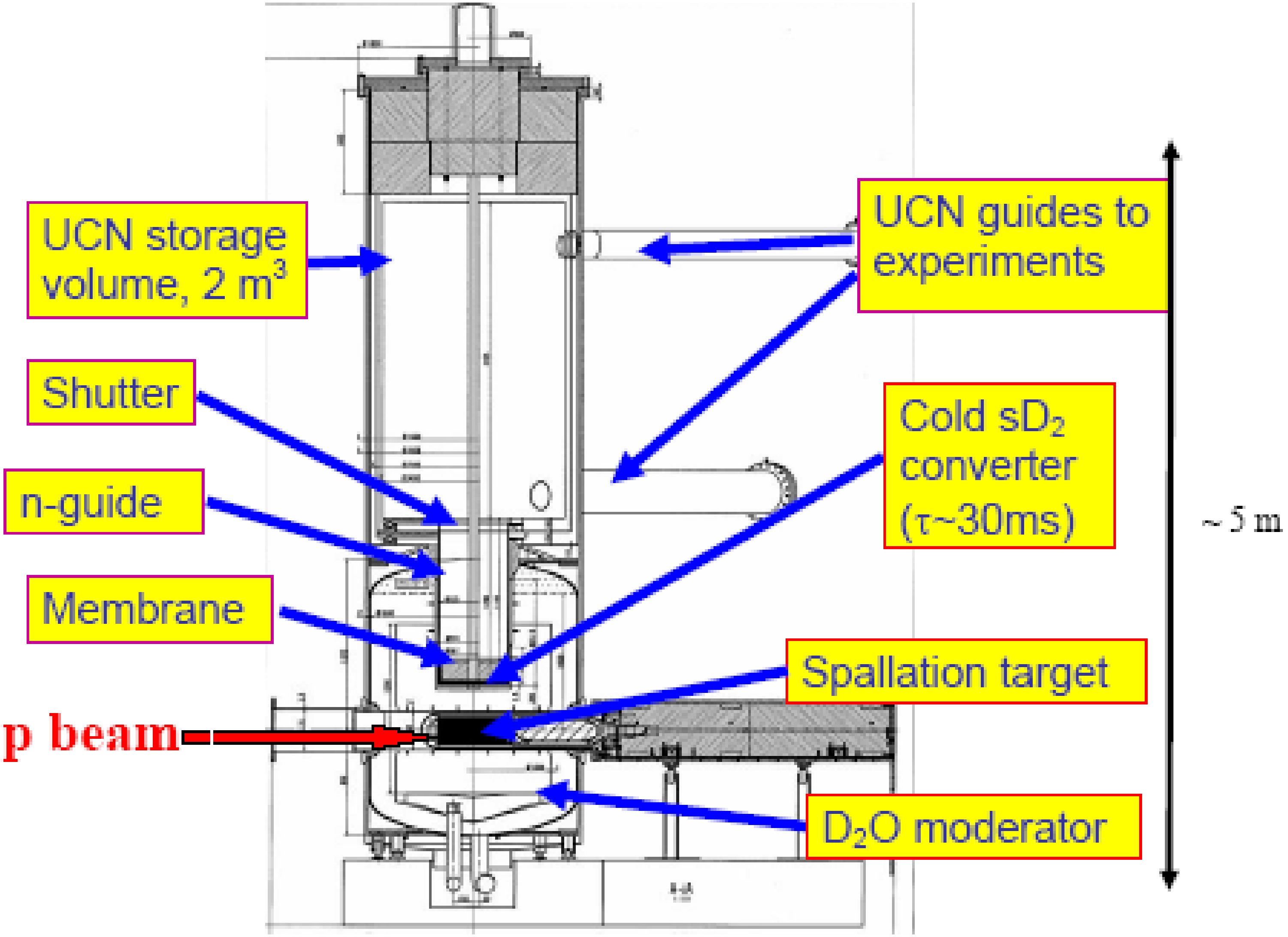
Solid deuterium (sD_2): $\sigma_{\mathrm{abs}} \neq 0 \rightarrow \tau \sim 0.15$ s $\rightarrow$ **in-pile needed**

Superfluid ^{4}He (He-II): $\sigma_{\mathrm{abs}} = 0 \rightarrow \tau \sim 800$ s ($< \tau_n$) $\rightarrow$ **beam possible**

Solid-D_2 UCN source at PSI

34 cm^{-3} in V = 25 l test vessel

B. Lauss, Phys. Proc. 51 (2014) 98



UCN storage volume, 2 m^3

Shutter

n-guide

Membrane

p beam

UCN guides to experiments

Cold sD_2 converter (τ~30ms)

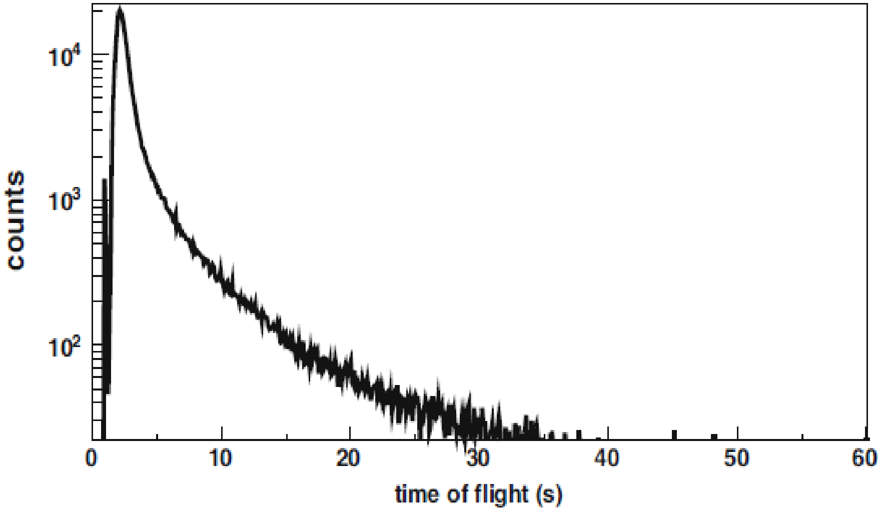
Spallation target

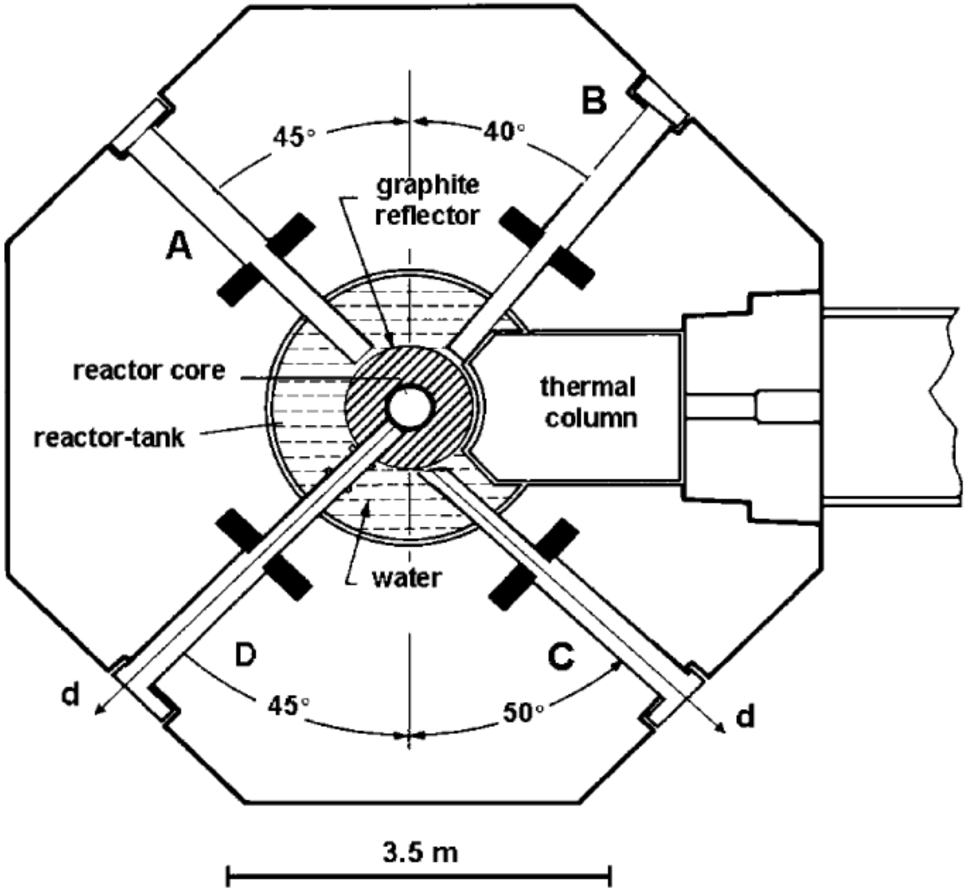
D_2O moderator

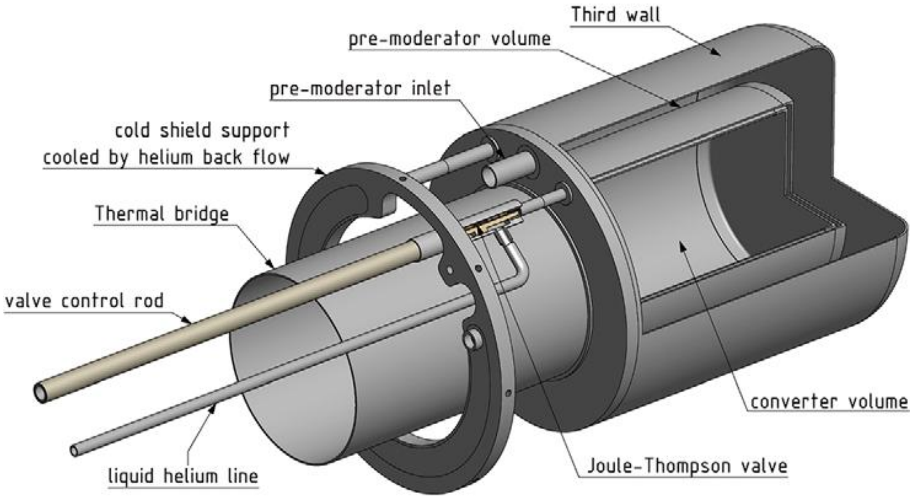
Solid-D$_2$ UCN source at TRIGA Mainz

18 cm^{-3} in *V* = 1.7 l test vessel

T. Lauer & T. Zechlau, Eur. Phys. J. A 49 (2013) 104

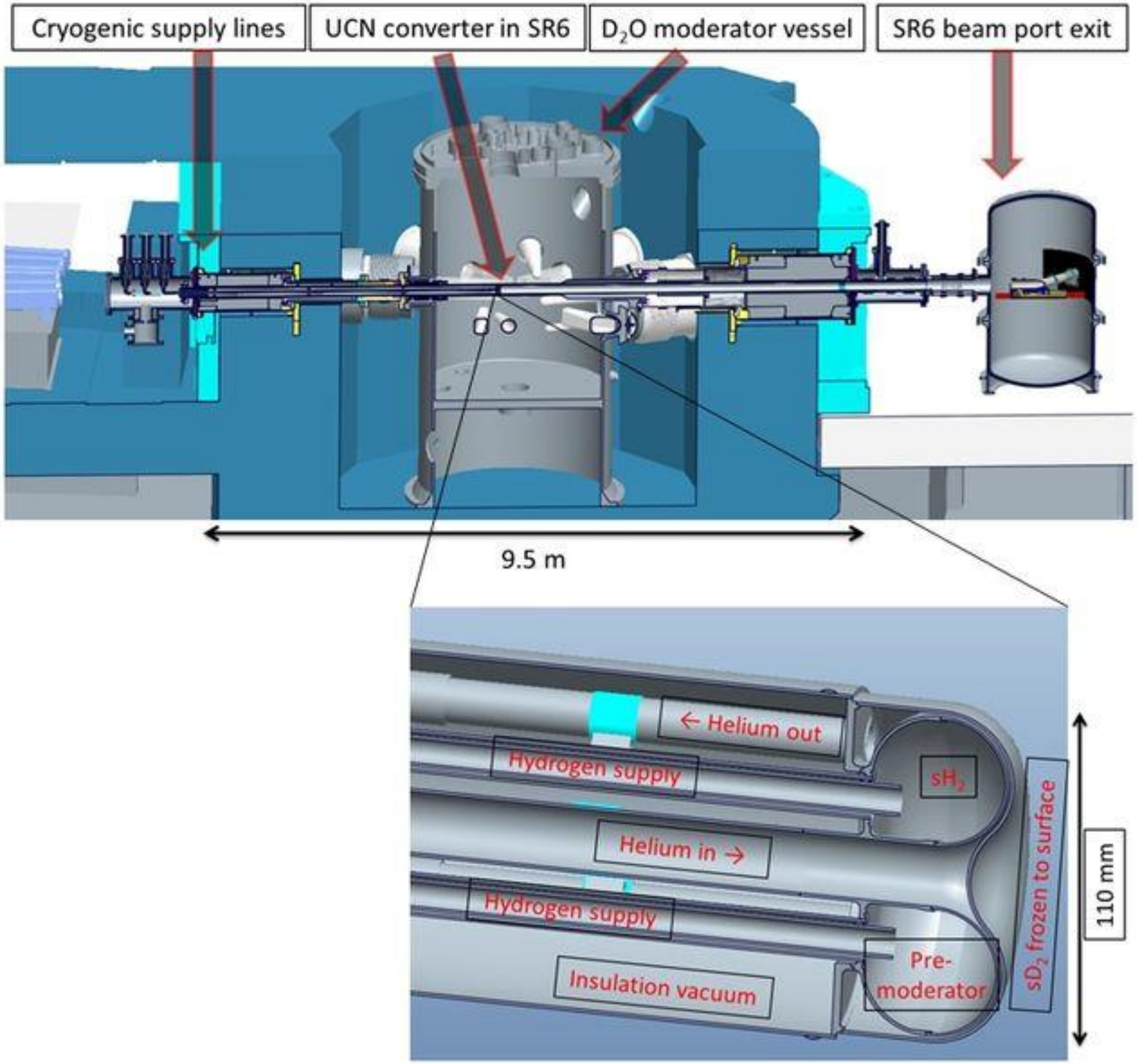






Solid-D_2 UCN source project at TU Munich

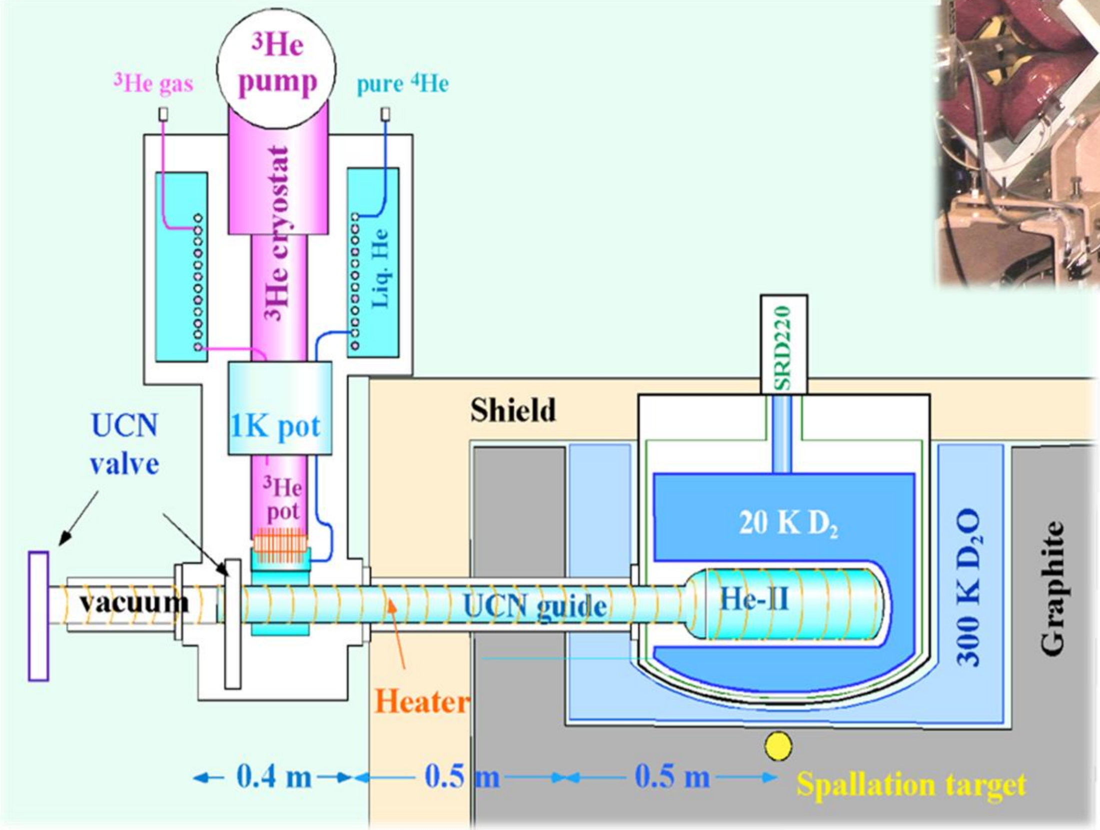
A. Frei, S. Paul et al.

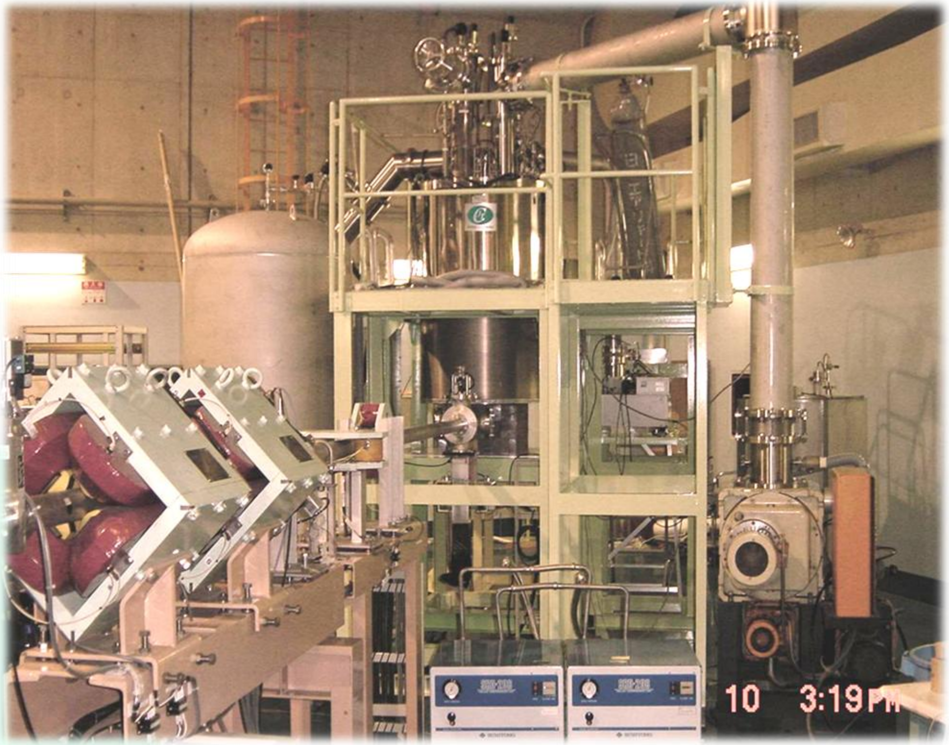


Japanese He-II UCN sources

Proposal for TRIUMF:

18000/cm^3 at exp. port





RCNP: 15/cm^3 in V = 36 liters

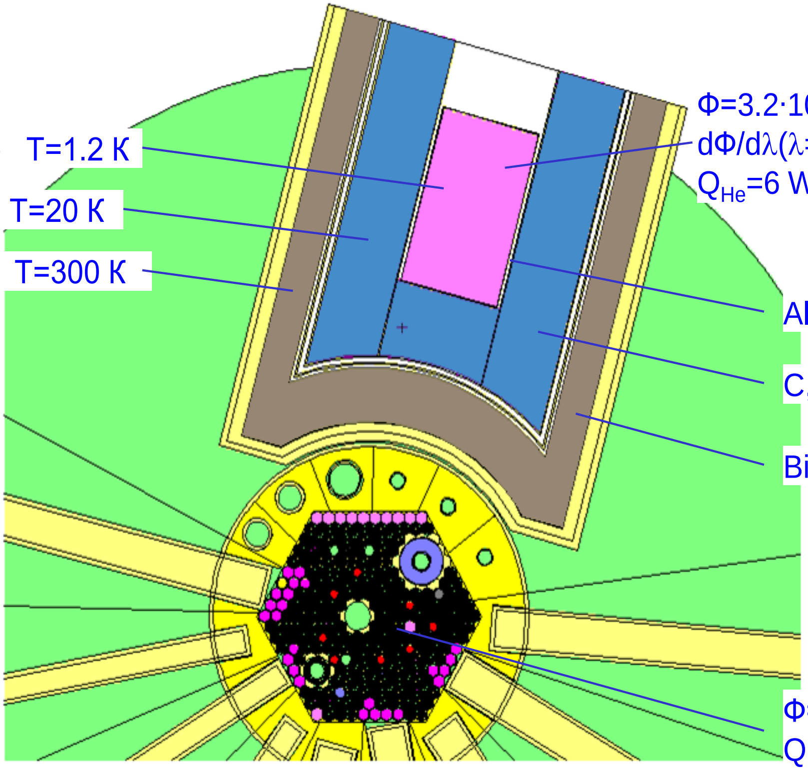
Spallation (400 MeV/ 1 μA p-beam)

Y. Masuda *et al.*, PRL 108 (2012) 134801

He-II UCN source proposed for PNPI WWR reactor

$10^4/cm^3$ in experiment

A. Serebrov et al., arXiv 0808.3978



He T=1.2 K

C T=20 K

Bi T=300 K

$\Phi=3.2\cdot10^{12}$ n/(cm^{2}s)

$d\Phi/d\lambda(\lambda=9$ Å$)=3.2\cdot10^{10}$ n/(cm^{2}sÅ)

$Q_{He}=6$ W

Al, $Q_{Al}=13$ W

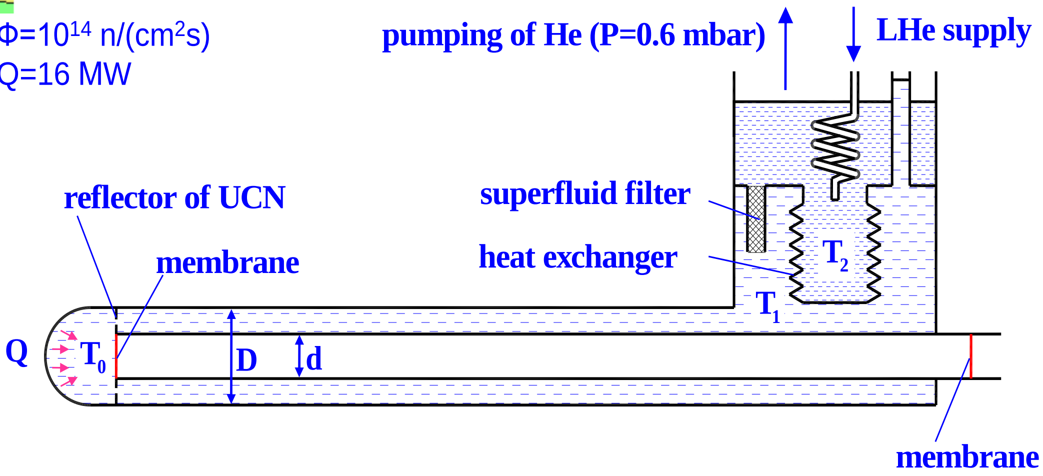
$\}$ 19 W

C, $Q_C=750$ W

Bi, $Q_{Pb}=16$ кW

$\Phi=10^{14}$ n/(cm^{2}s)

Q=16 MW



International source projects – not updated

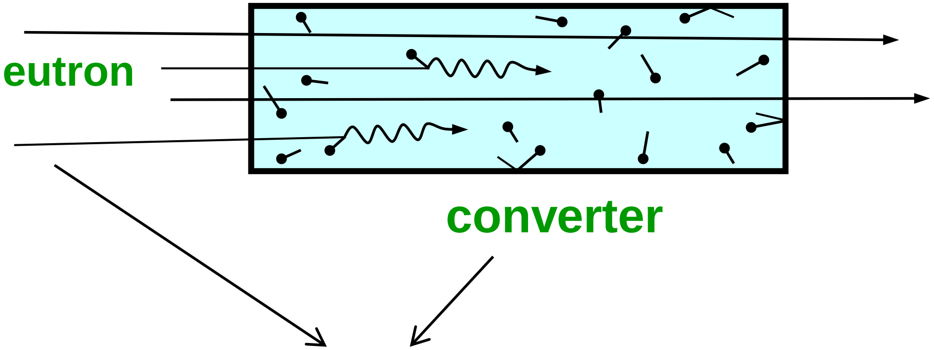
Source location	Source type	UCN density [cm^{-3}]	comment	when?
ILL Grenoble, PF2	LD_2 + turbine	~ 30	still THE source	> 1985
Los Alamos, 2.4 kW_{av} proton	SD_2	120	in source	now
Mainz TRIGA *upgraded*	SD_2	20 *~ 200*	in V = 10 l	now 2010
PSI, 12 kW_{av} proton	SD_2	> 1000	in V = 2000 l	2010
North Carolina, 1 MW reactor	SD_2	1300	in source	2011
Munich, 20 MW reactor	SD_2	~ 10000	in source	2011
PNPI, 16 MW reactor	He-II (1.2 K)	13000 7700	in 35 l exp. bottle in 350 l exp. bottle	2012
TRIUMF, 5 kW_{av} proton	He-II (0.8 K)	18000	at exp. port	proposed

+ insitu He-II UCN sources at ILL (Cryo-EDM), NIST (n-lifetime), and SNS (EDM)

UCN production in He-II

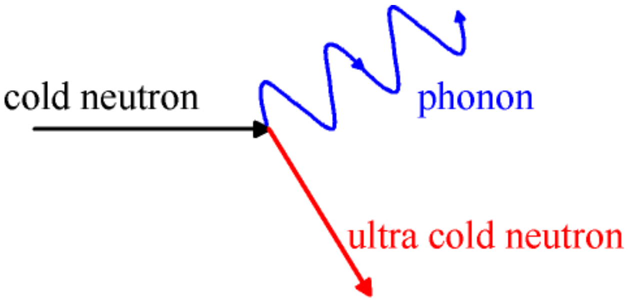
R. Golub, J.M. Pendlebury, PL **53A** (1975) 133

$\sigma_{\mathrm{capture}}\,(^4\mathrm{He}) = 0$



cold neutron beam

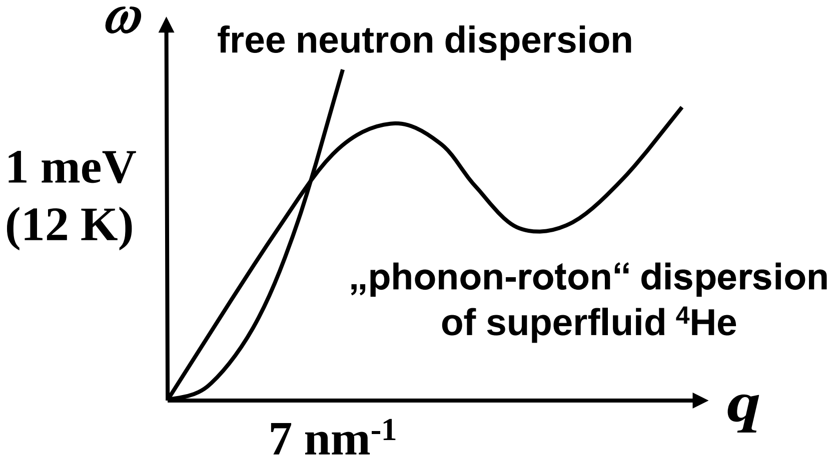
converter



$$\rho_{\mathrm{UCN}} = P\tau$$

$$\tau^{-1} = \tau^{-1}_{\mathrm{decay}} + \tau^{-1}_{\mathrm{upscattering}} + \tau^{-1}_{\mathrm{capture}} + \tau^{-1}_{\mathrm{wall\ losses}}$$

T [K]	τ_{max} [s]
1	100
0.8	310
0.7	510
0.5	820
0	880



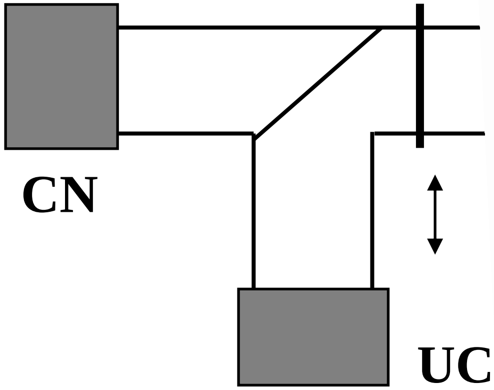
→ need T < 0.5 - 0.6 K
and low-loss walls

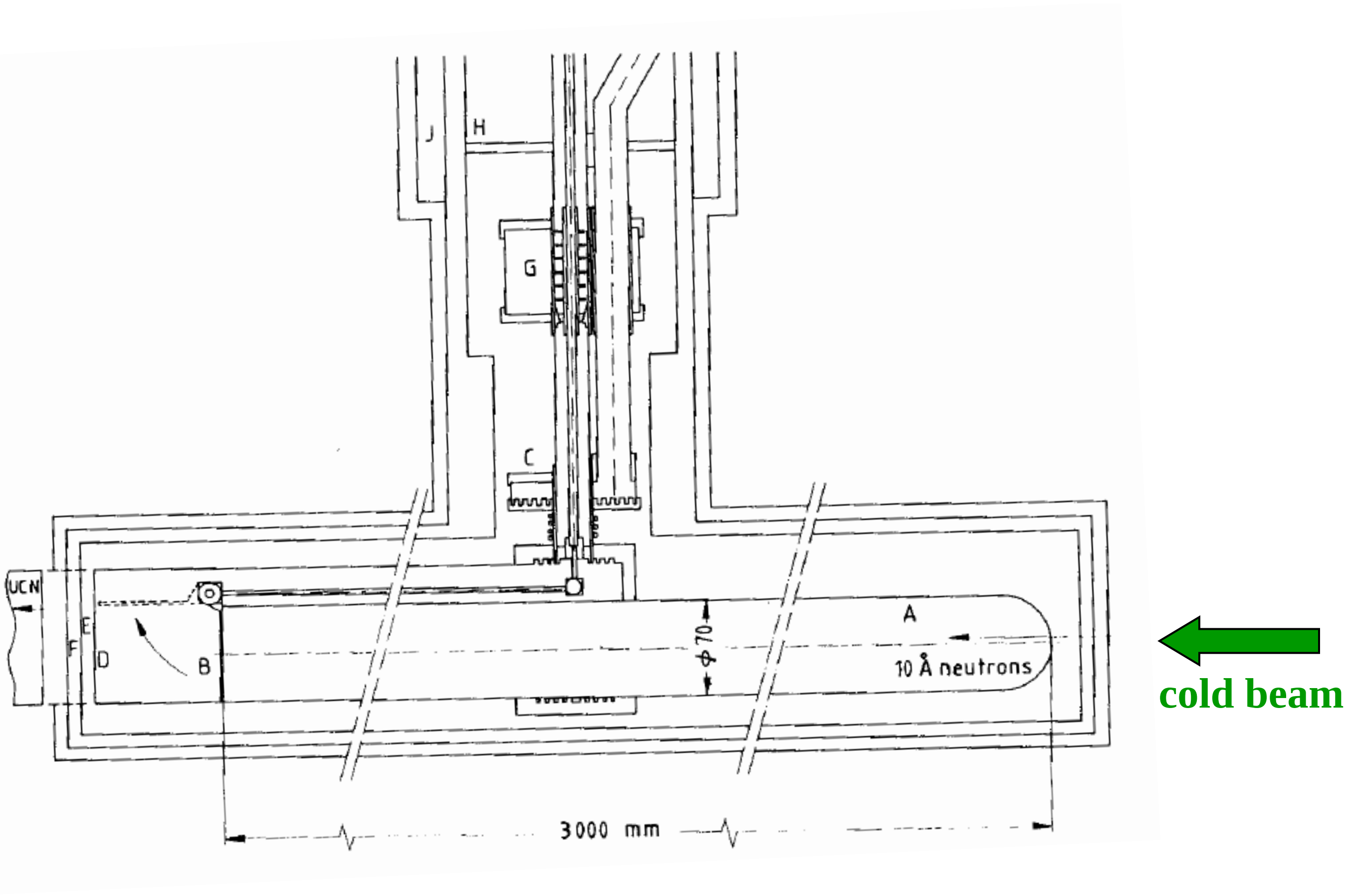
UCN accumulation and extraction?

- Factor 50 missing in late 1980‘s experiment at H17 at ILL

  → extraction of accumulated UCN to experiment at 300K not viable

  → „in-situ“ experiment development (cryo-EDM, NIST n-lifetime)



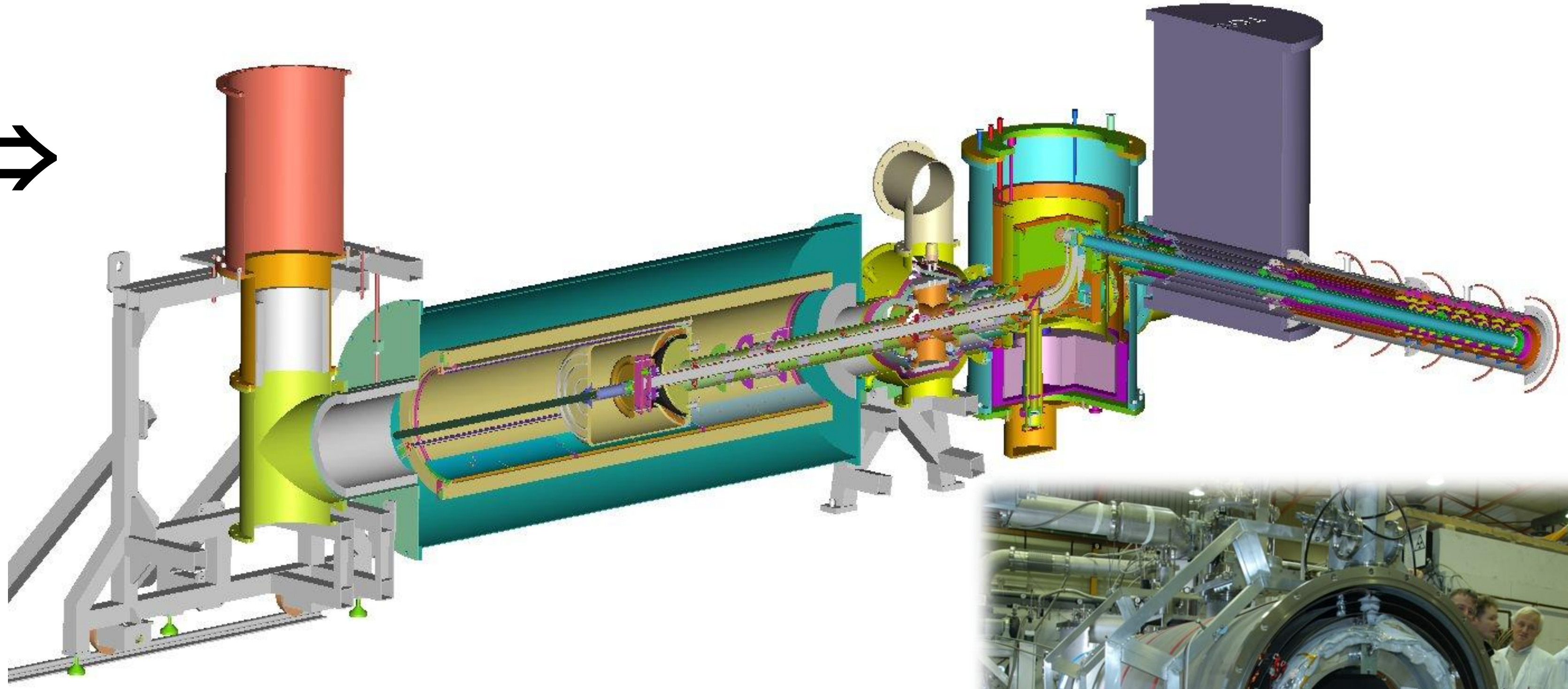


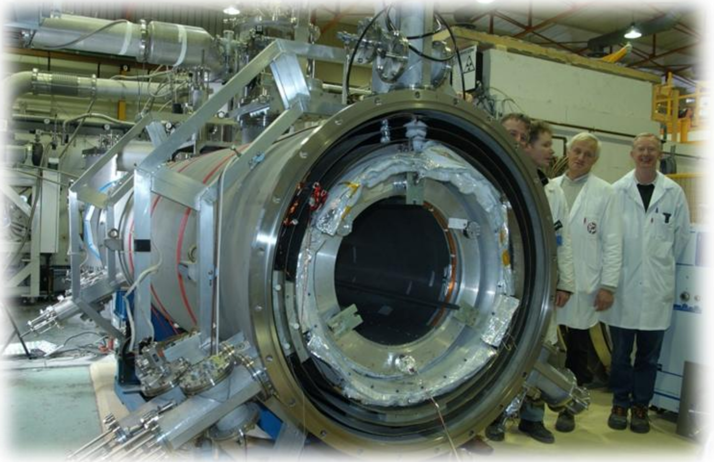
A.I. Kilvington *et al.*, PL A **125** (1987) 416

Dogma (before 2006):

"One cannot efficiently extract UCN accumulated in the superfluid to an experiment at room temperature"

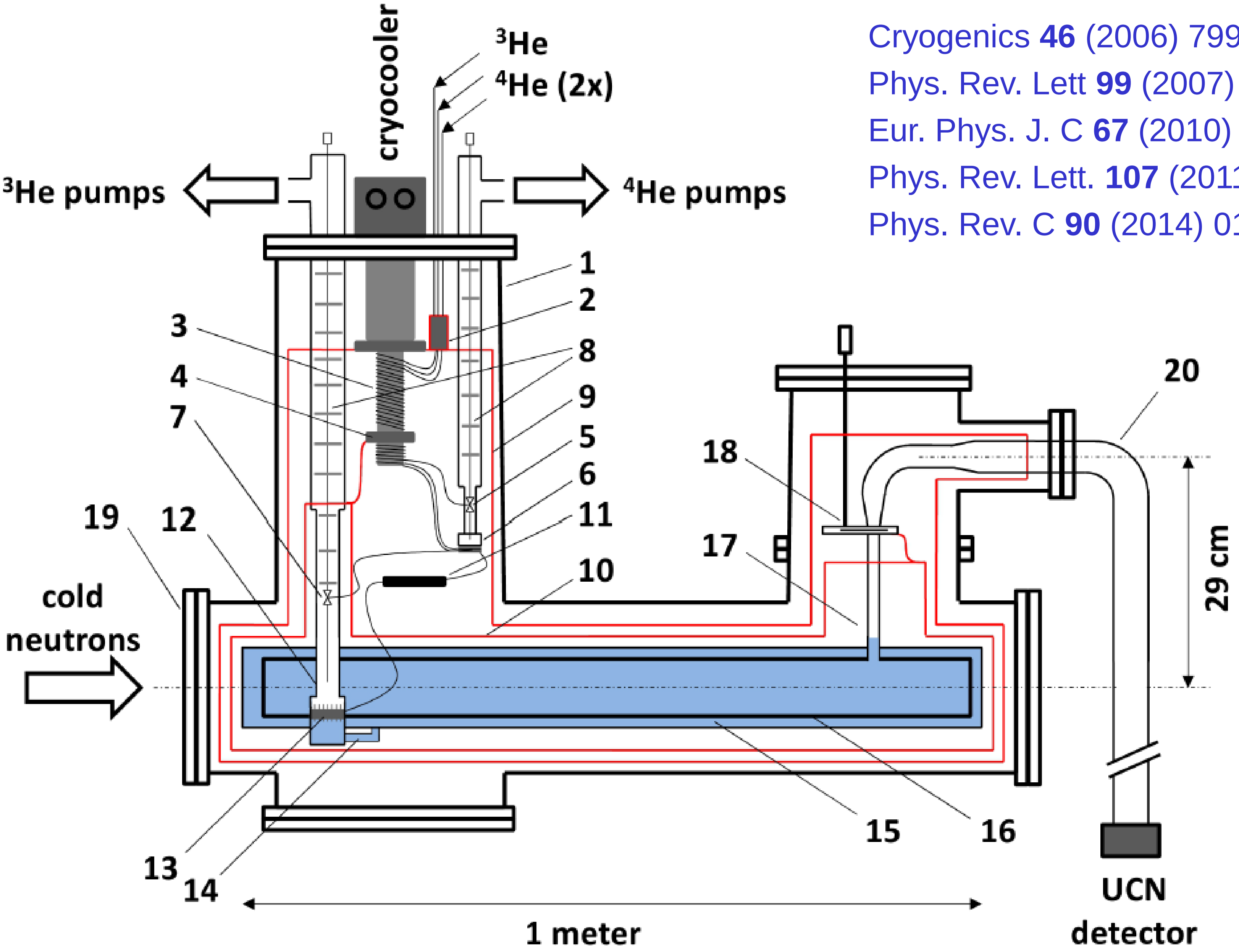
⇒





however: **huge potential for better UCN source if dogma is not valid**

Layout of source prototype SUN-1



Cryogenics **46** (2006) 799

Phys. Rev. Lett **99** (2007) 104801

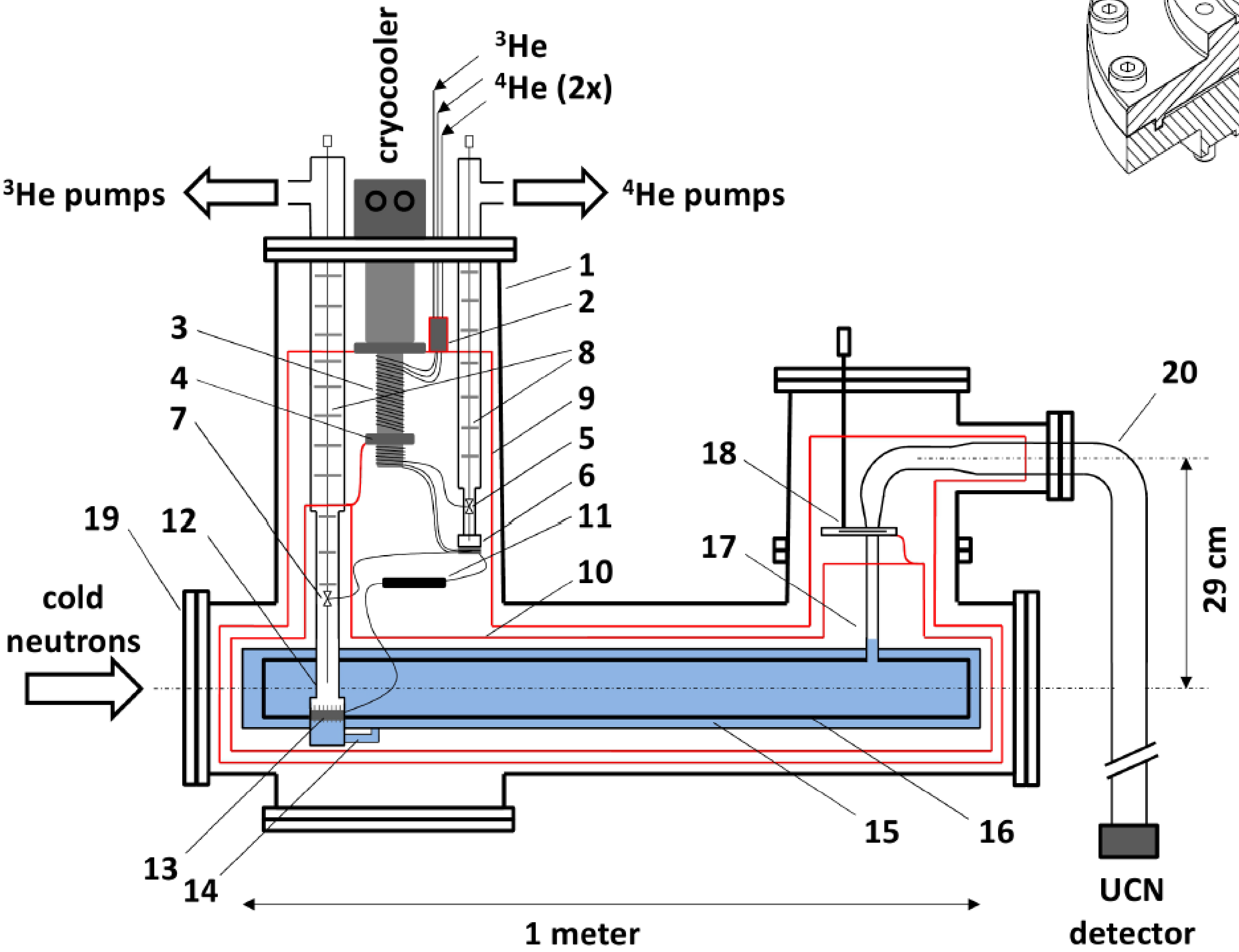
Eur. Phys. J. C **67** (2010) 589

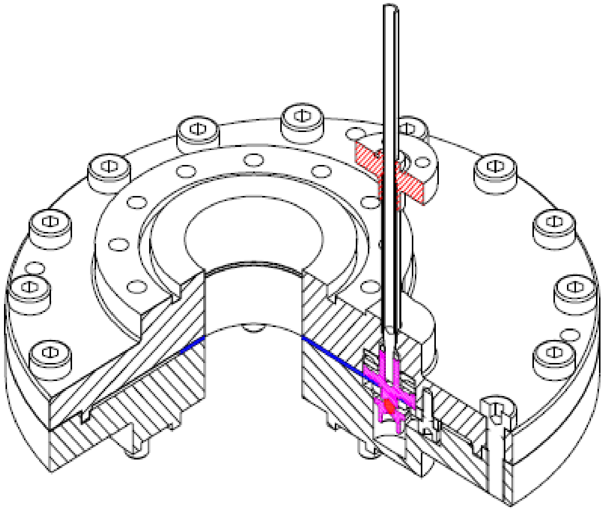
Phys. Rev. Lett. **107** (2011) 134801

Phys. Rev. C **90** (2014) 015501

Cold UCN valve (18)

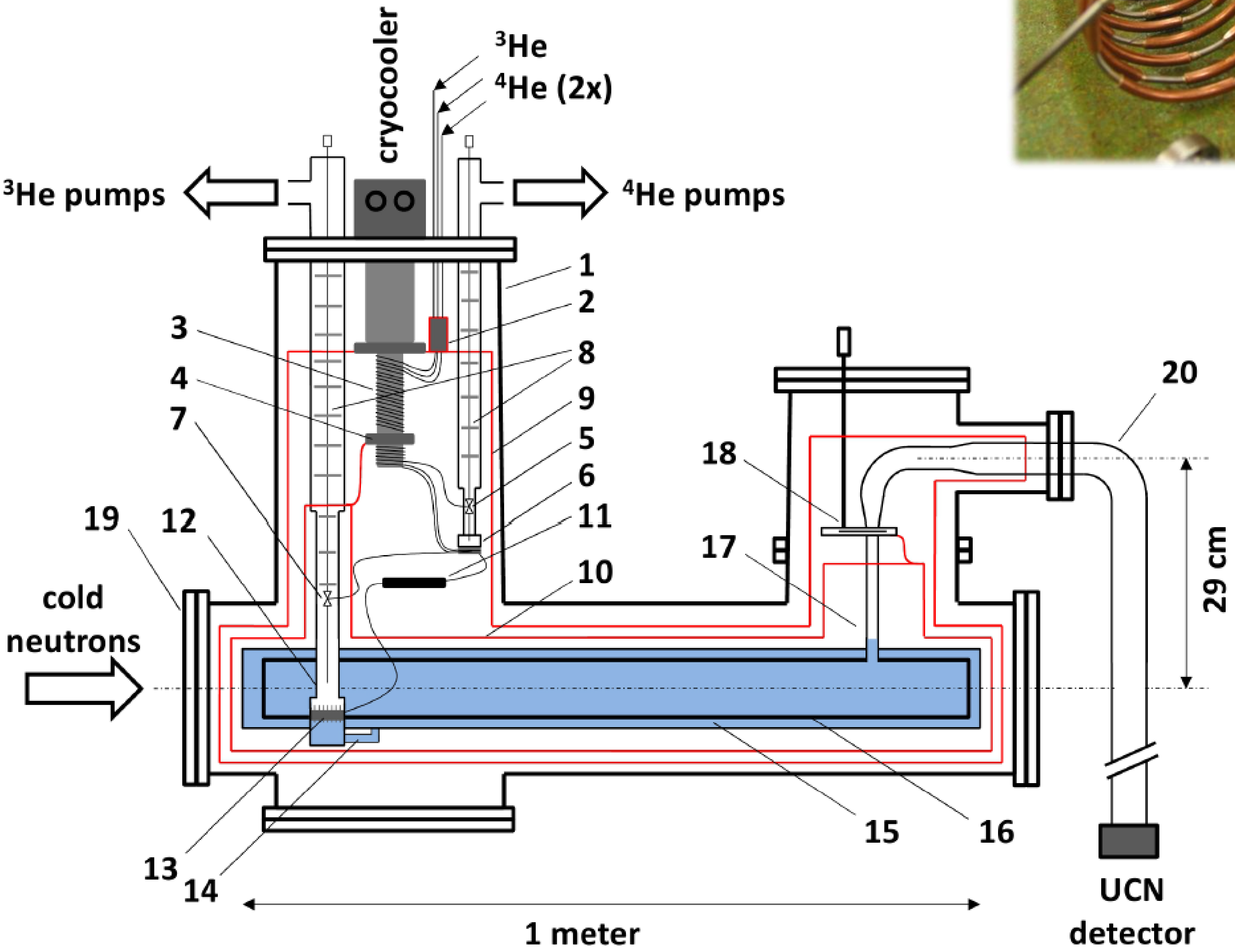
Main point: **windowless, vertical UCN extraction**

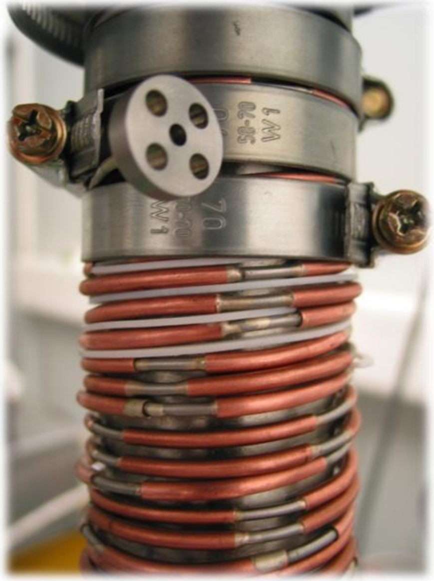




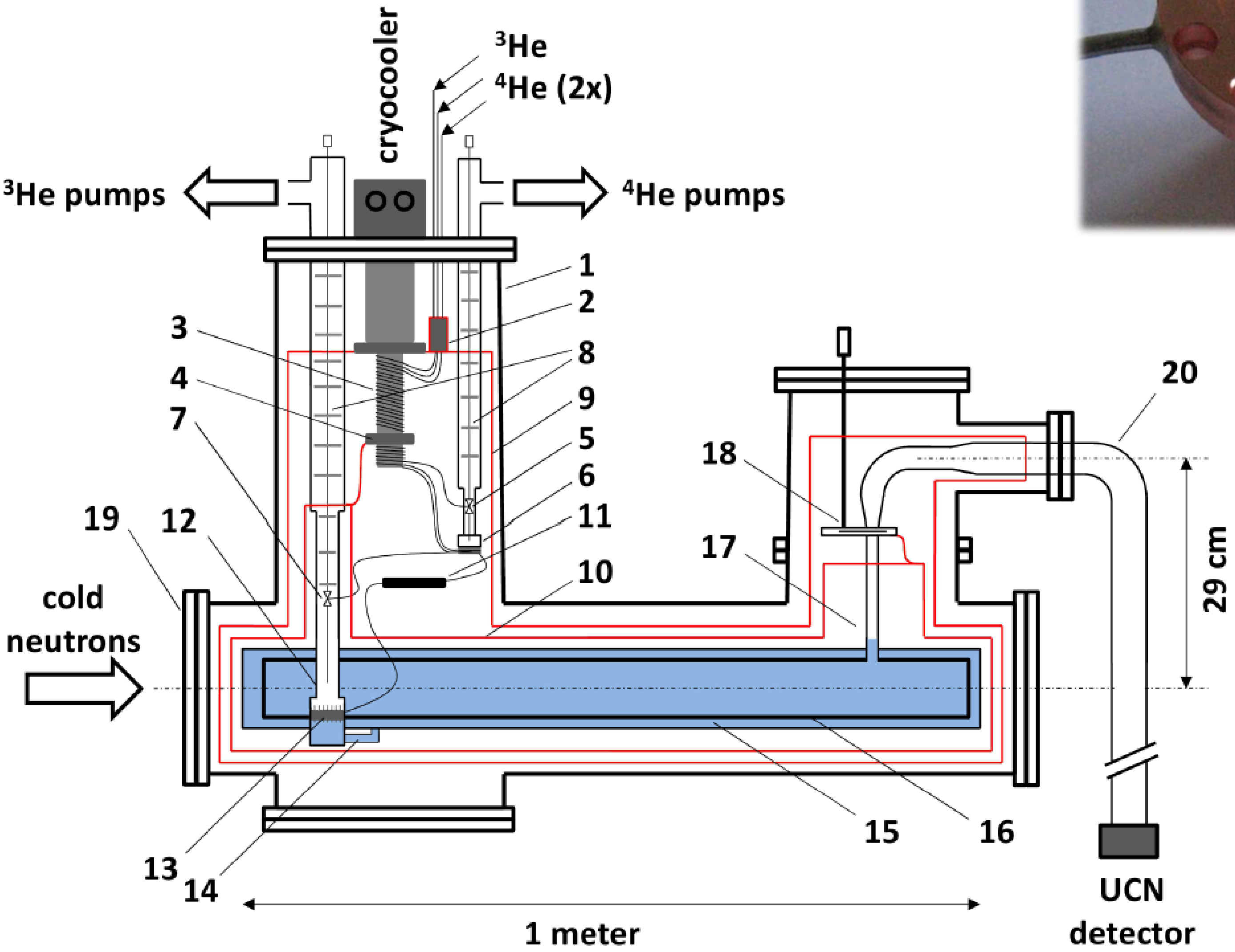
Spiral heat exchanger (3)

Cryogenics **46** (2006) 799

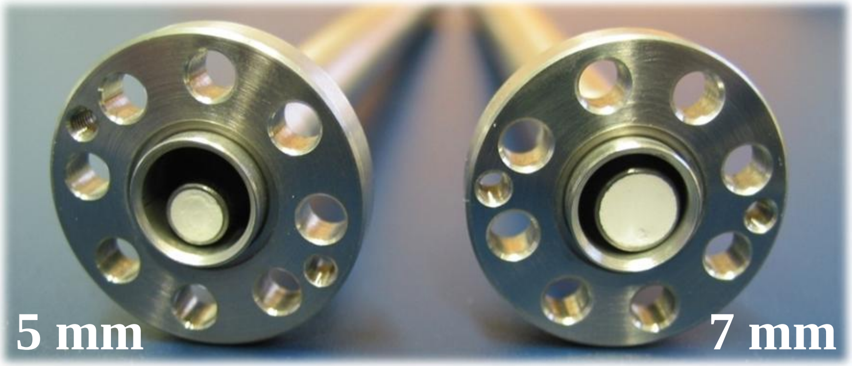




He3-He4 heat exchanger (13)

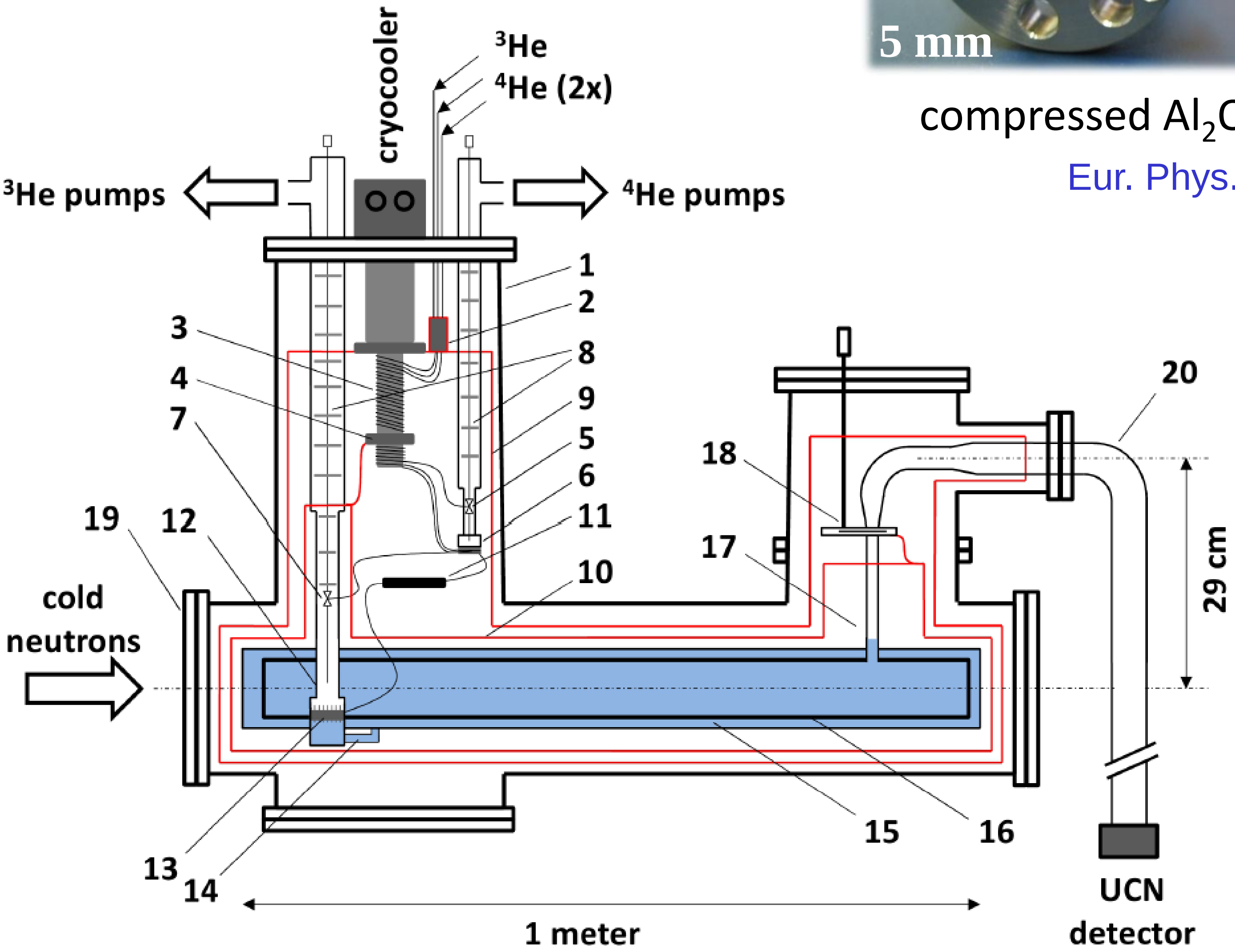


Superleak (11)

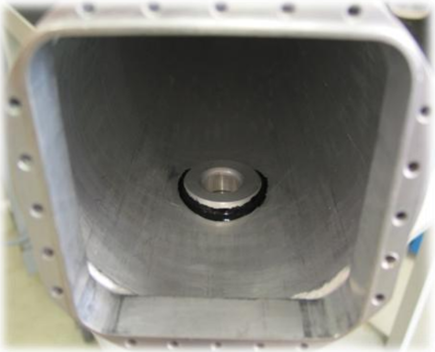


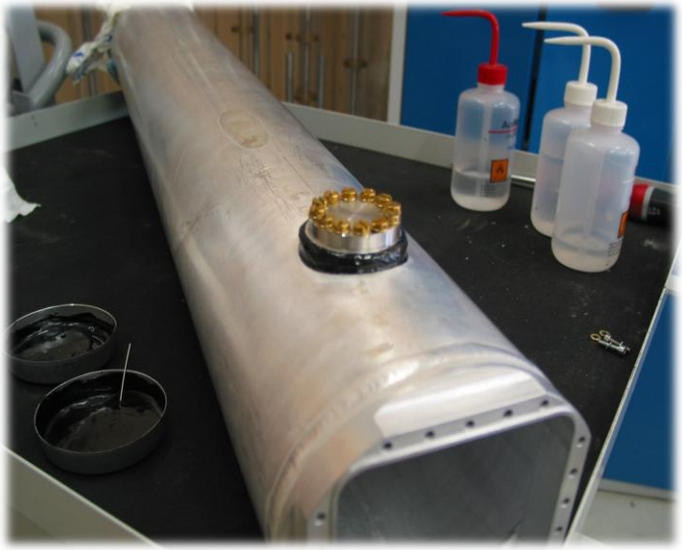
compressed Al_2O_3 powder (50 nm)

Eur. Phys. J. C **67** (2010) 589

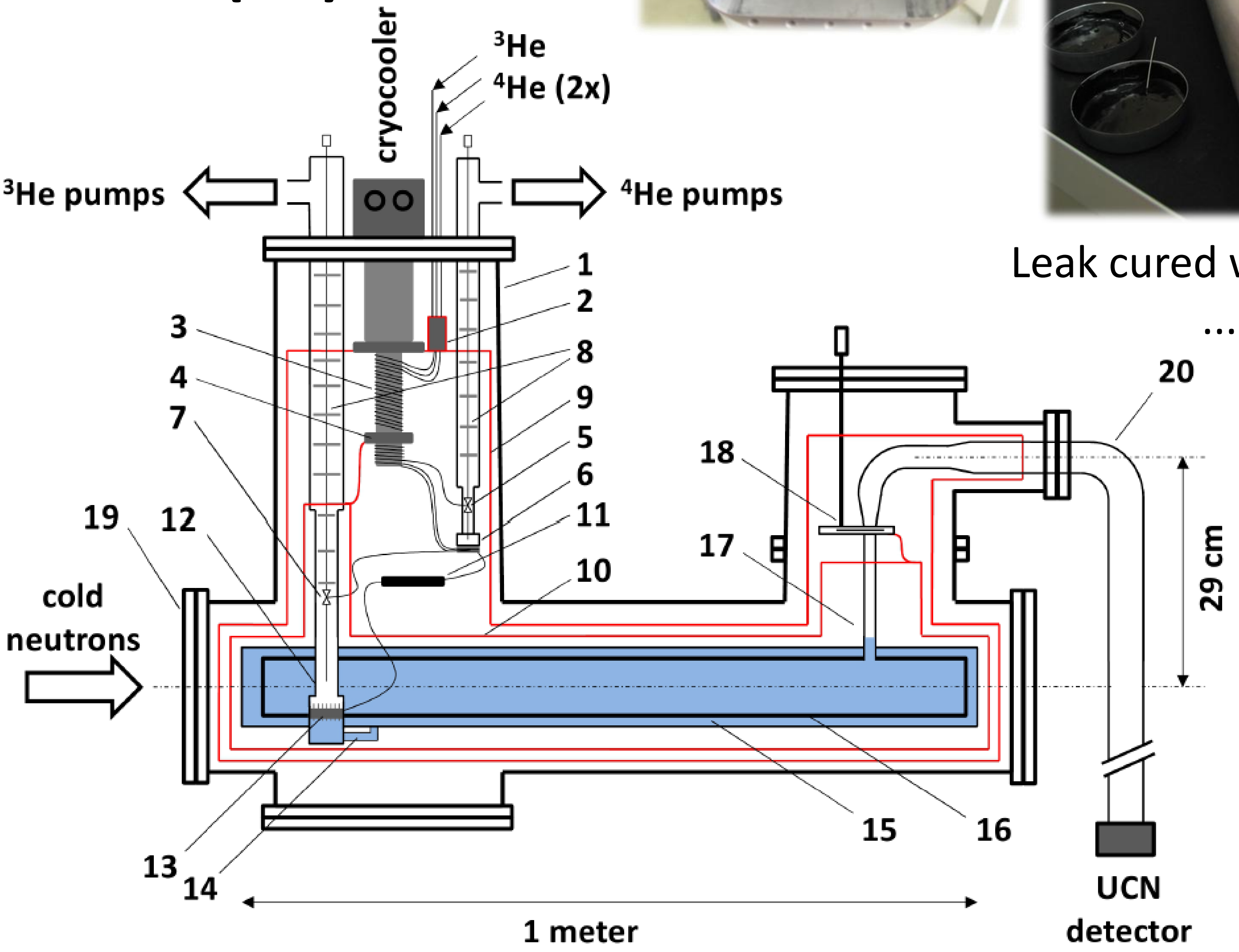


Superfluid He container vessel (15)

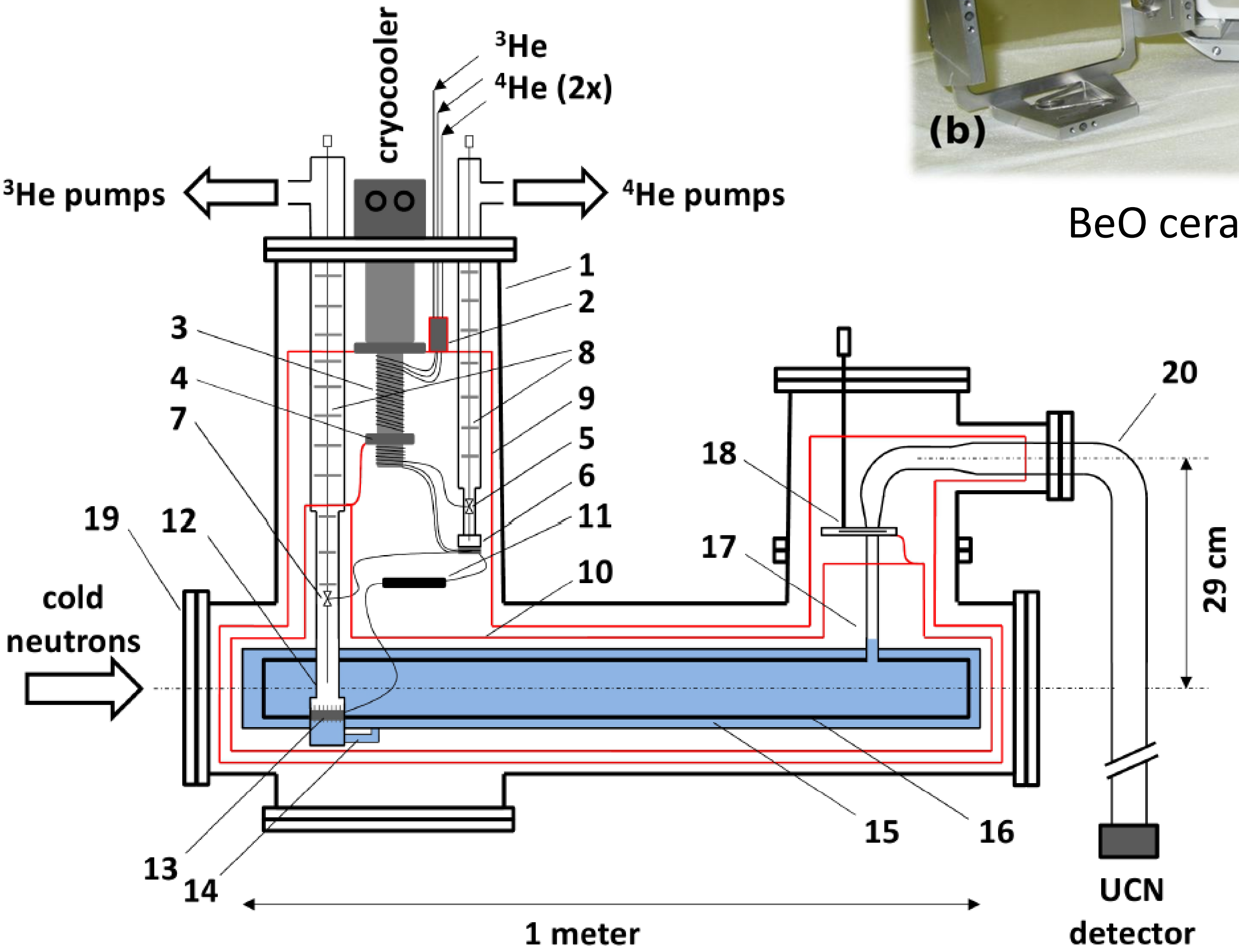




Leak cured with Stycast 2850 FT, ...25 cooldowns since

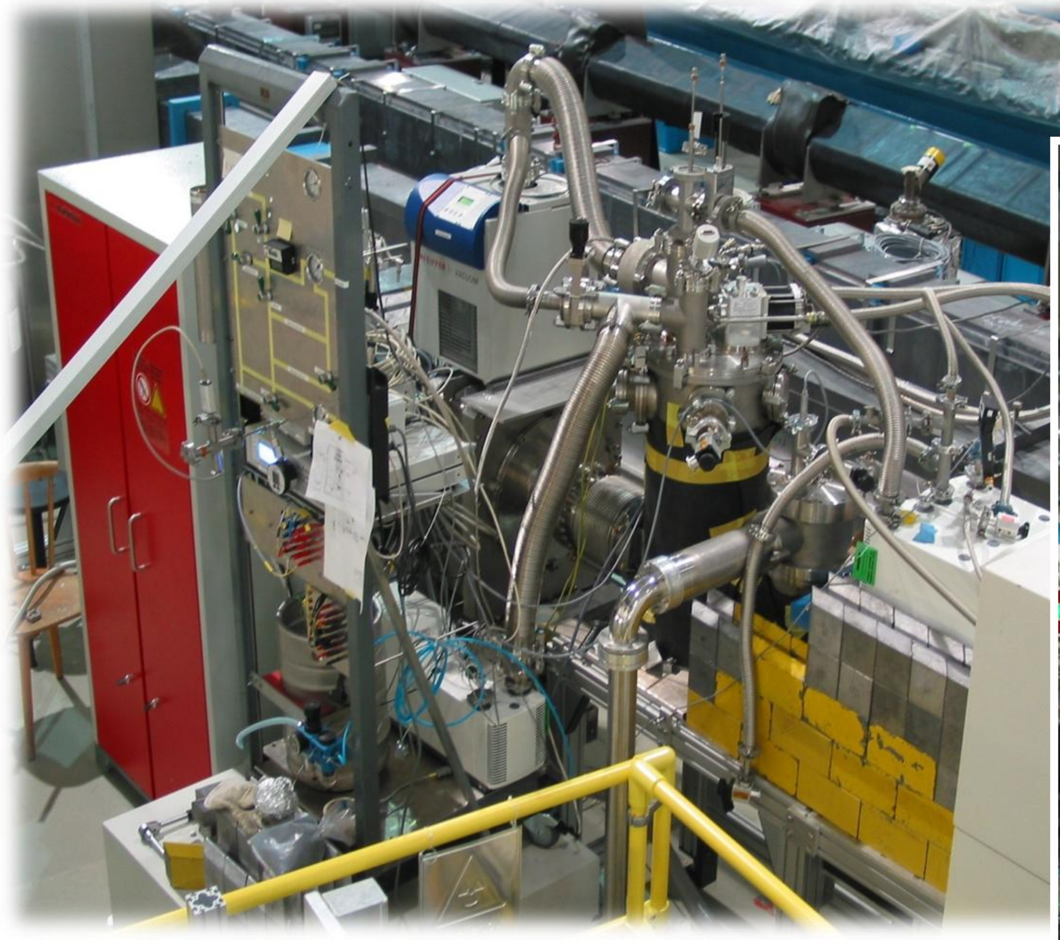


UCN converter vessel (16)



BeO ceramics, Be windows

...installed at the research reactor FRM II in Munich (2006)

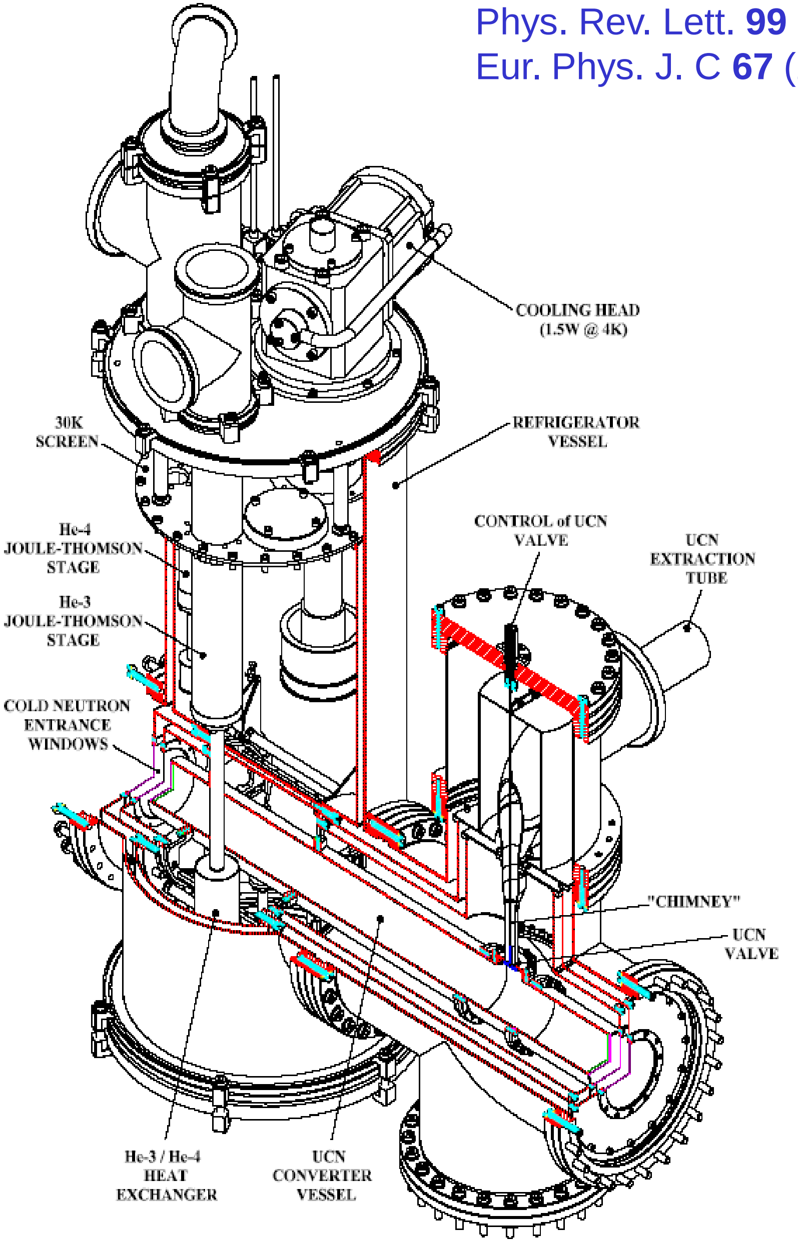


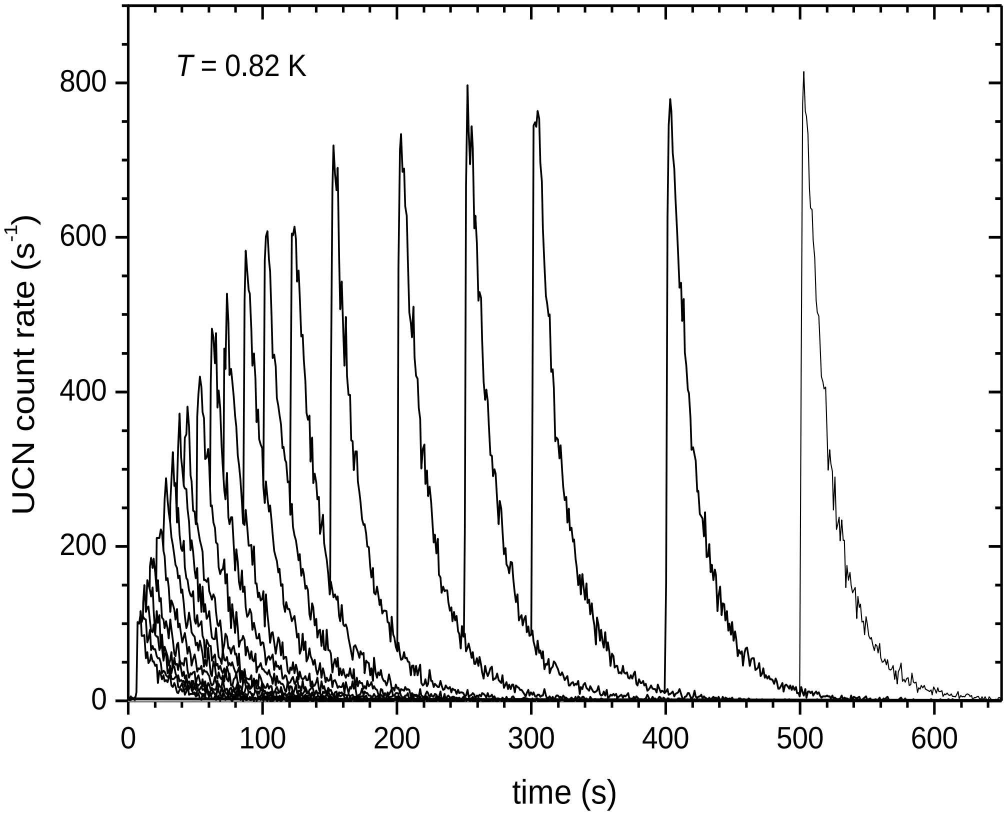
successful extraction of UCN accumulated in superfluid helium

Phys. Rev. Lett. **99** (2007) 104801
Eur. Phys. J. C **67** (2010) 589

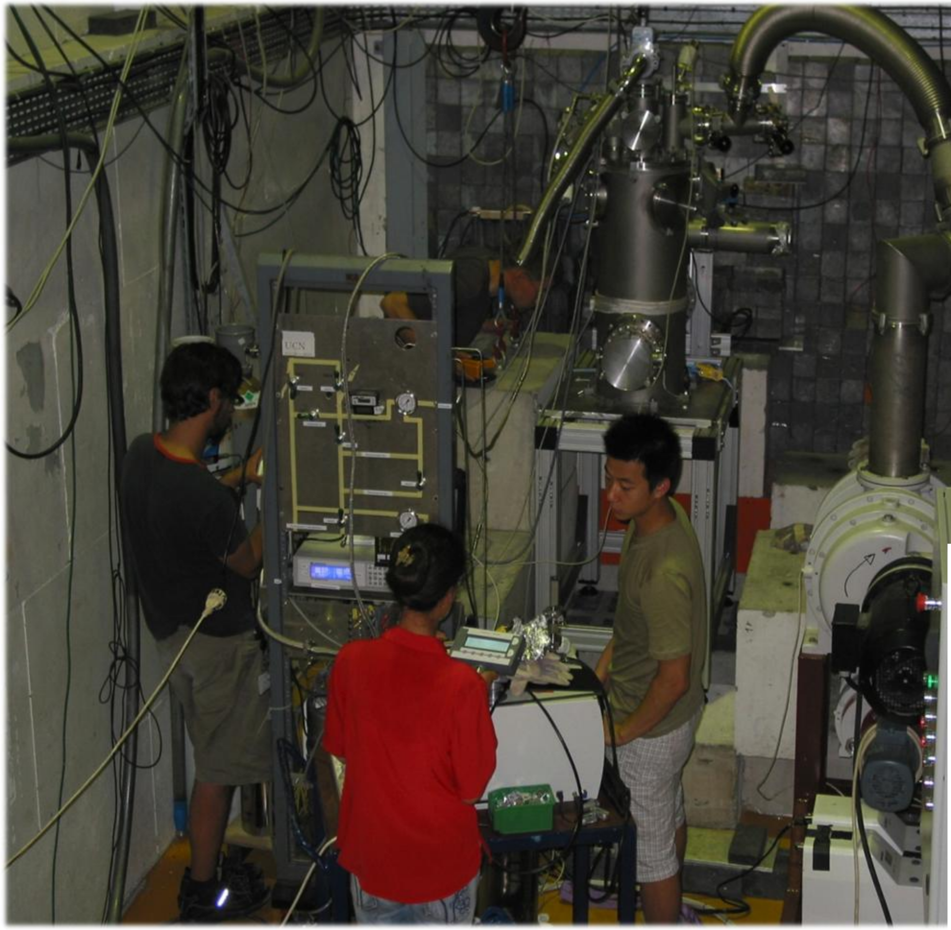
Extraction of UCN accumulated in He-II (@ FRM II)

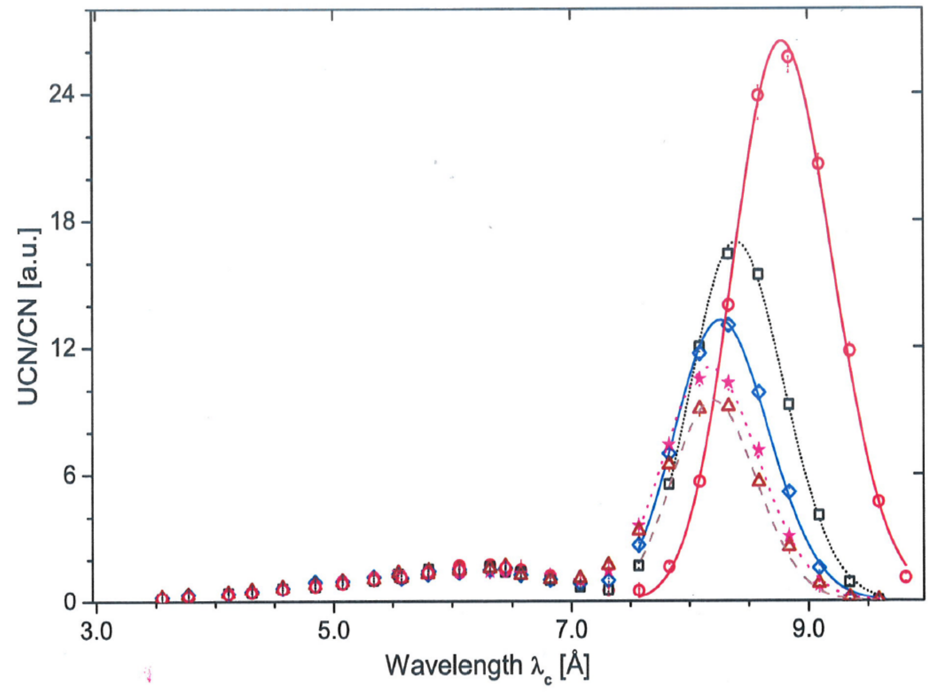
Phys. Rev. Lett. **99** (2007) 104801
Eur. Phys. J. C **67** (2010) 589



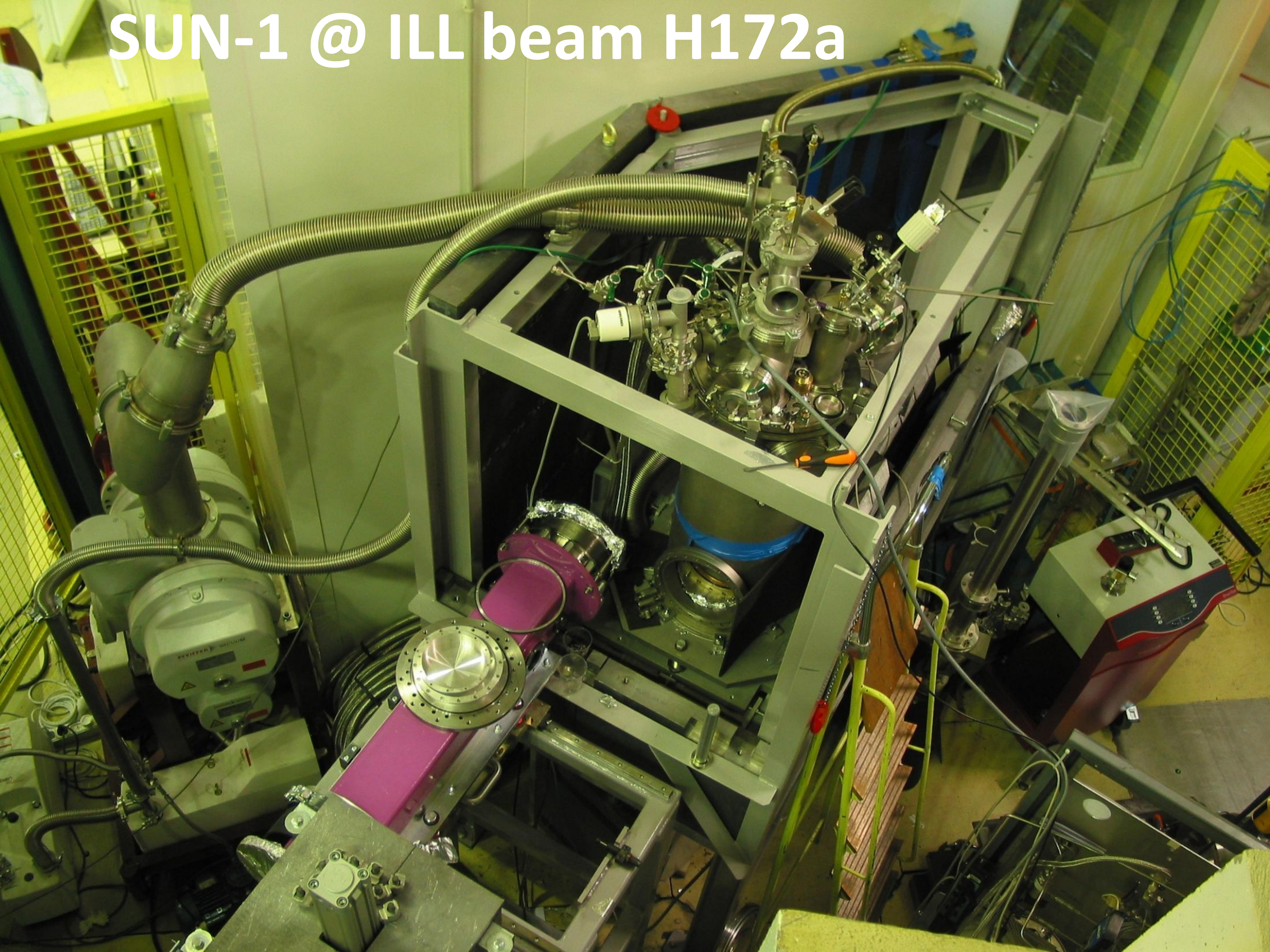


UCN production in pressurized He-II (@ PF1b, ILL)

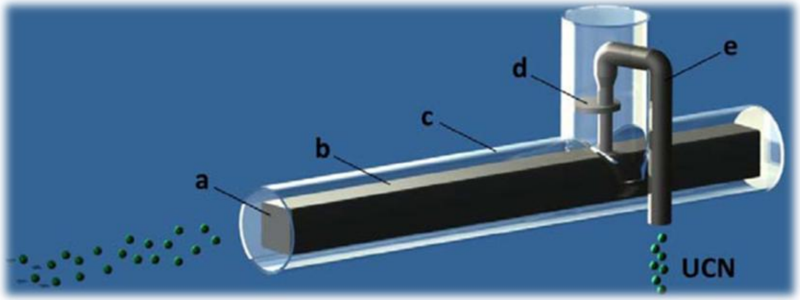


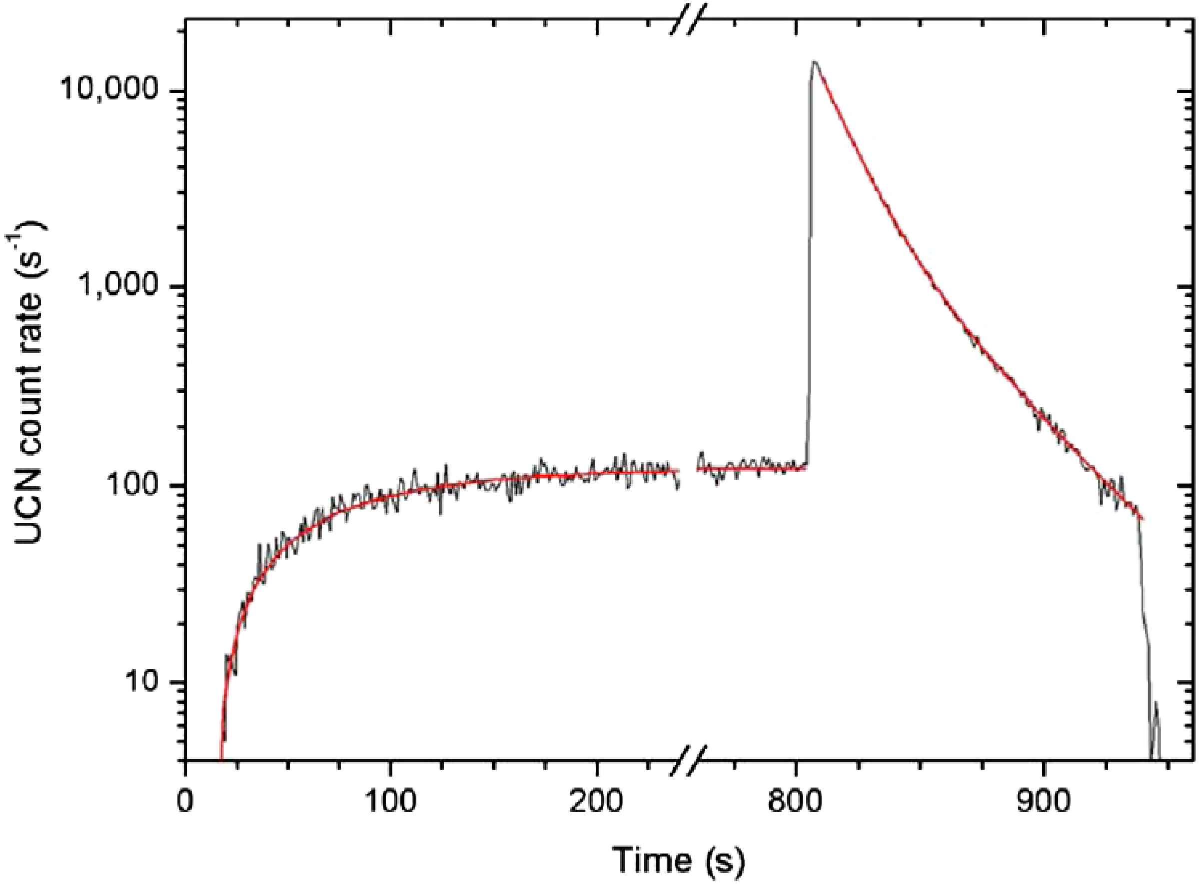


SUN-1 @ ILL beam H172a



Encouraging result:





274,000 counts

from 5 liters:

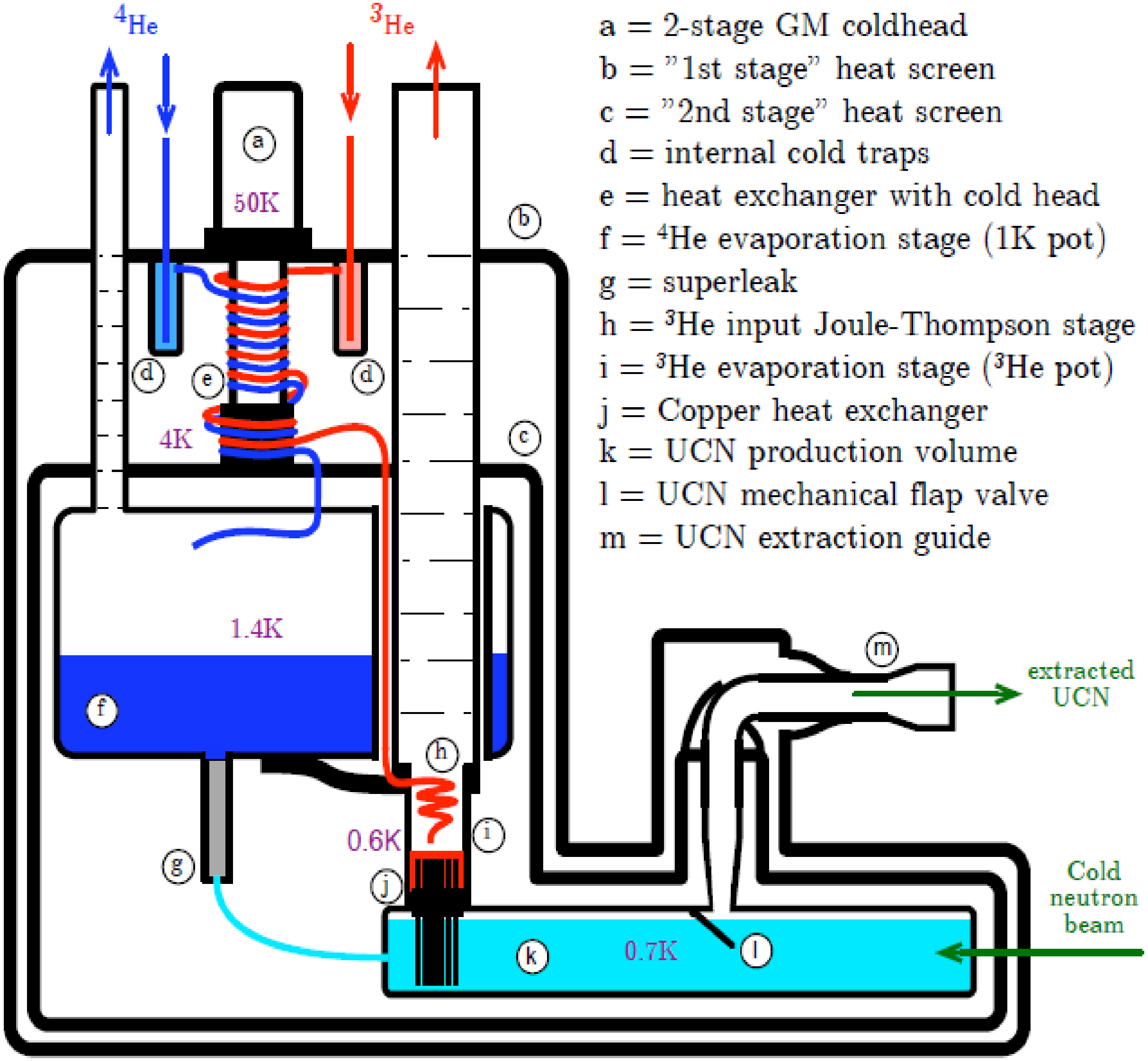
55 per ccm

PRL **107** (2011) 134801 **(PRL highlight)**

Layout of source prototype SUN-2

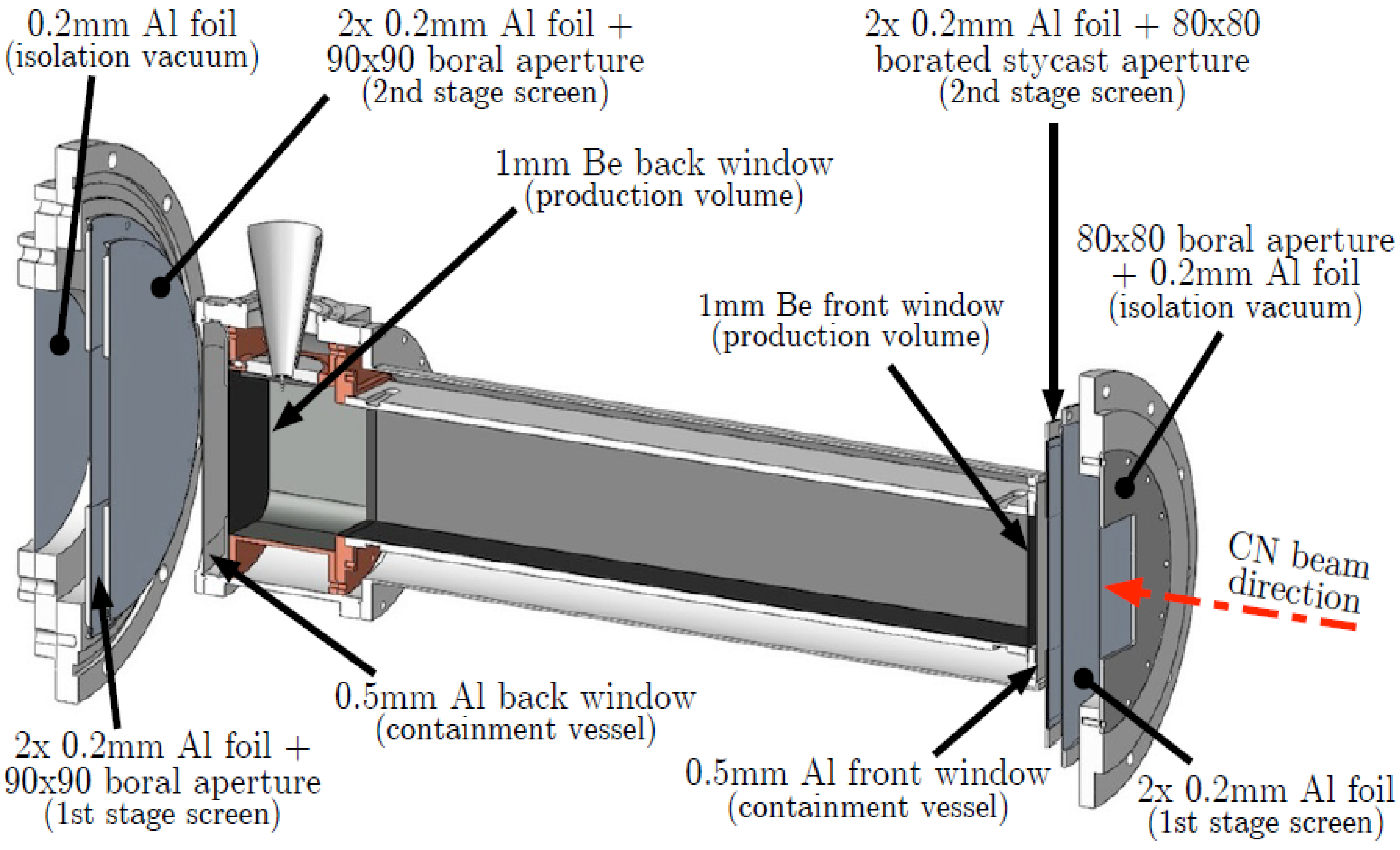
Development goals

- **modularity: converter r&d**
- **shorter turnaround time**
- **more cooling power**



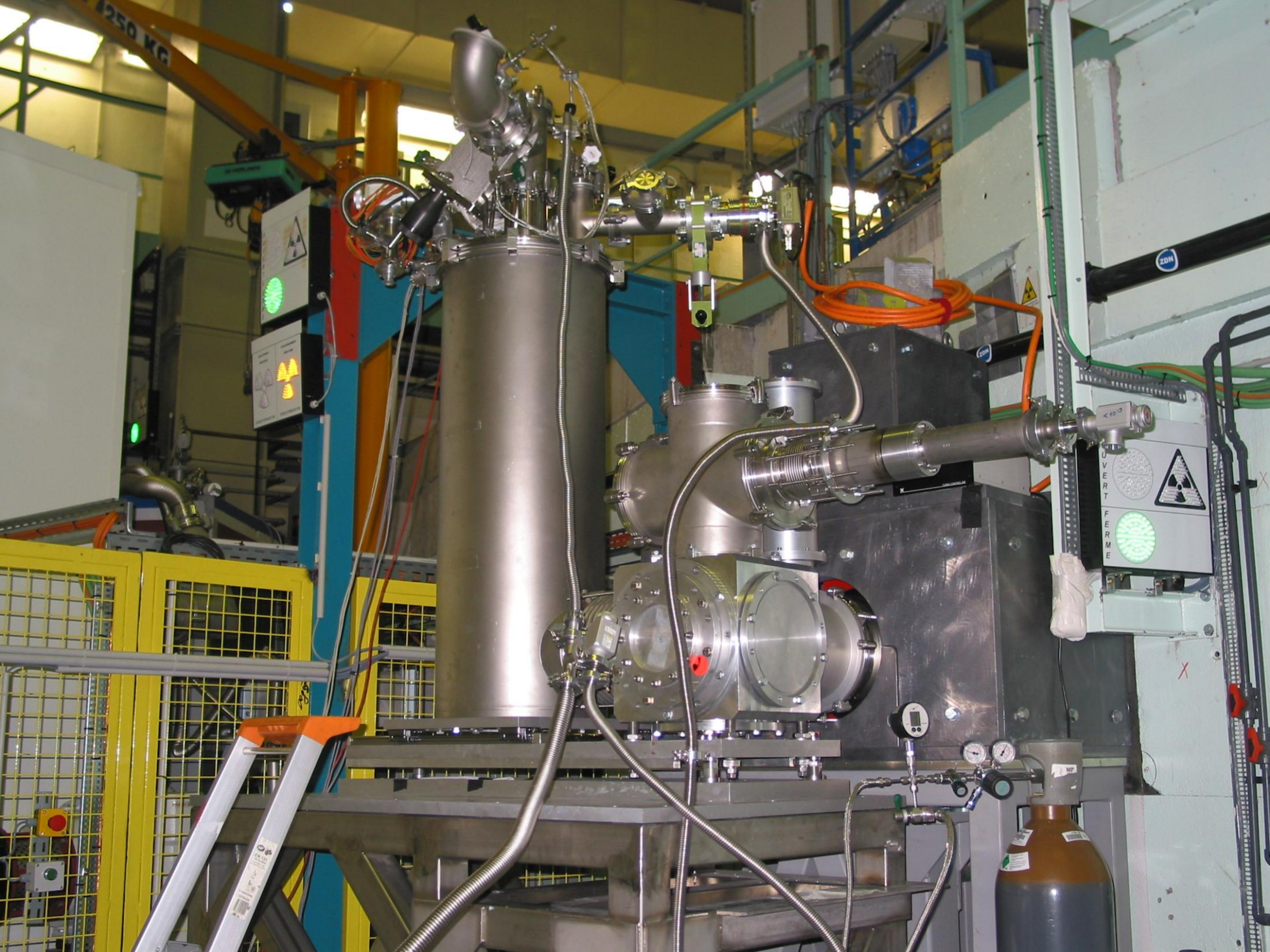
a = 2-stage GM coldhead
b = "1st stage" heat screen
c = "2nd stage" heat screen
d = internal cold traps
e = heat exchanger with cold head
f = ^{4}He evaporation stage (1K pot)
g = superleak
h = ^{3}He input Joule-Thompson stage
i = ^{3}He evaporation stage (^{3}He pot)
j = Copper heat exchanger
k = UCN production volume
l = UCN mechanical flap valve
m = UCN extraction guide

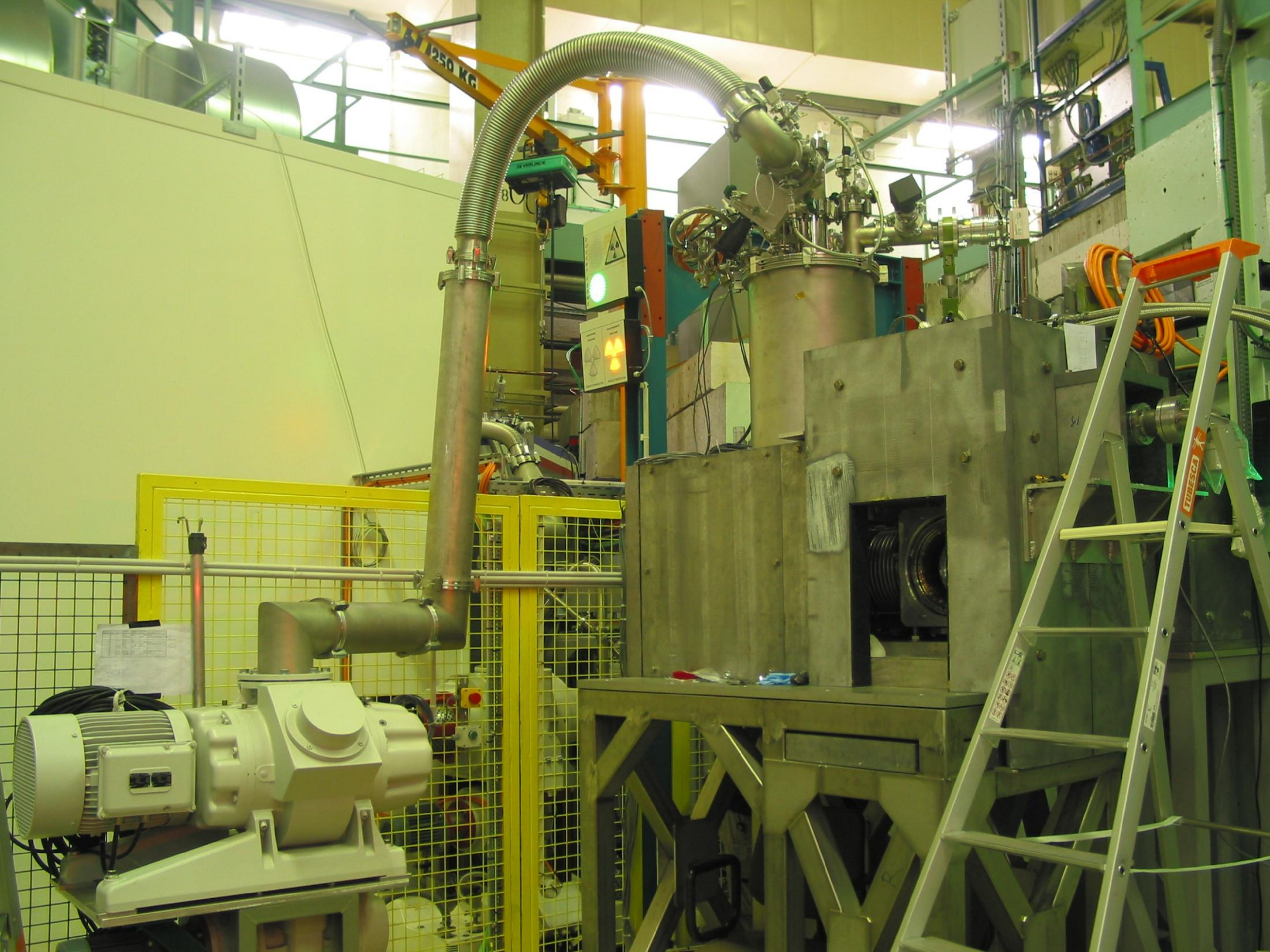
Schematics of SUN-2 converter vessel

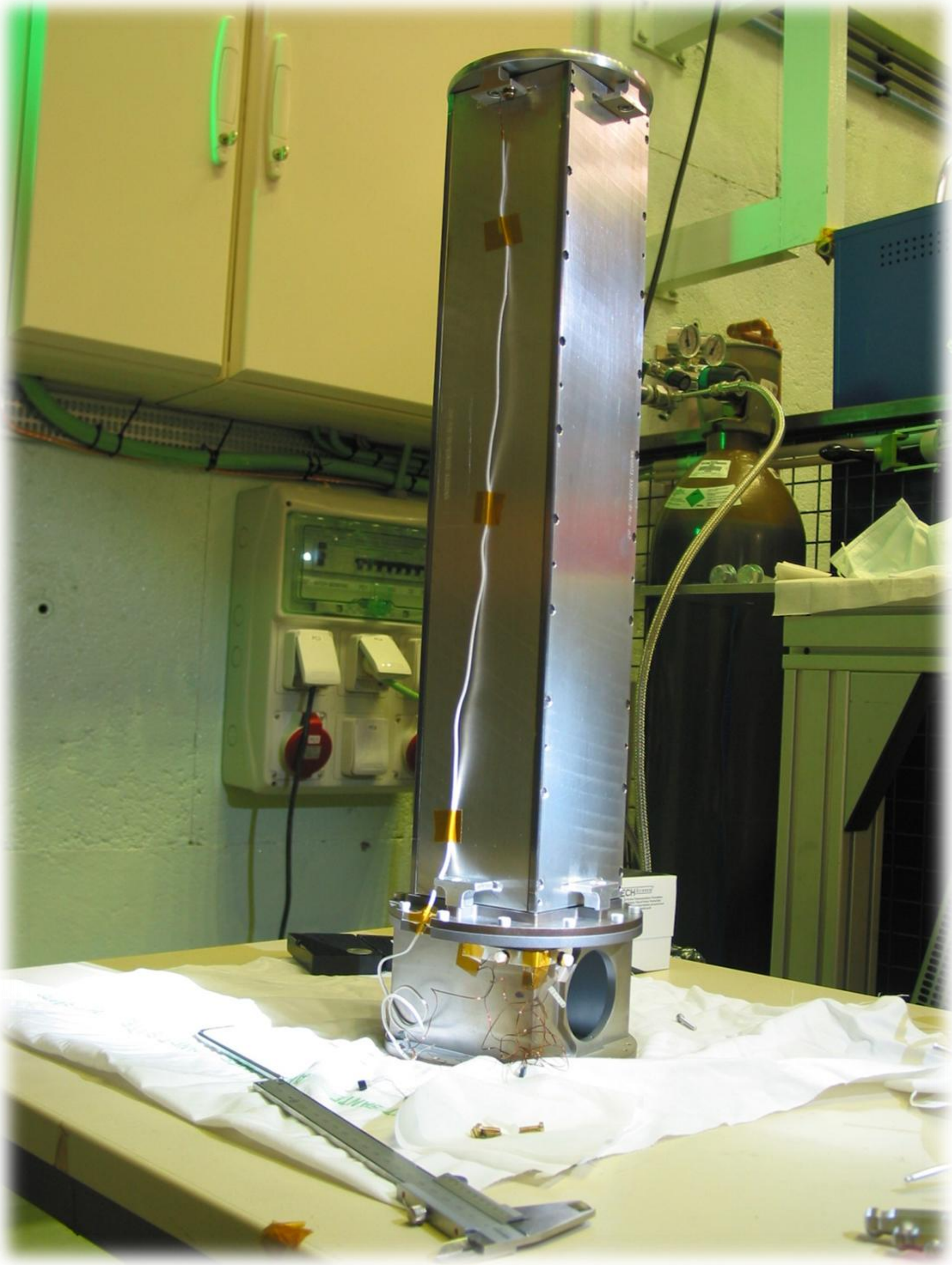


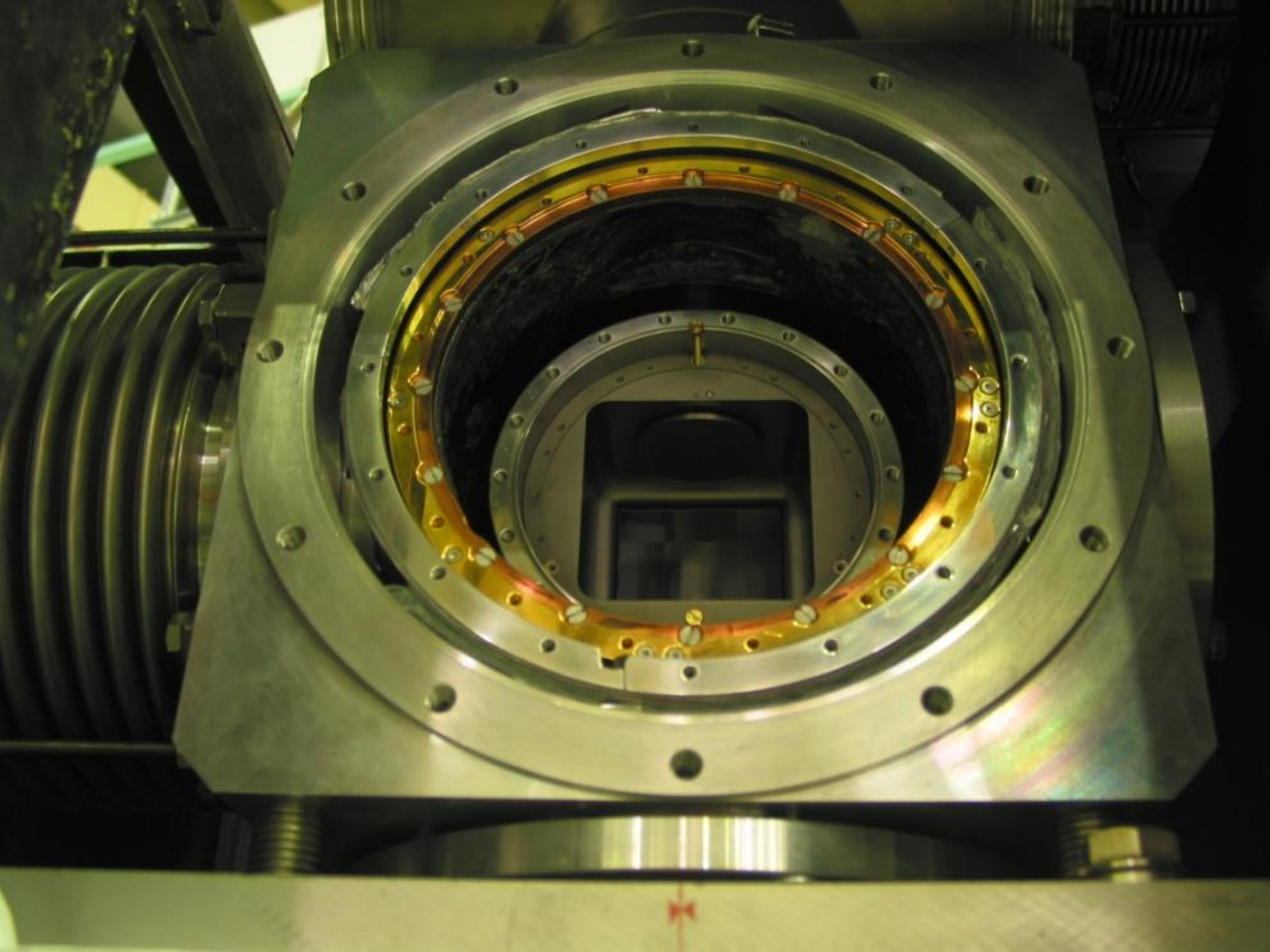
SUN-2 assembly

Martin Simson

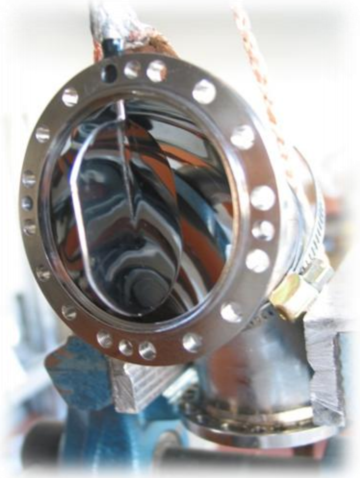

250 KG
ZDN
ZDN
< 10^-3
OUVERT
FERME


1250 KG
TUBESCA



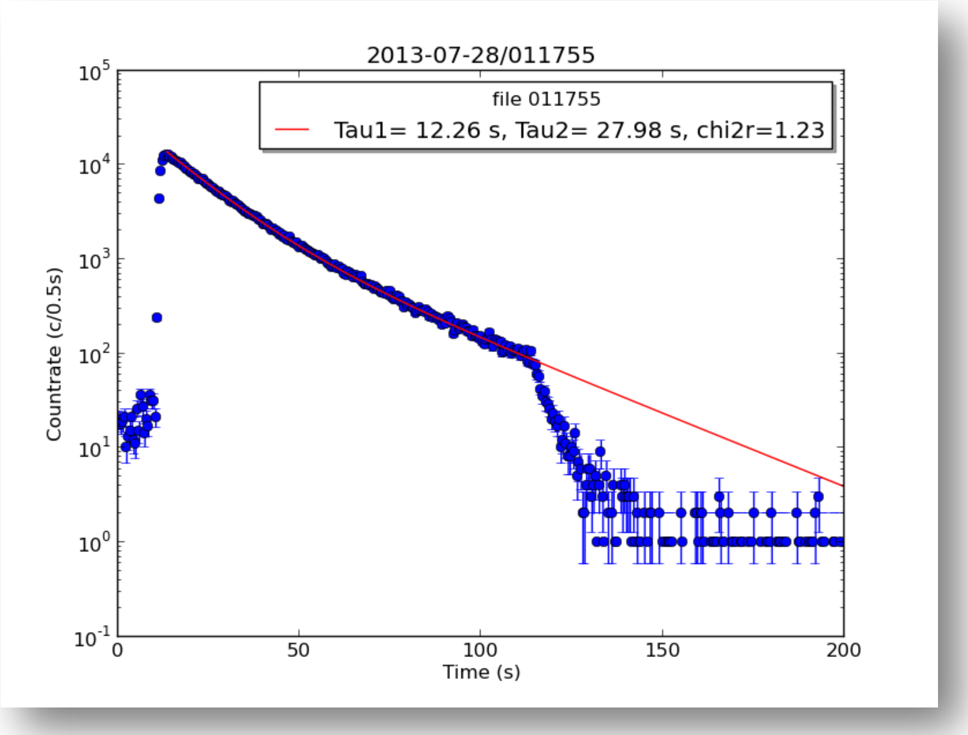


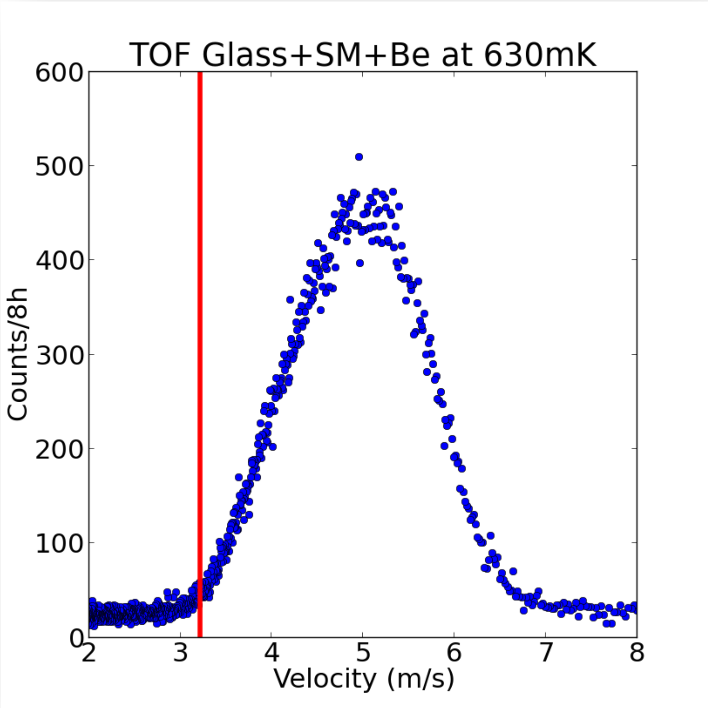
World-record UCN density (summer 2013)



supermirror converter vessel with Be-coating

0.64 K, $\tau_{\text{buildup}} \approx 1$ min



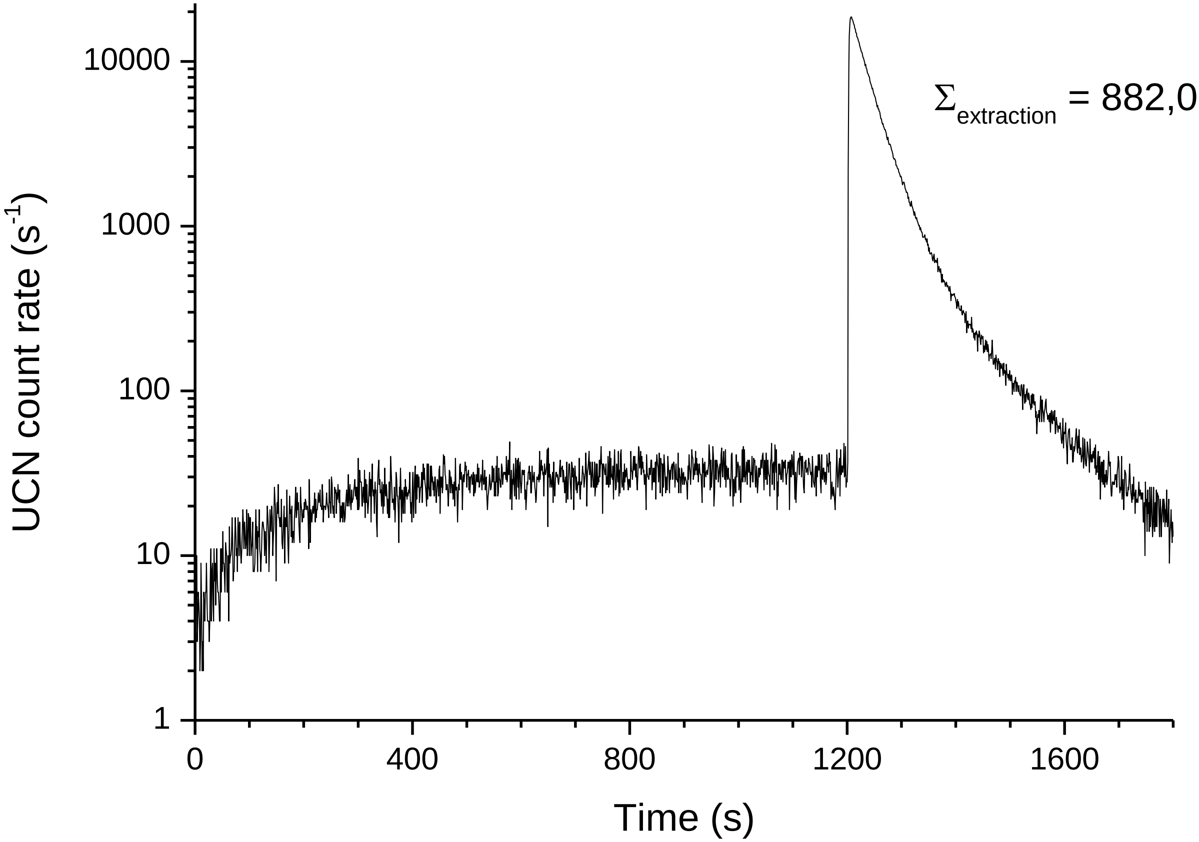


493000 accumulated UCN from 4 liters He-II **~ 120/cm³**

Recent achievement (16 July 2015)

(fomblin grease on Be on Al converter vessel)

with Ge/DLC photon windows
and plug in extraction guide



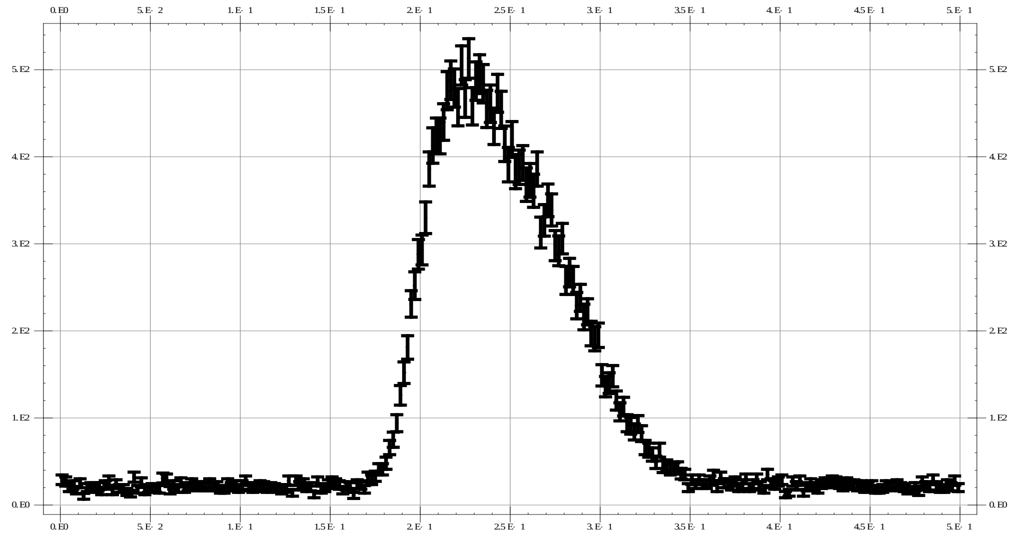
$\tau_{\text{buildup}} \approx 200$ s

$V \approx 70$ neV

0.61 K: **882000** accumulated UCN from 4 litres He-II **~ 220/cm^3**

Time-of-flight spectra

(fomblin grease on Be on Al converter vessel)



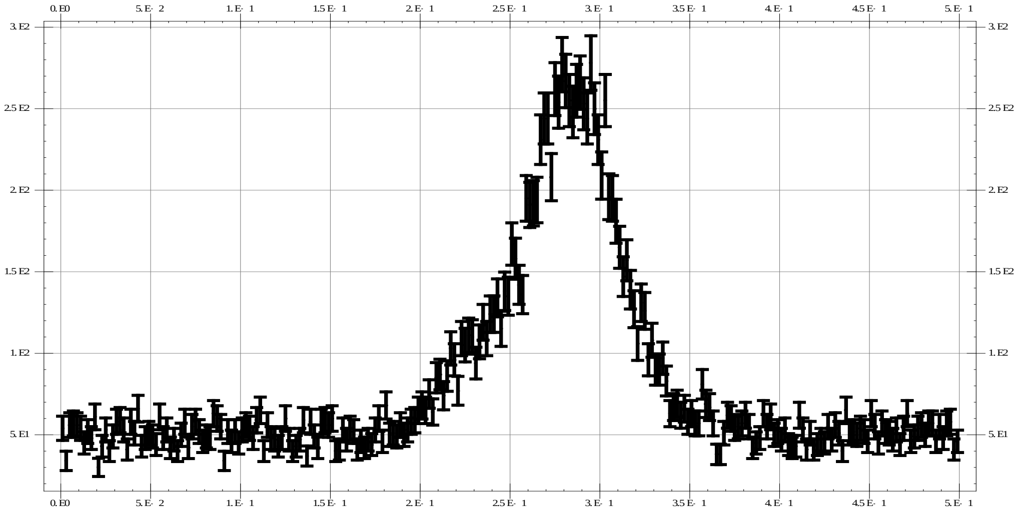
Open converter

$v(\max) = 5.1$ m/s

$E_{\|} = 144$ neV

$v_{max} = 6.7$ m/s

$v_{min} = 3.5$ m/s



200 s accumulation

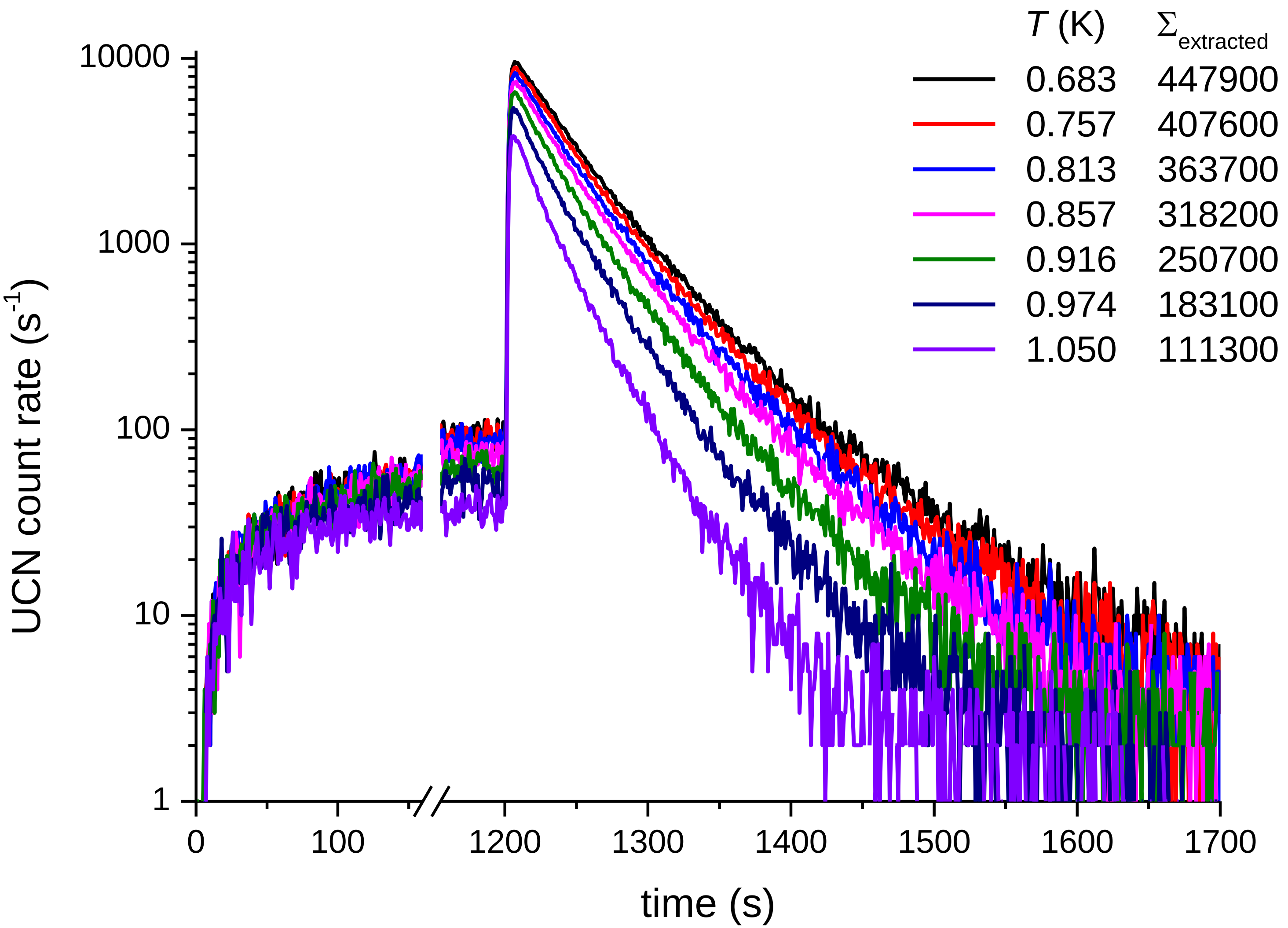
$v(\max) = 3.9$ m/s

$E_{\|} = 81$ neV

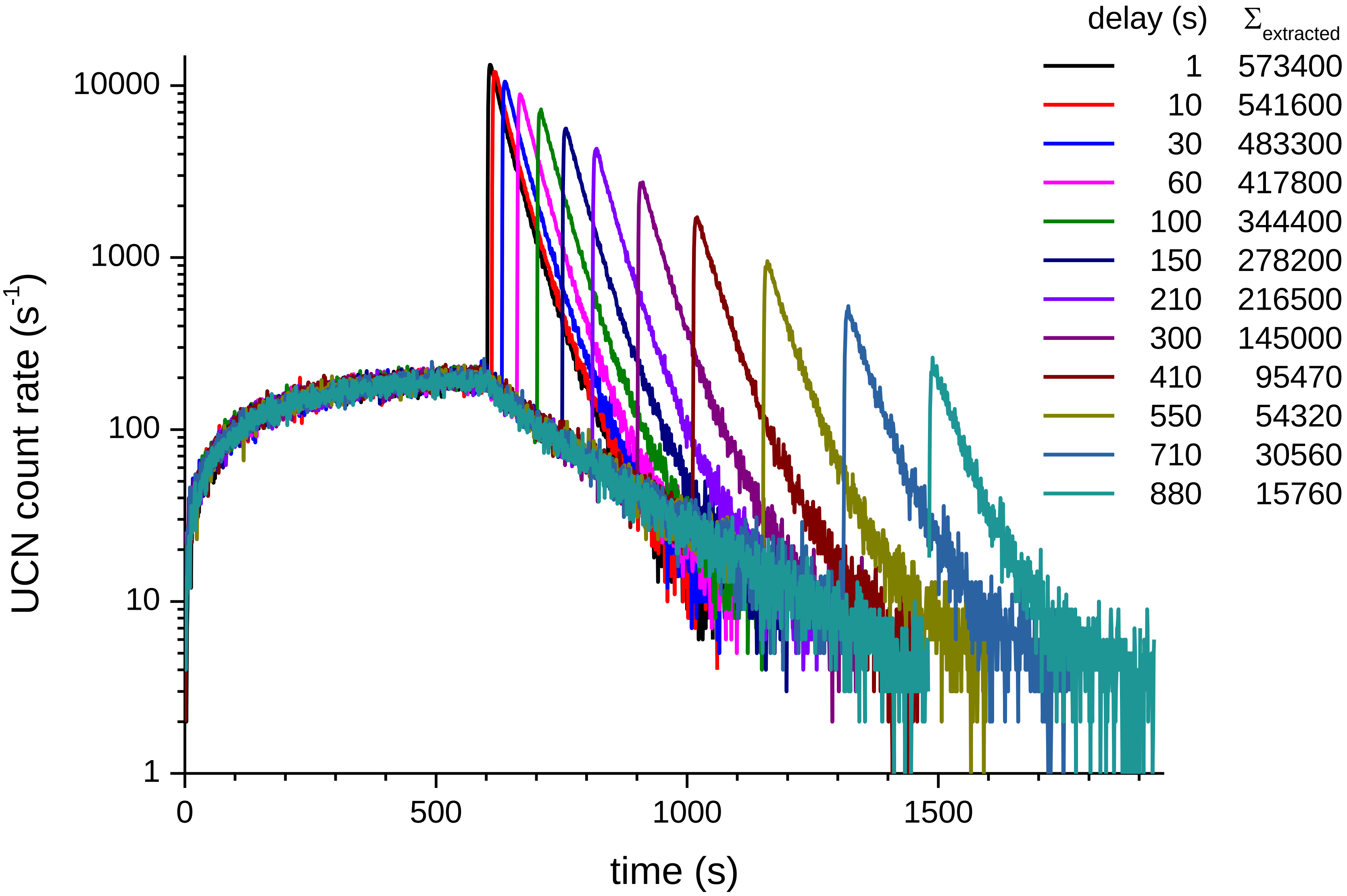
$v_{max} = 6.1$ m/s

$v_{min} = 3.5$ m/s

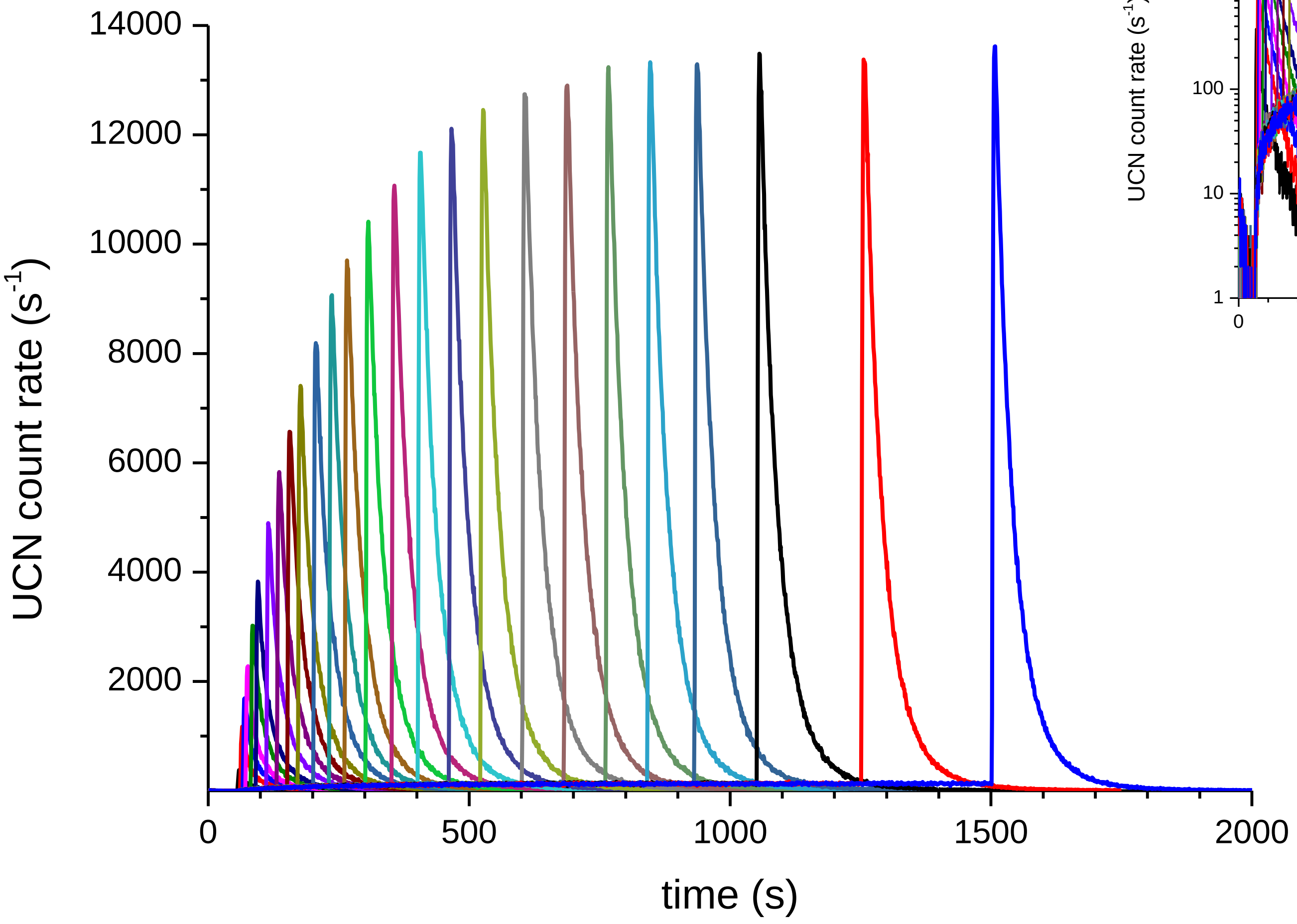
Illustration of effect of He temperature:

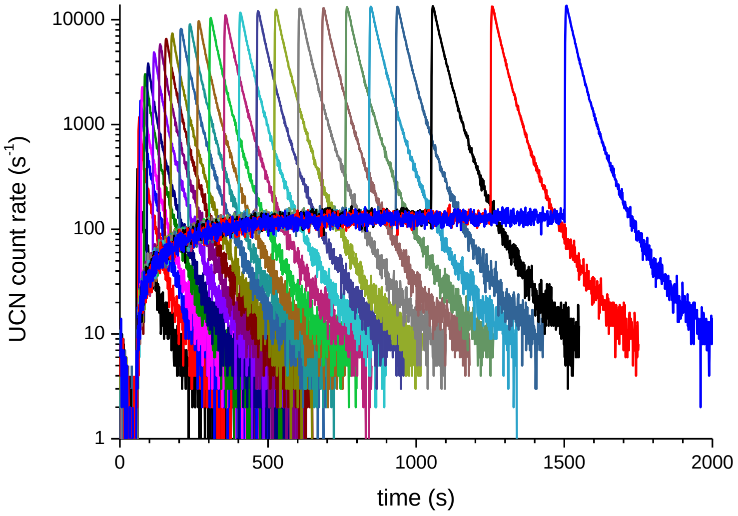


Delayed-extraction measurements at 0.68 K:

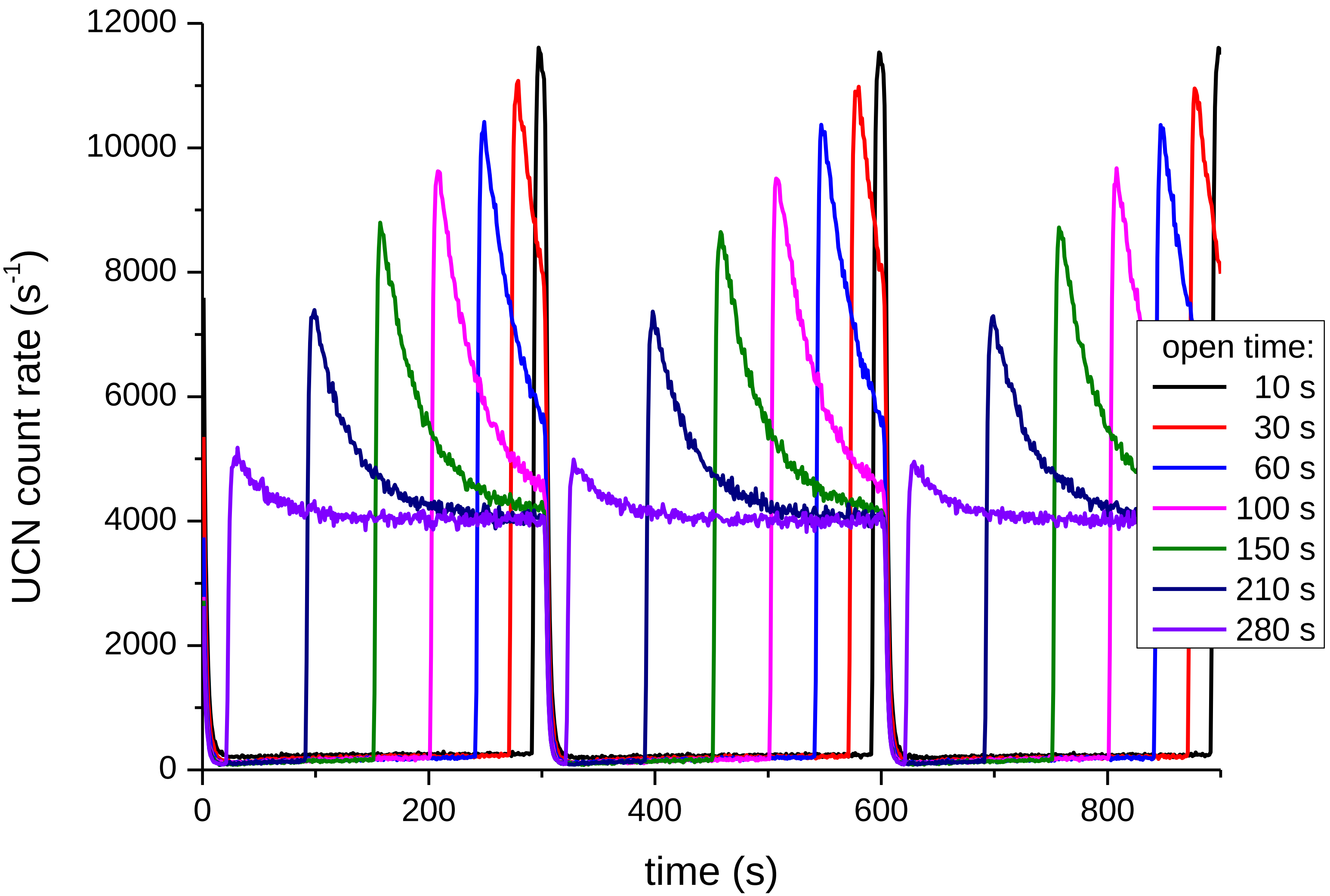


UCN buildup measurements at 0.67 K:

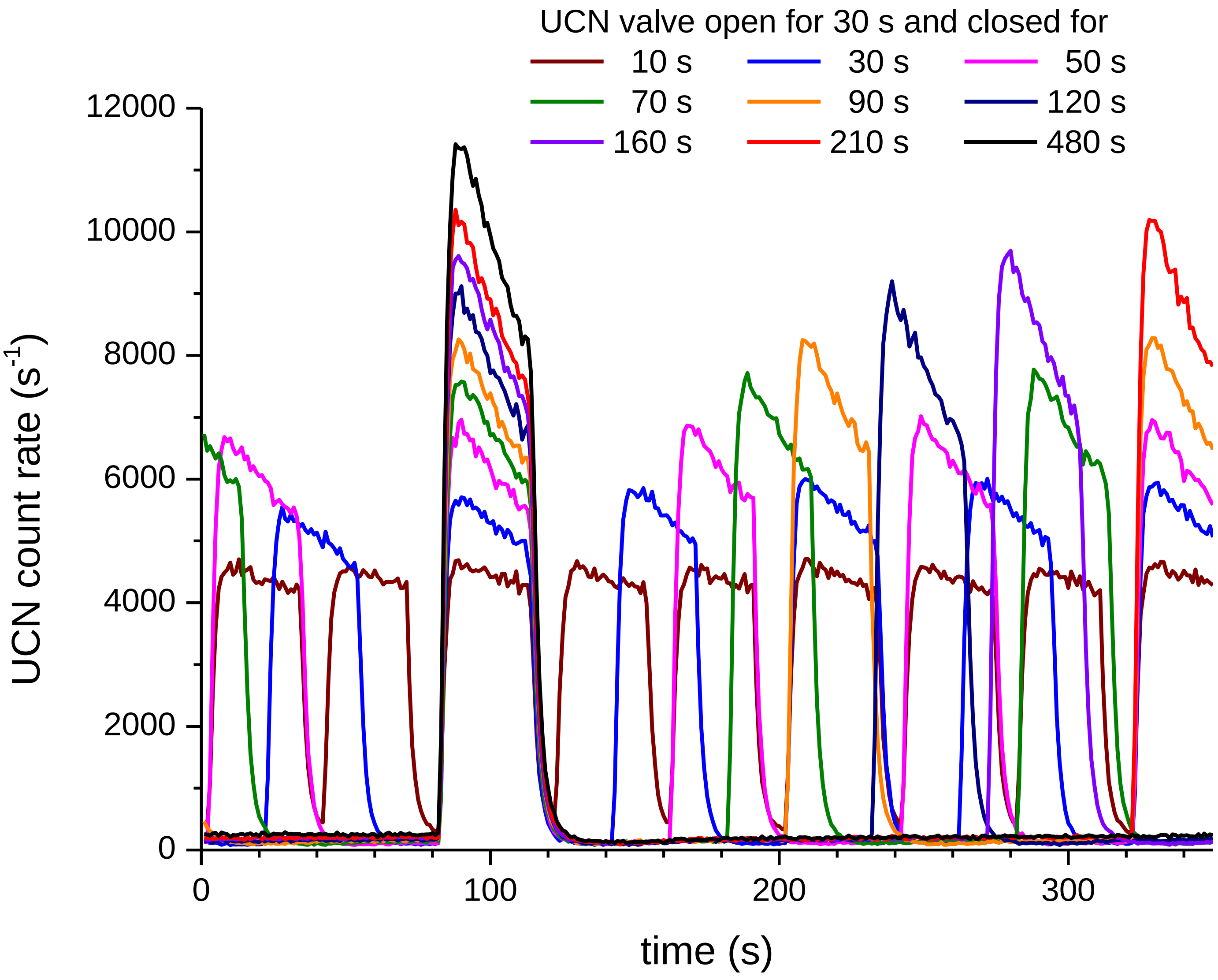




Measurements at 0.68 K with beam on all time:

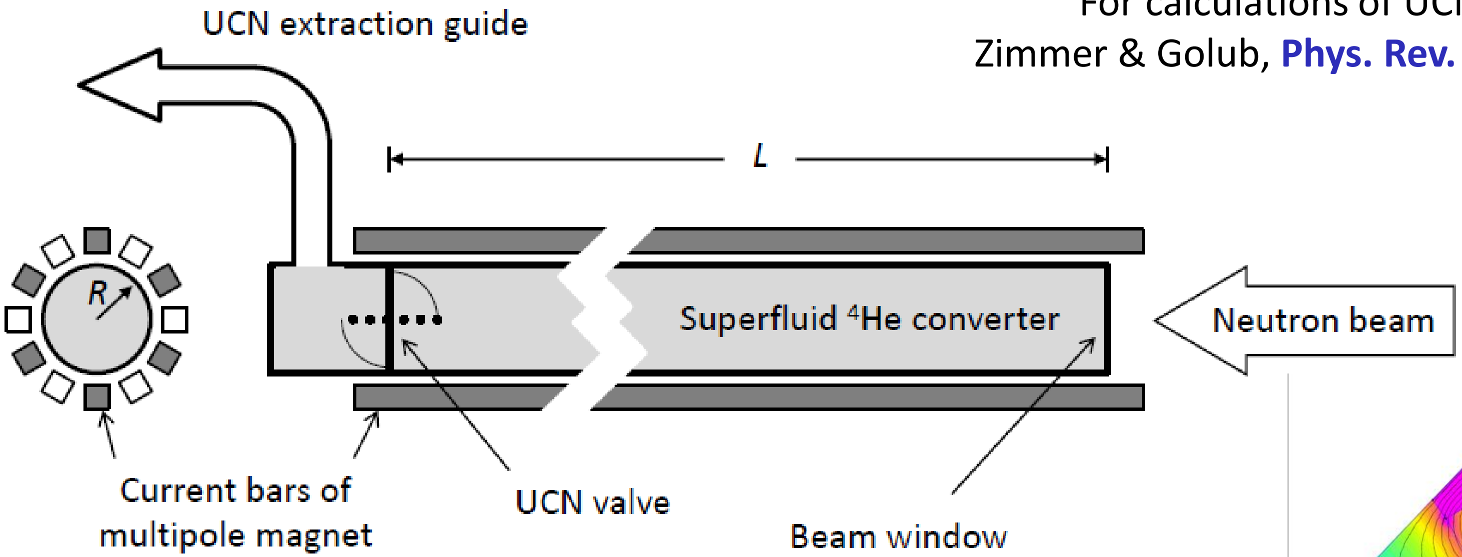


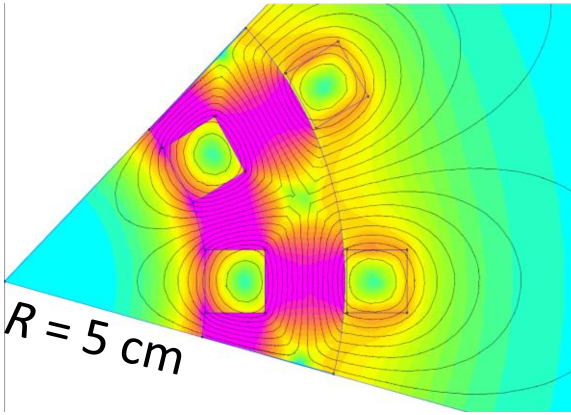
Measurements at 0.68 K with beam on all time:



ILL project **SuperSUN** (3 m magnetic 12-pole UCN reflector)

For calculations of UCN storage see:
Zimmer & Golub, **Phys. Rev. C 92 (2015) 015501**





- In-situ UCN polarizer
- Weak dependence of ρ_{UCN} on wall quality:

$f = W/V$	3×10^{-5}	1×10^{-4}	2×10^{-4}	4×10^{-4}
$n_{\mathrm{up,sat}}$ for V_{trap} = 210 neV (2.5 T surface field)	1880	1430	1210	1050
$n_{\mathrm{up,sat}}$ for V_{trap} = 210 neV (without magnet)	820	390	230	130

Numbers for differential 0.89 nm flux 1×10^9 cm^{-2}s^{-1}nm^{-1}

SUN-2 & HOPE team

(left to right):

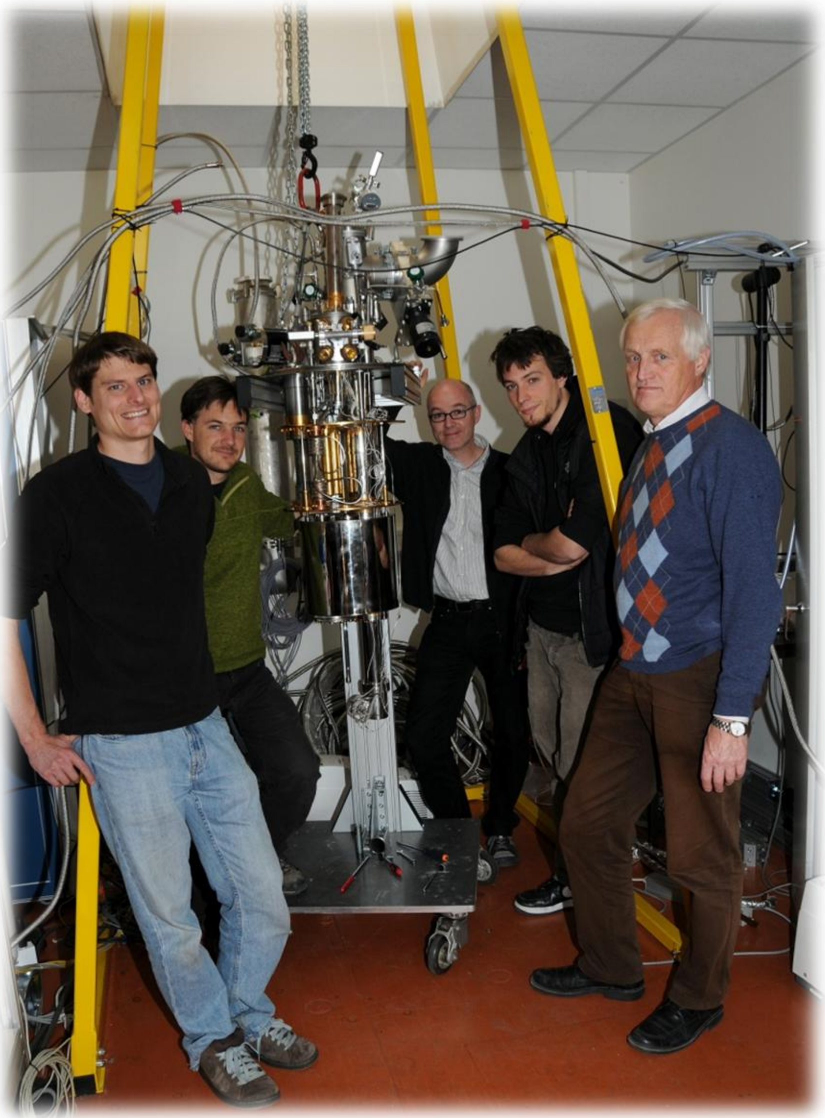
Martin Simson

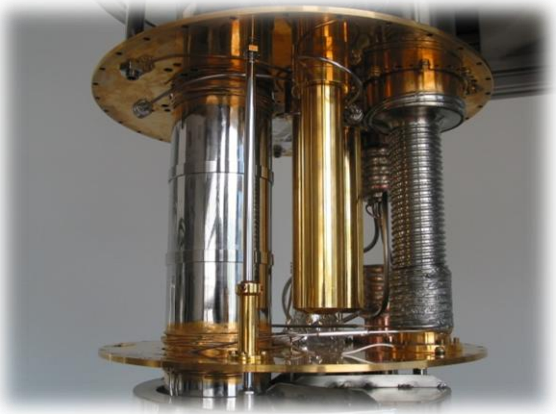
Florian Martin

a technician

Felix Rosenau

Sergey Ivanov





Thank you for your attention!