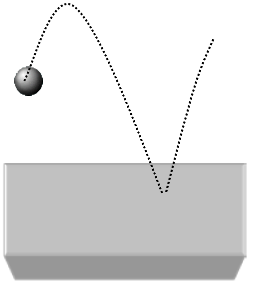
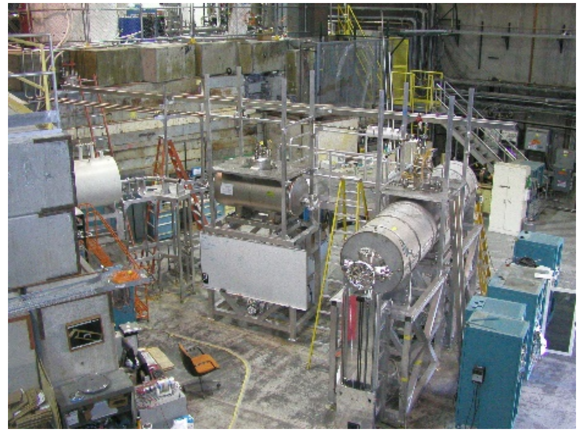
A Brief Overview of Ultracold Neutron Source Development and Some Points of Personal Interest

Albert R. Young
North Carolina State University

1998...



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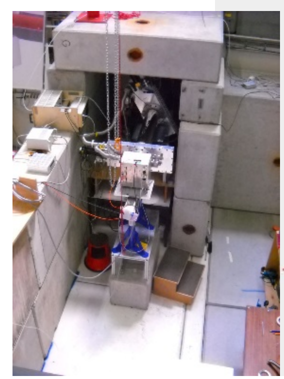
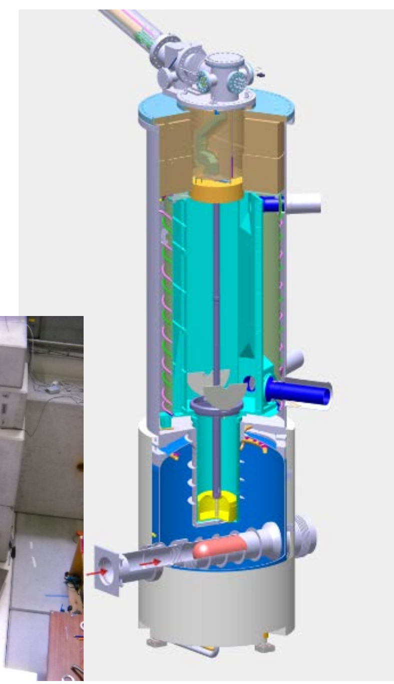
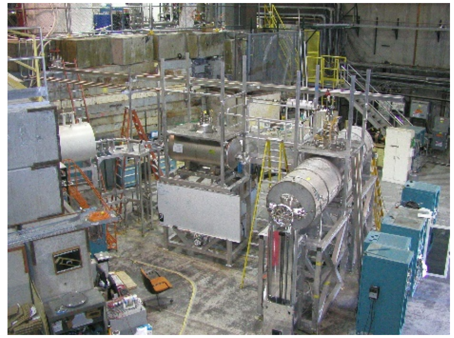
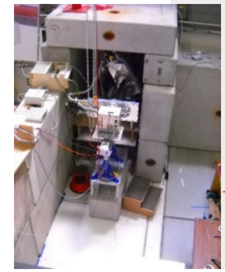
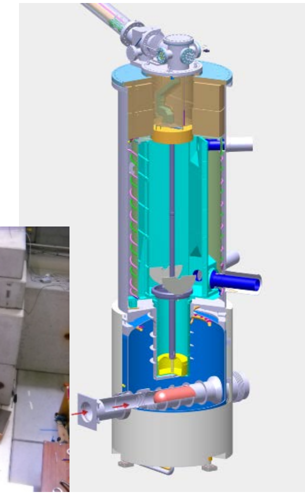



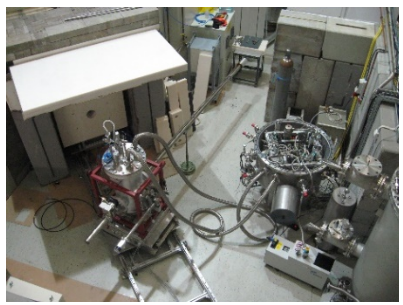


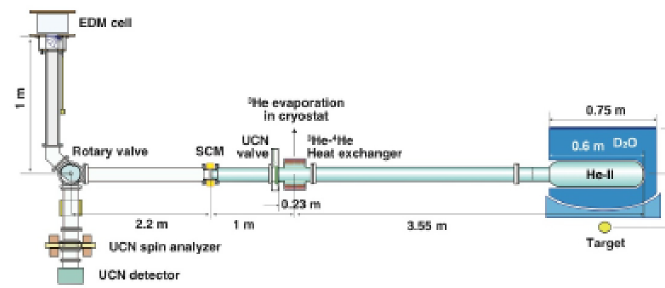


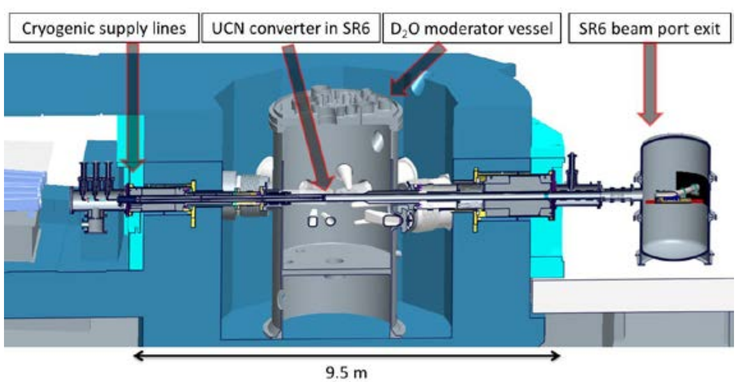


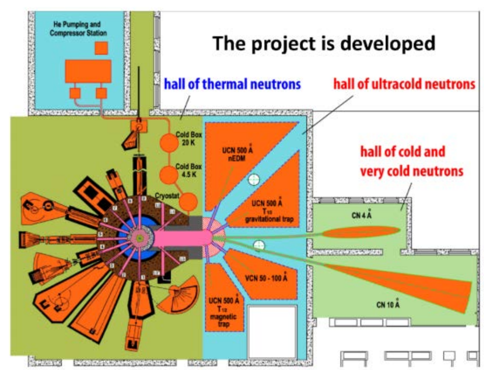
and Coming Soon!

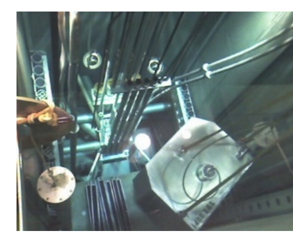
UCN availability increasing **dramatically**











Outline

- A Baseline: the ILL Turbine Source
- Superthermal Source Fundamentals
- Liquid He Sources
- Solid Deuterium Sources
- Conclusion

The ILL Turbine source

A. Steyerl, H. Nagel, F.K. Schrieber, K.A. Steinhauser, R. G□ahler, W. Gl□aser, P. Ageron, J.M. Astruc, W. Drexel, R. Gervais, and W. Mampe. Phys. Lett., 116A:347-352, 1986.

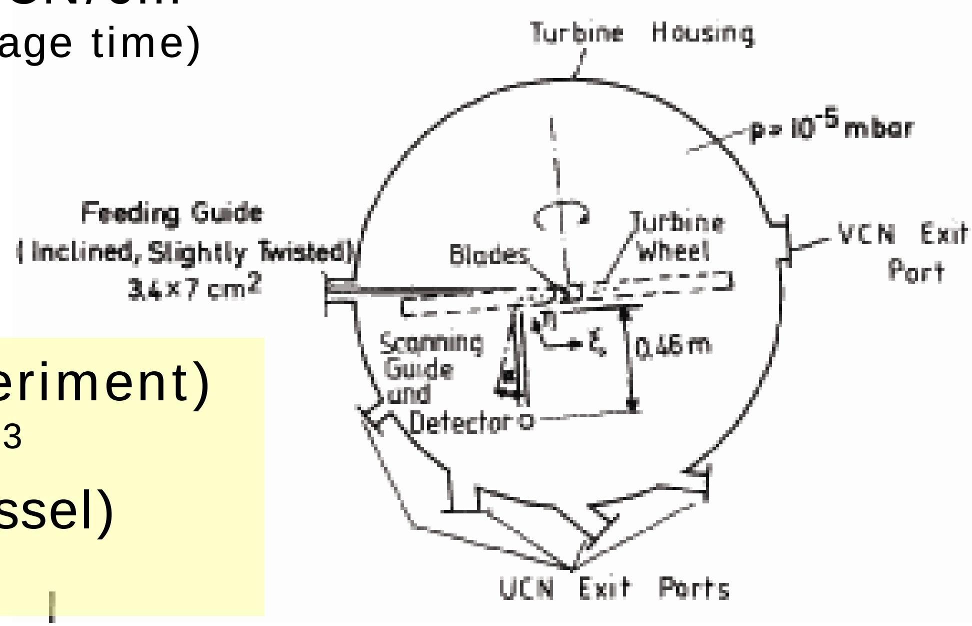
Talk: **P. Geltenbort**

Turbine: ~**110** UCN/cm^3 from TOF

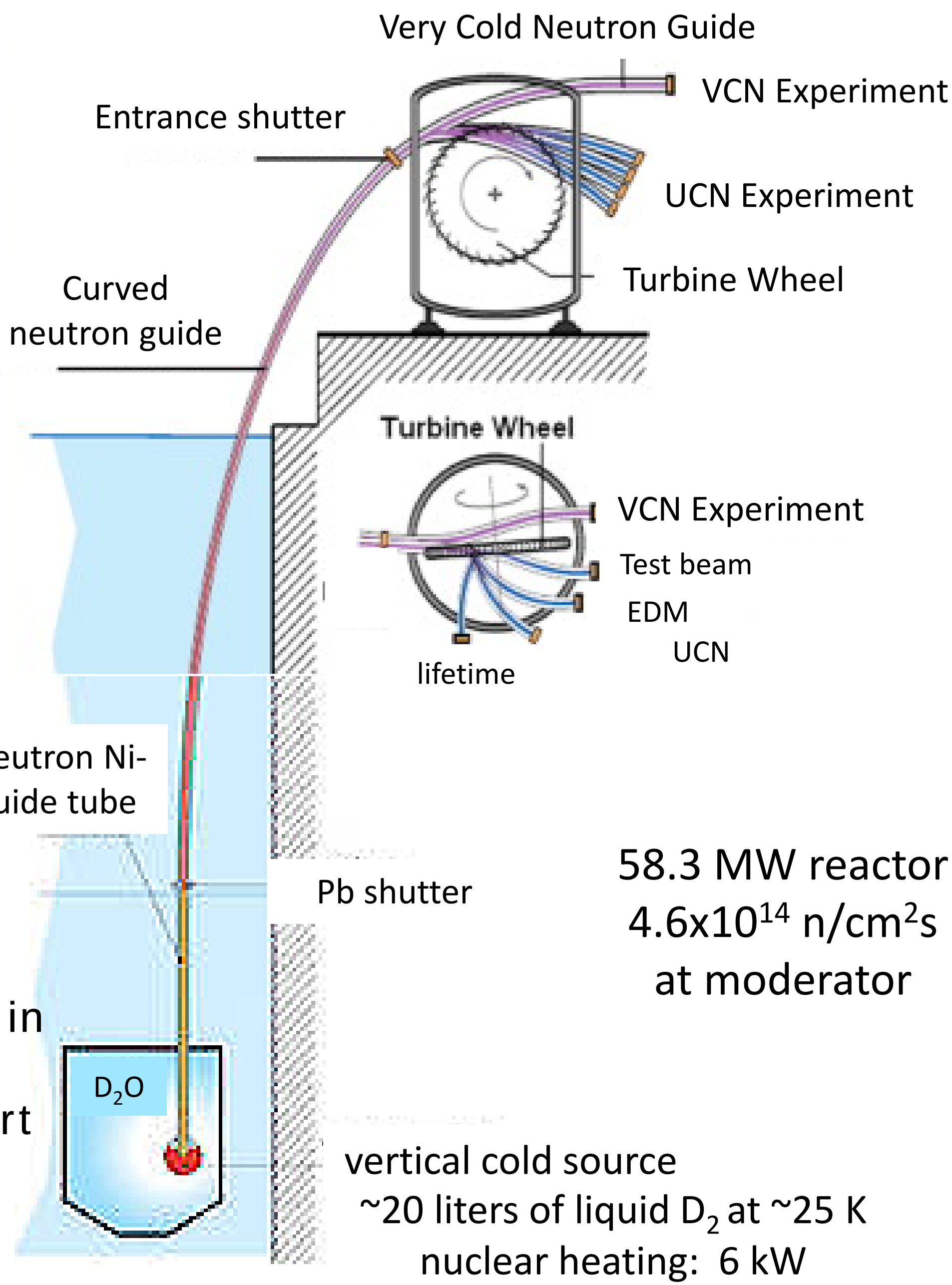
SS guide/bottle at exit: **39** UCN/cm^3
(factor of 0.4 in bottling w/ 70s storage time)

UCN current: 1-2×10^6 s^{-1}

Useful UCN (e.g. in EDM experiment)
~ 1 polarized UCN/cm^3
(in large spectrometer vessel)
~ 7 UCN/cm^3



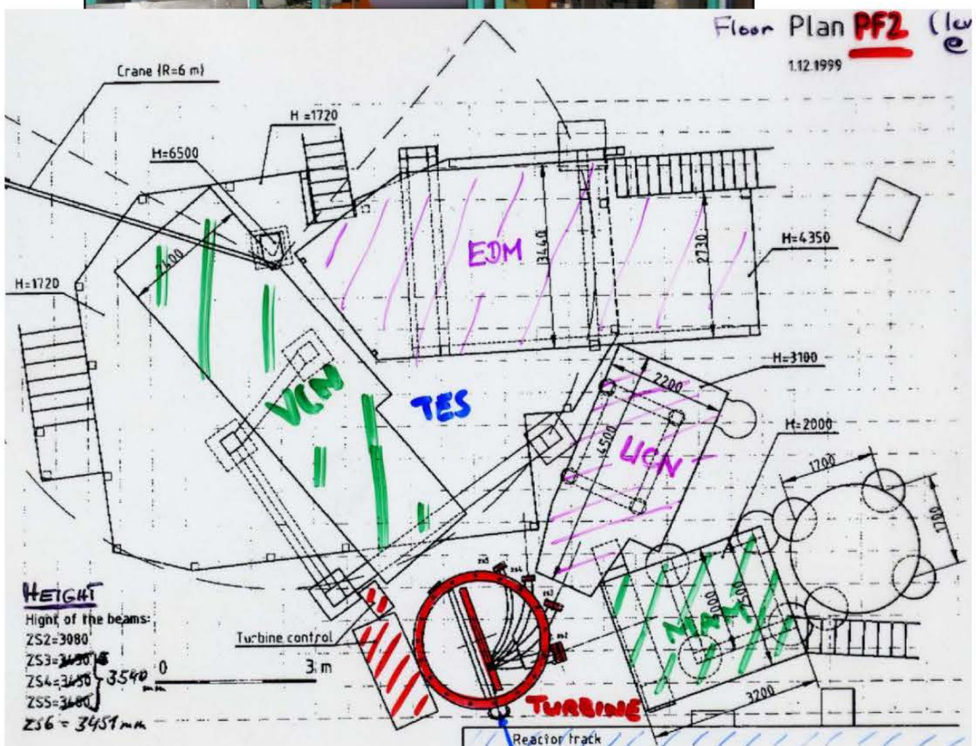
Works by extracting the low energy tail of neutrons **thermalized** in a 25K liquid D_2 source



58.3 MW reactor
4.6×10^{14} n/cm^{2}s
at moderator

1. Neutrons extracted through moderator window as VCN (~50 m/s)
2. VCN Doppler-shifted to UCN in turbine after vertical rise
3. Turbine establishes very short UCN survival time in source and very high current

The PF2 beam facility



PF2: Physique Fondamentale 2
2nd installation for fundamental physics

4 positions for Ultracold Neutrons (UCN)

- *MAM*
- *EDM*
- *UCN*

$v = 5\ ms^{-1}$

39 UCN cm^{-3} : SS bottle
$\sim$1 pol. UCN cm^{-3} in EDM

- *TES*

1 position for Very Cold Neutrons (VCN)

- *VCN beam* $v = 50\ ms^{-1}$
$= 10^8\ cm^{-2}\ s^{-1}$

Plenty of room at PF2
Gamma backgrounds?

Alternative: Avoid Thermal Equilibrium! *e.g.* Superthermal Sources

Original idea

1. Operate source at temperatures which effectively suppress thermal upscatter

2. Expose UCN converter material to cold neutron flux to produce UCN

3. Accumulate UCN in a storage volume for times approaching neutron lifetime (works for LHe or a thin-flim of source material such as D_2)

High(er) densities possible with much lower thermal power in converter!

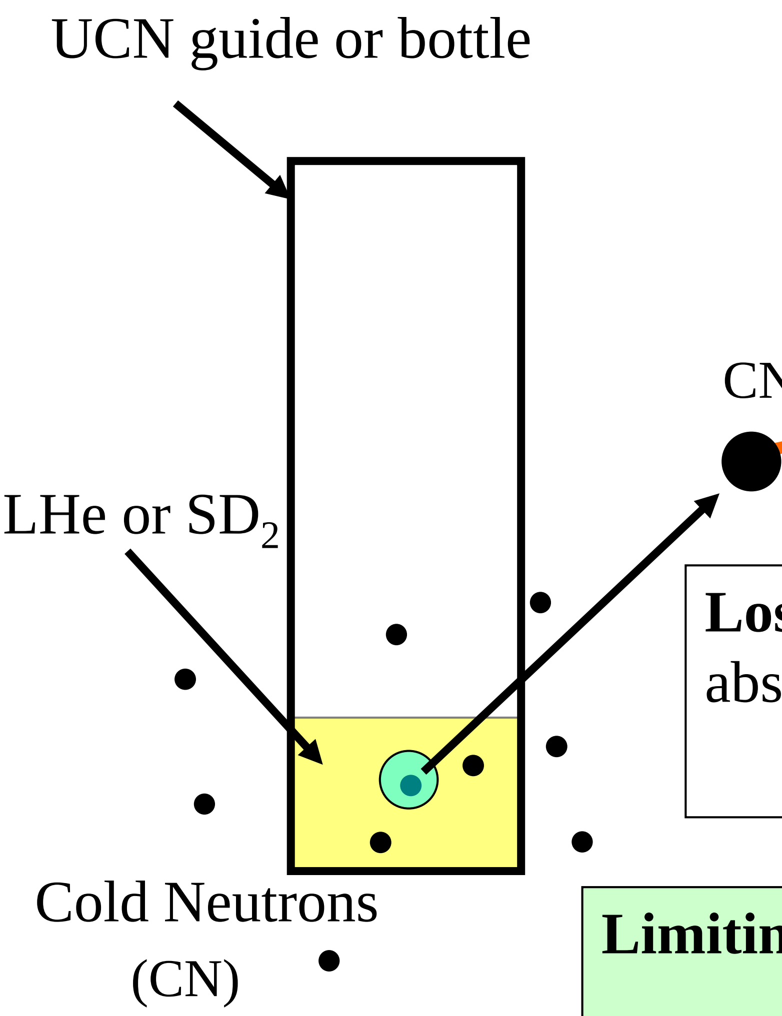
Key LHe references

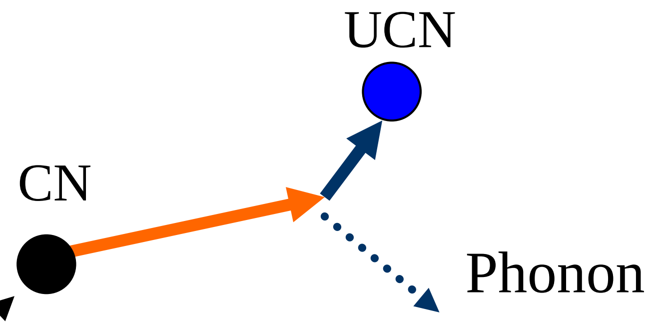
R. Golub and J. M. Pendlebury, Phys. Lett. **53A**, 133 (1975)
R. Golub and J. M. Pendlebury, Phys. Lett. **62A**, 337 (1977)
P. Ageron, W. Mampe, R. Golub and M. Pendlebury, Phys. Lett. **66A** 469 (1978)
R. Golub *et al*, Z. Phys. **B 51**, 187 (1983)

Establishing the Limiting density

Inelastic scattering is dominated (He and ortho-Deuterium) by a **single interaction** with phonons in source

Production (R): CN downscatter, producing a phonon and giving up almost all energy to become a UCN





Loss (N/τ): For any real source, losses via nuclear absorption, thermal upscatter and β-decay

$$1/\tau = 1/\tau_{thermal} + 1/\tau_{abs} + 1/\tau_{\beta}$$

Limiting Density: Loss balances production: $R = N/\tau$

$$\mathbf{N = R\tau}$$

Technical Aside on Production

Using SD_2 as a generic example:

The UCN production rate from cold neutrons with energy E' is proportional to

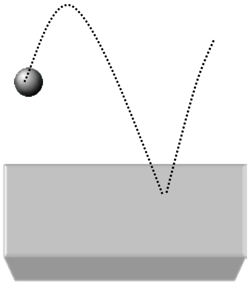
$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)^{1\ phonon}_{J\to J'} = \frac{k'}{k}\frac{\hbar^2\kappa^2}{2M_{D_2}} e^{-2W(\kappa)} S_{J,J'}(2J'+1)$$

$$\times \sum_n \left(\frac{\hbar\kappa^2}{2M_{D_2}\omega}\right)^n \frac{1}{n!} \sum_{l=|J'-J|}^{J'+J} |A_{nl}|^2 C'^2(JJ'l;00)$$

$$\times \frac{Z(E_{ph})}{E_{ph}} \begin{cases} n(E_{ph})+1 & \text{if } E_{ph} >= 0 \\ n(E_{ph}) & \text{if } E_{ph} < 0, \end{cases}$$

Favors low mass species for efficient momentum and energy transfer in collision

Thesis, C-Y Liu



Favors low Debye T materials with good overlap with CN distribution (T ~ 30 K)

Superthermal Source Candidates

Need very low neutron capture cross-sections!

Isotope	$\sigma_{coh}(barns)$	$\sigma_{inc}(barns)$	$\sigma_a(barns)$	σ_s/σ_a	purity(%)	Debye T(K)
^{4}D	5.59	2.04	0.000519	1.47×10^{4}	99.82	110
^{4}He	1.13	0	0	∞	100	20
^{15}N	5.23	0.0005	0.000024	2.1×10^{5}	99.9999	80
^{16}O	4.23	0	0.00010	2.2×10^{4}	99.95	104
^{208}Pb	11.7	0	0.00049	2.38×10^{4}	99.93	105

Table 7.1: Candidates for a superthermal source[8].

See end of talk....

Thesis: C.-Y. Liu

- He has (by far) longest absorption time (limited by ^{3}He contamination) : high densities accessible
- D_2 has larger cross-sections: higher production rates accessible (good for flow-through experiments)

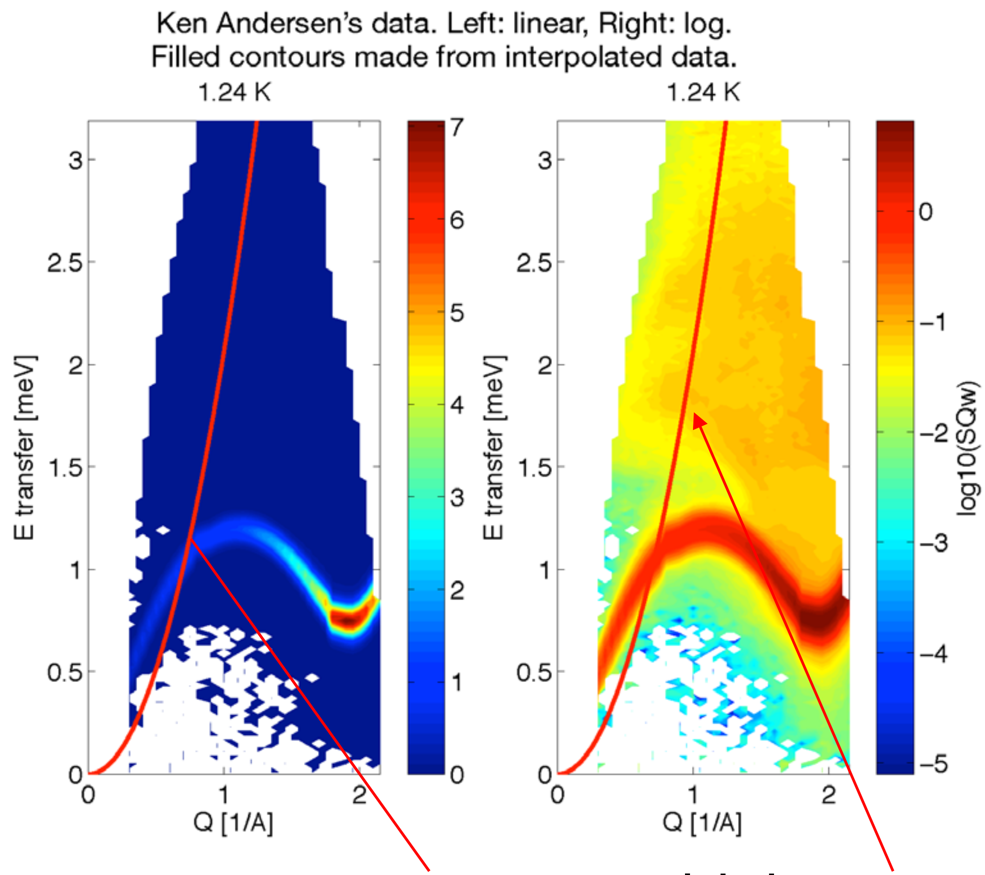
Inelastic Scattering in ^{4}He

UCN production via **1 phonon** scattering occurs when the ^{4}He dispersion curve intersects that of the free neutron

(E and p conservation in coherent scattering)

Well characterized for early work on superthermal sources

Scattering data eventually provided a very complete picture...



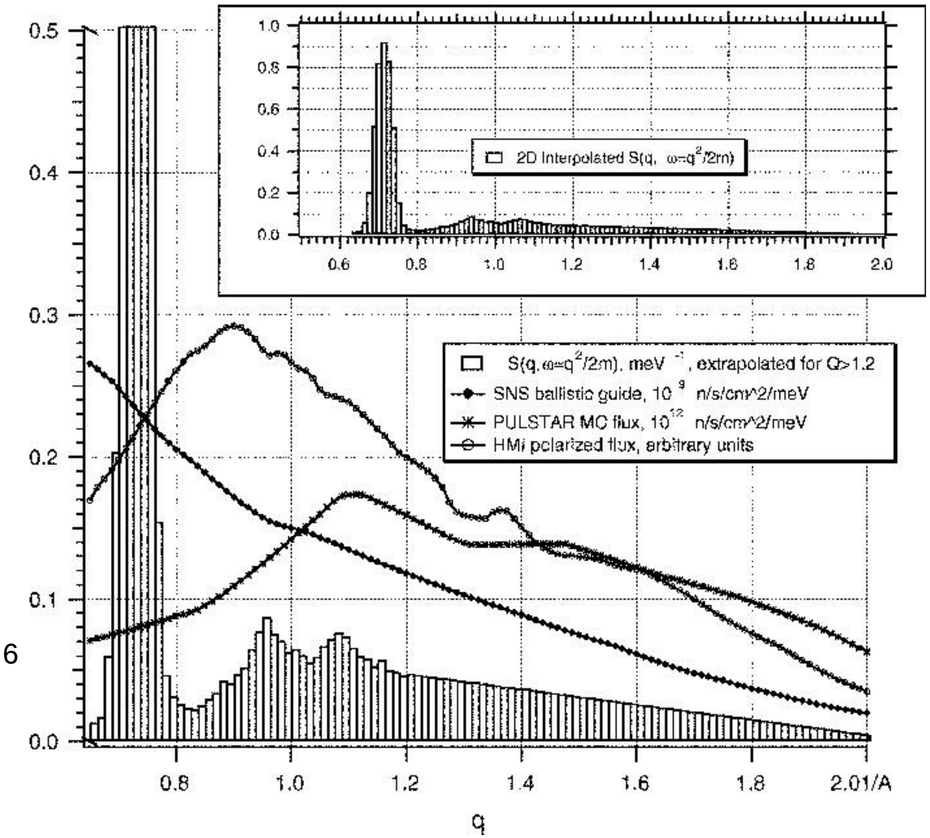
1-phonon production

multiphonon prod peaks

K. H. Anderson and W. G. Stirling, J. Phys: Cond. Matt. 6, 5805 (1994).

Production for various CN sources

E.Korobkina et al. / Physics Letters A 301 (2002) 462–469



Korobkina *et al.* calculate contribution from single and multiphonon prod for various CN distributions

Large volume source produces I > 10^6
Very high densities!

Table 1
Predicted production rates

	NC State [a]	SNS ord [a]	SNS ball [a]	HMI a.u.	Maxwell
Multi-ph	490	1.0	0.94	4.7	1.7
Single-ph	375	1.8	2.4	5.5	1.5
Mph/1ph	1.4	0.55	0.4	0.85	1.13

[a] UCN cm $^{-3}$ s $^{-1}$.

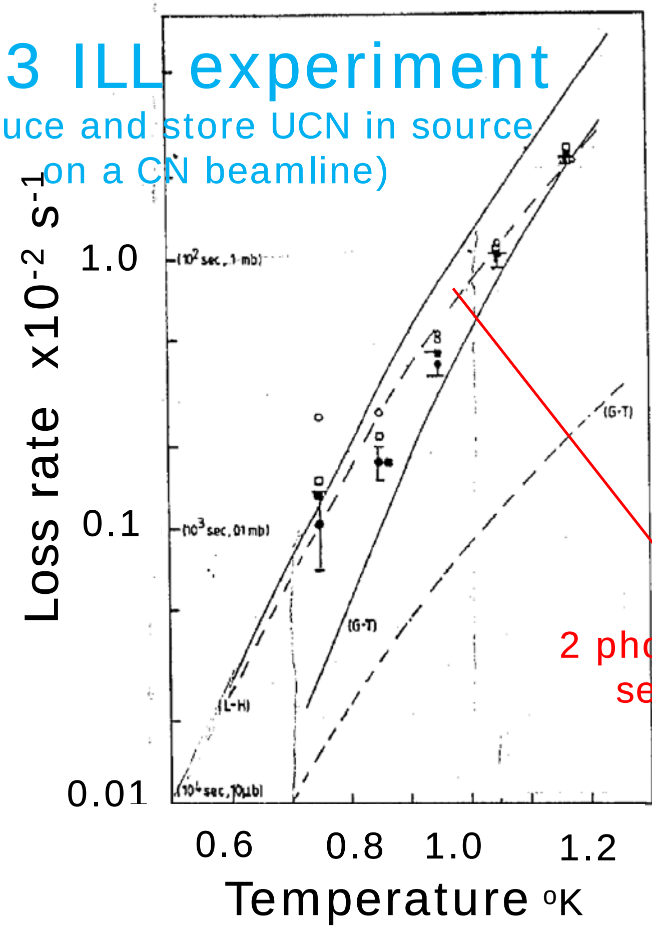
Significant multiphonon contributions possible...

UCN Loss Rate in ^{4}He

(also reasonably well characterized)

1983 ILL experiment

(produce and store UCN in source on a CN beamline)



2 phonon model sensitivity

R. Golub et al., Z. Phys. B 51, 187-193 (1983)

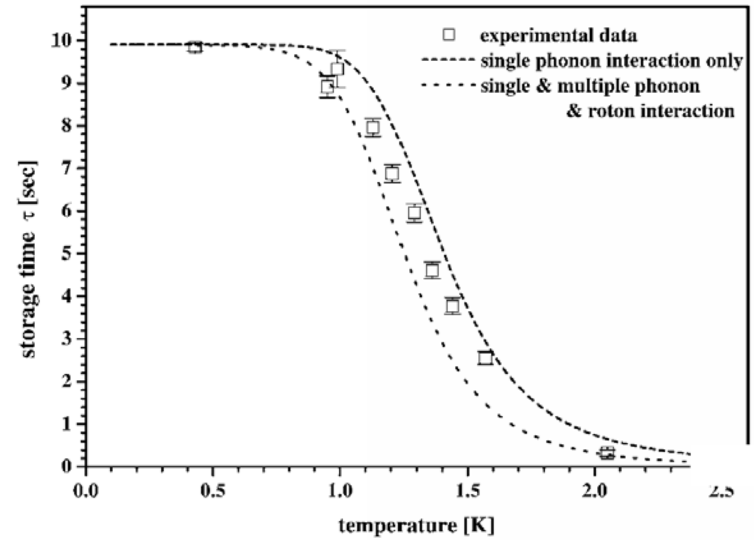


Fig. 4. Experimental measurement of the temperature dependence of UCN storage lifetime, together with the theoretical expectations [6] from two models of phonon and roton interactions.

H. Yoshiki et al., Phys. Lett. 308, 67-74 (2003)

$$1/\tau(T) = Ae^{-12/T} + BT^7 + CT^{3/2}e^{-8.6/T}$$

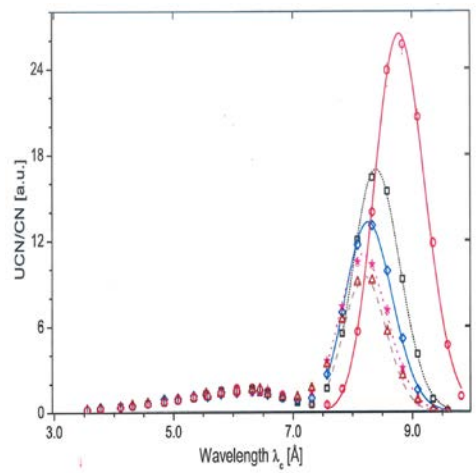
1 phonon — 2 phonon — roton

best fit: B = 0.008, A=C=0

Ongoing Work: Characterization of UCN Production and Upscatter in LHe vs. T and P

(Zimmer's group)

[1] UCN production in pressurized He: Schmidt-Wellenburg et al., PRC **92**(2015) 024004



P=SVP, 6, 11, 16, 20

[2] K. K. H. Leung, S. Ivanov, F. M. Piegsa, M. Simson, and O. Zimmer. Ultracold-neutron production and up-scattering in superfluid helium between 1.1 K and 2.4 K. Phys. Rev. C, 93:025501, Feb 2016.

Studied UCN upscattering in temperature range 1.1K to 2.4K.: "Our analysis [from scanning A, B & C coefficients] for T < 1.95 K rules out the contributions from roton-phonon scattering to <29% (95% C.I.) and from one-phonon absorption to <47% (95% C.I.) of their predicted levels."

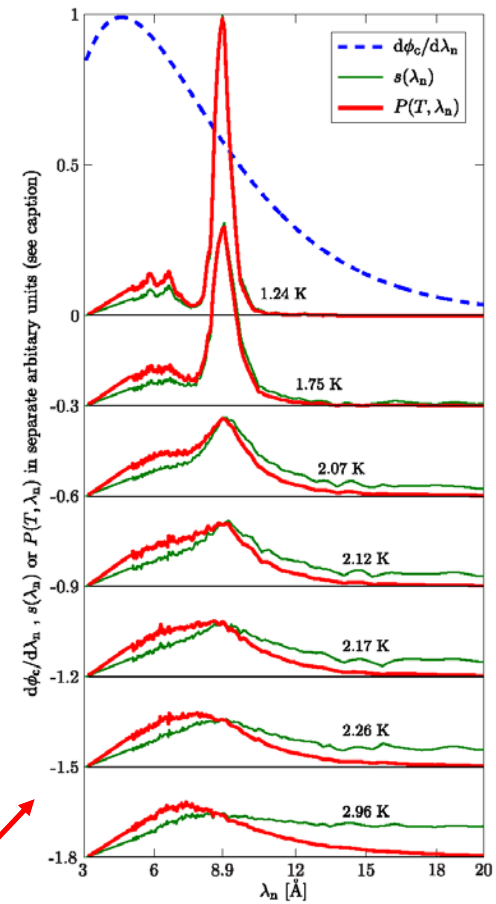


FIG. 10. The PF1B CN capture flux $d\phi_c/d\lambda_n$, $s(\lambda_n)$ [Eq. (A2)], and the differential UCN production rate $P(T,\lambda_n)$ used for the calculations of $P_{rel}(T)$, at selected temperatures. Each separate quantity plotted is in the same arbitrary units for all temperatures, but the plots for incrementally increasing temperatures are offset by −0.3 (arbitrary units) from the previous. Details of the calculations are described in the text.

Back to the 1983 ILL Experiment:

Already a potentially useful source

10.5 l ^{4}He bath, T < 0.5 K

$\tau_S > 62\ s^{-1}$

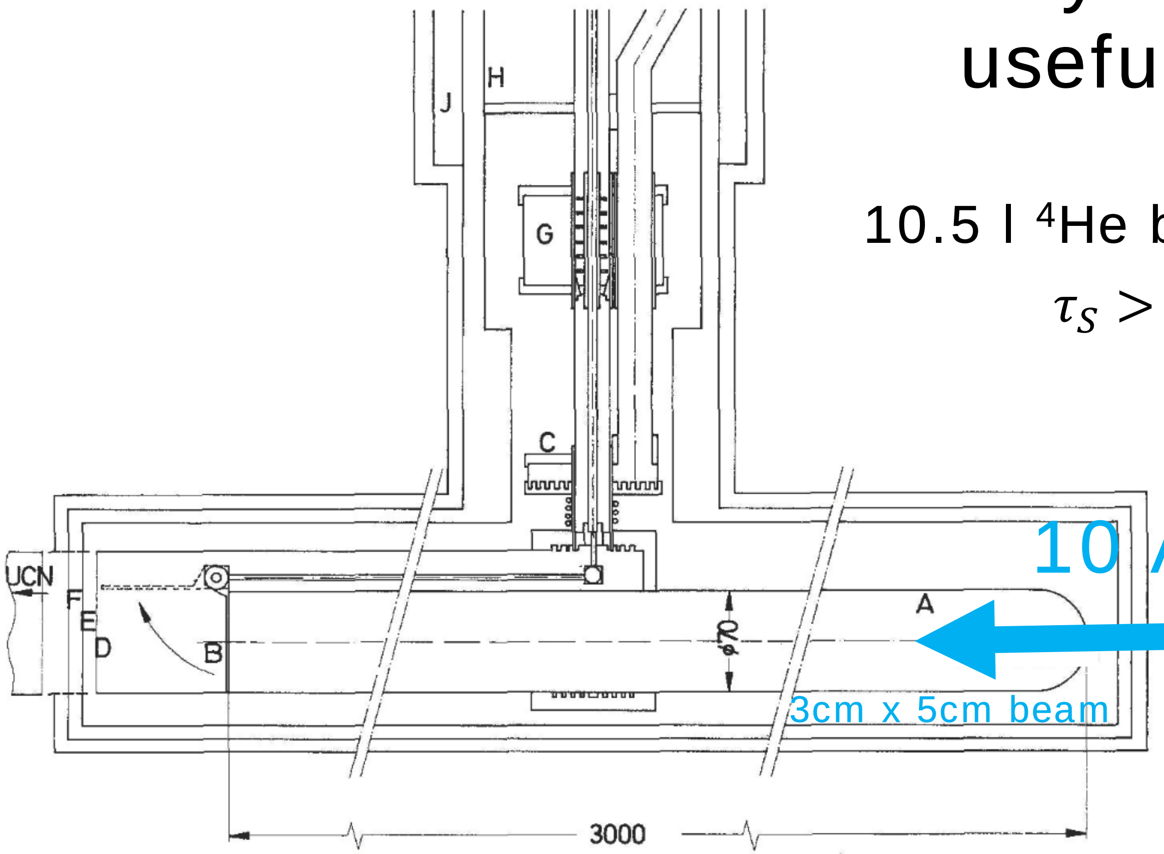


Fig. 1. Superthermal Source UCN storage cryostat: A – Stainless steel UCN storage vessel; B – UCN flap valve; C – He^3 evaporation pot; D – 0.6 K window; E – 4 K window; F – 77 K window; G – 1 K He^4 pot; H – 4 K He^4 reservoir; J – 77 K liquid Nitrogen reservoir

Internal UCN density ~20 UCN cm^{-3}, but measured through flapper & foils → ~1 UCN cm^{-3}

Solid understanding of the performance of this source from the LHe studies...

Technical Issues to Optimize Source:

1. Maximize CN intensity and usefulness (overlap with production)
2. Optimize Extraction of UCN
3. Eliminate losses due to absorption, upscatter and wall interactions

One solution to item 2 is **not to extract**, perform experiment in LHe bath with dedicated source

SNS nEDM is pursuing this path – I will concentrate on sources which extract UCN ...

Comparing sources

The UCN density one can load into an experiment depends on a number of source parameters:

UCN storage time in the source, integrated flux (UCN/s), spectrum, filling mode (batch vs. flow-through), etc…

Different experimental geometries couple to these parameters in a unique way (e.g. larger experimental volumes favor higher current sources, etc…)

UCN densities measured in different ways:
^{3}He gas counters , B-coated scintillators, sample activation, direct detection of beta decay
With different transport to detectors…

Solutions

(1) Determine true density and spectrum by understanding detector response (measurements and modeling – apply corrections)

+ Permits others to model and predict response to other detectors or experiments
- Forces others to model detector response

(2) Use the same “standard” test cell and detector on each source, with “typical” transport from source

+ removes detector and geometry ambiguity
- still need to model UCN spectral sensitivity to understand performance of other experiments

Talk: D. Reis

The LHe sources – Overview
(ILL turbine included for comparison)

Name	Density in cell	Useful average current (10^4 s^{-1})	Source storage time (s)
ILL Turbine	39	100-200	Few s
Talk: **P. Geltenbort**			
ILL SUN-2	~15 peak(60s,30 l)*	Max = 1 Drain time ~150 s	200 (4 l, Fomblin grease, ~ 80 neV)
SuperSUN	~150 peak(60s,30l)*	10 polarized	800 (12 l, 230 neV magnetic trap)
RCNP/KEK	26	3.2	81 (Ni)
TRIUMF/KEK	600 polarized	~100 polarized	100 (NiP)
Talk: **Y. Masuda**			
PNPI	12000	7000	10 (from He @ 1.2 K)
Talk: **V. Lyamkin**			

Available Now

SUN-2 and Super-SUN

- Logical extension of early superthermal source geometry

    - Solid systematic study of basic physics processes
    - Increase production by increasing incident beam
    - Refined extraction to control heat-load (interesting IR window technology)
    - Explored various wall coatings to control losses – BeO, supermirrors, Al + Fomblin

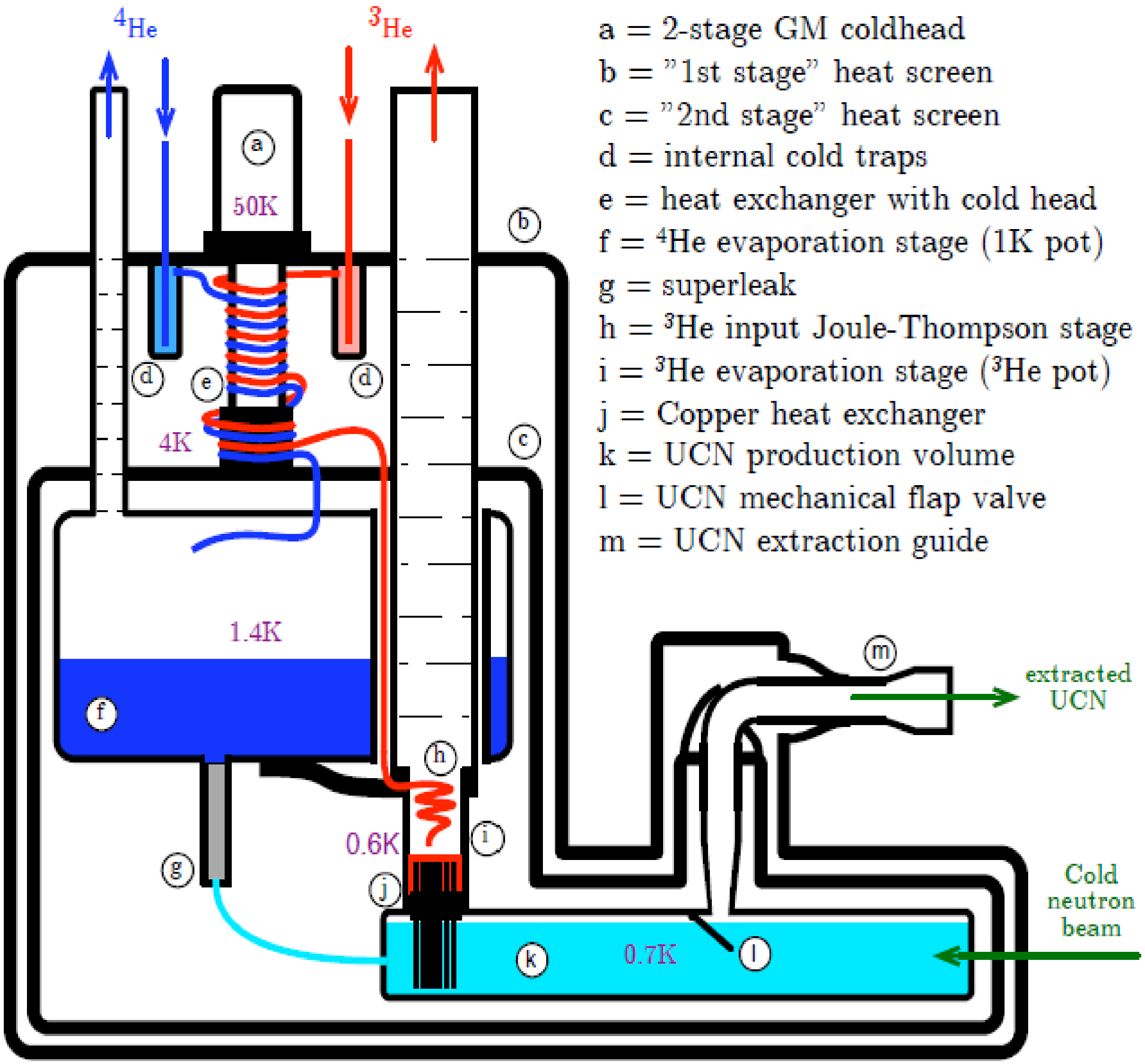
- Super-SUNS will increase production volume and simultaneously increase trap depth and holding time using trapping magnet (delivers polarized UCN)

- Production rates limited by available beam intensity

Constructed second source prototype "SUN-2"

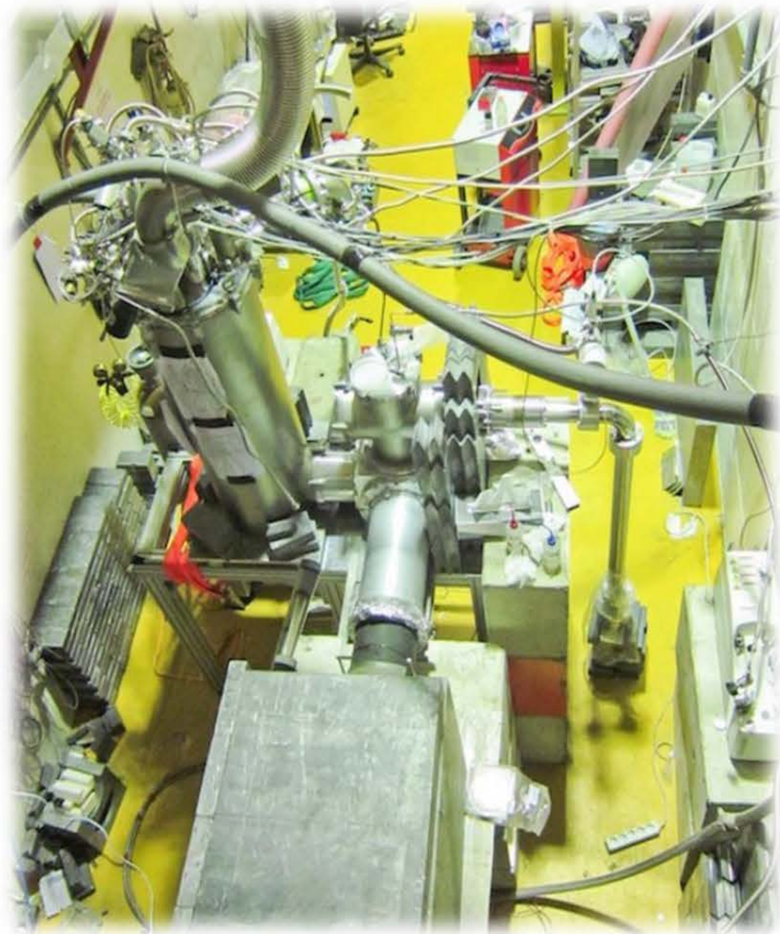
Development goals

- **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

SUN-2 relocatable source
...first test @ white cold beam PF1b (2011)

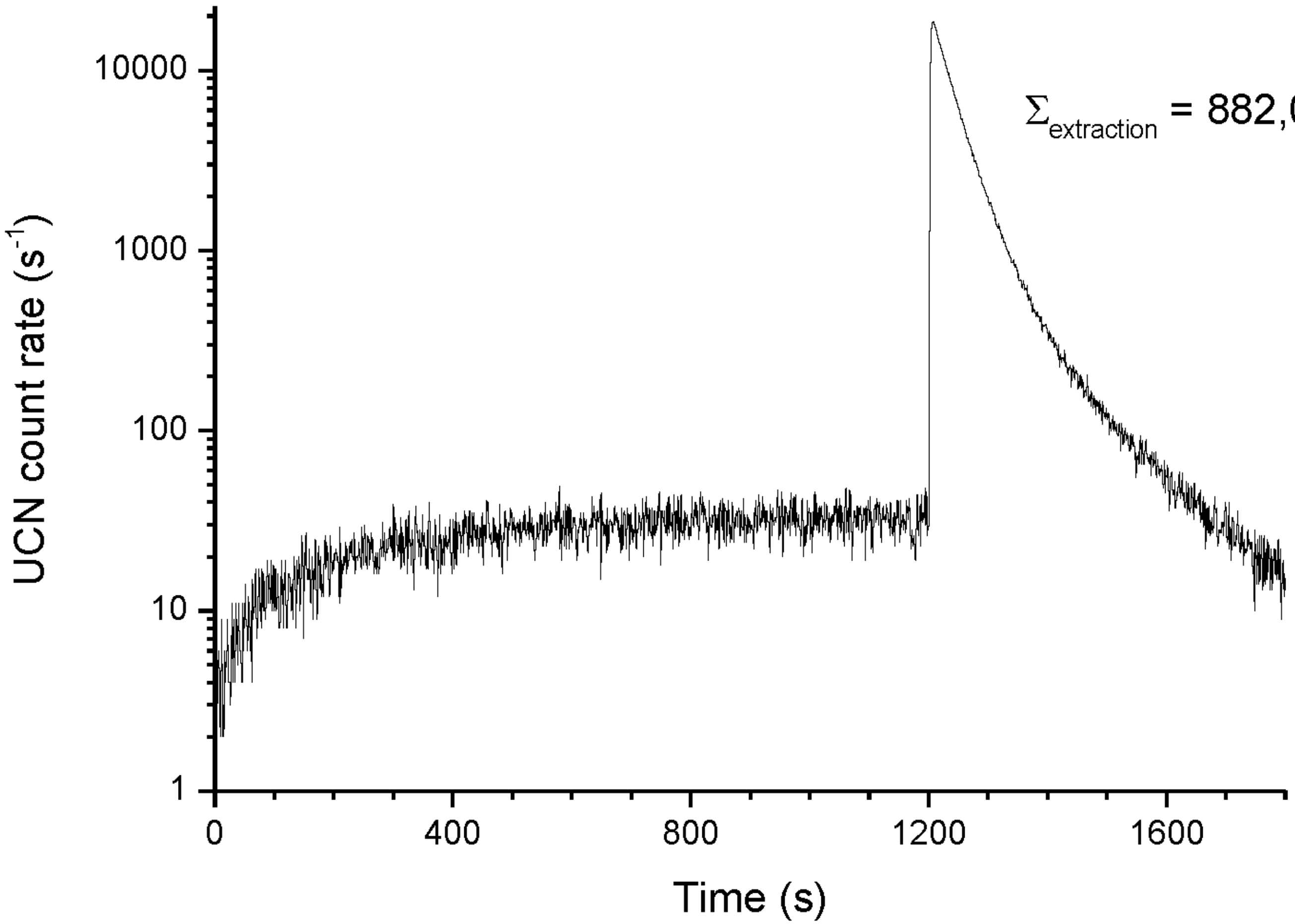


Leung et al., PRC **93** (2016) 025501

Ultracold neutron production and up-scattering in superfluid helium between 1.1 K and 2.4 K

Recent achievement (16 July 2015, repeated since)

(fomblin grease on Be on Al converter vessel, long pumping)



0.61 K: **882000** accumulated UCN from 4 litres He-II **~ 220/cm³**

The KEK/TRIUMF Source

- Uses a 40 uA proton beam at 480 MeV incident on a Ta-clad W target, with liquid and solid D2O for CN moderators
  - Low heat loads for spallation makes high production rate ($I > 10^6\ s^{-1}$) in source possible
  - Target density in cell 600 polarized UCN cm^{-3}

- Vertical extraction approach for prototype being changed to horizontal extraction from 12 l production volume, with magnetically-assisted transport out of the bath through Al foils

- Source assembly scheduled to be complete and installed at end of **2016**, with an upgrade of cold moderator also planned

RCNP Source – Masuda
(upgrade will be moved to TRIUMF)

Spallation power: ~400W
(1 uA x 400 MeV)
$\Phi \approx 1.9 \times 10^{9}$ n/cm^{2}s
n ≈ 26 UCN/cm^{3}
I ≈ 3.2×10^{4}/s
V_p = 8 liter (V_F = 210 neV)
V_s = 120 liter
τ_s = 81 s

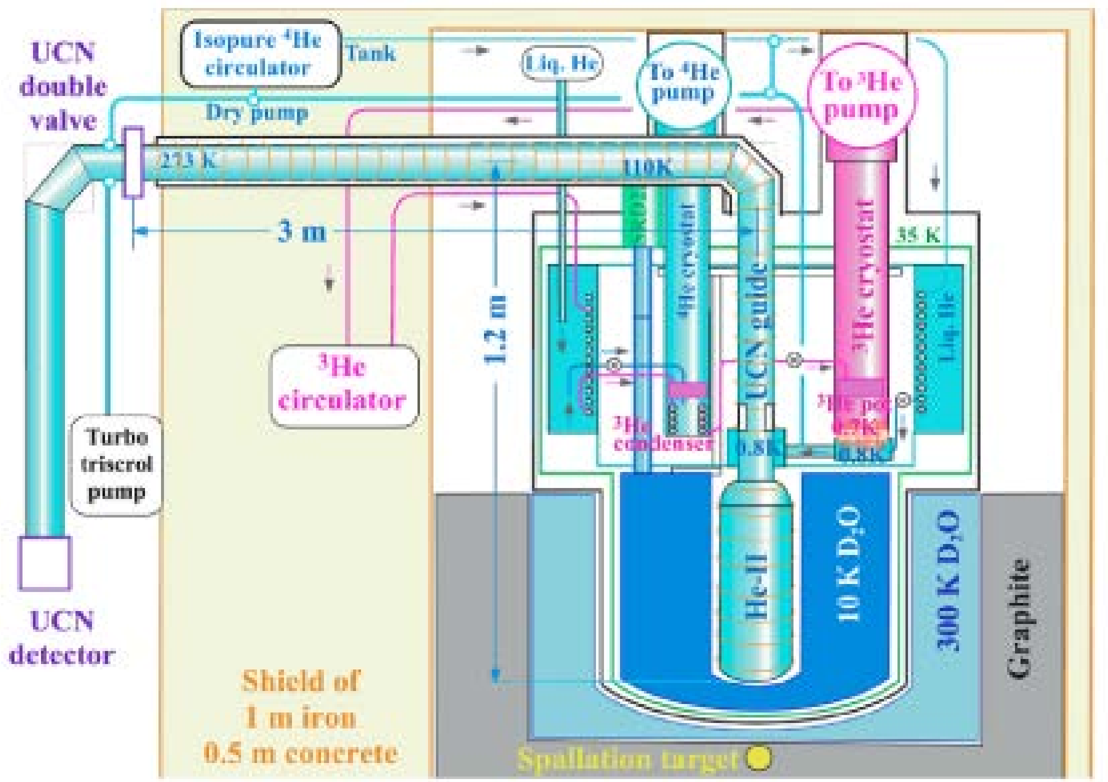
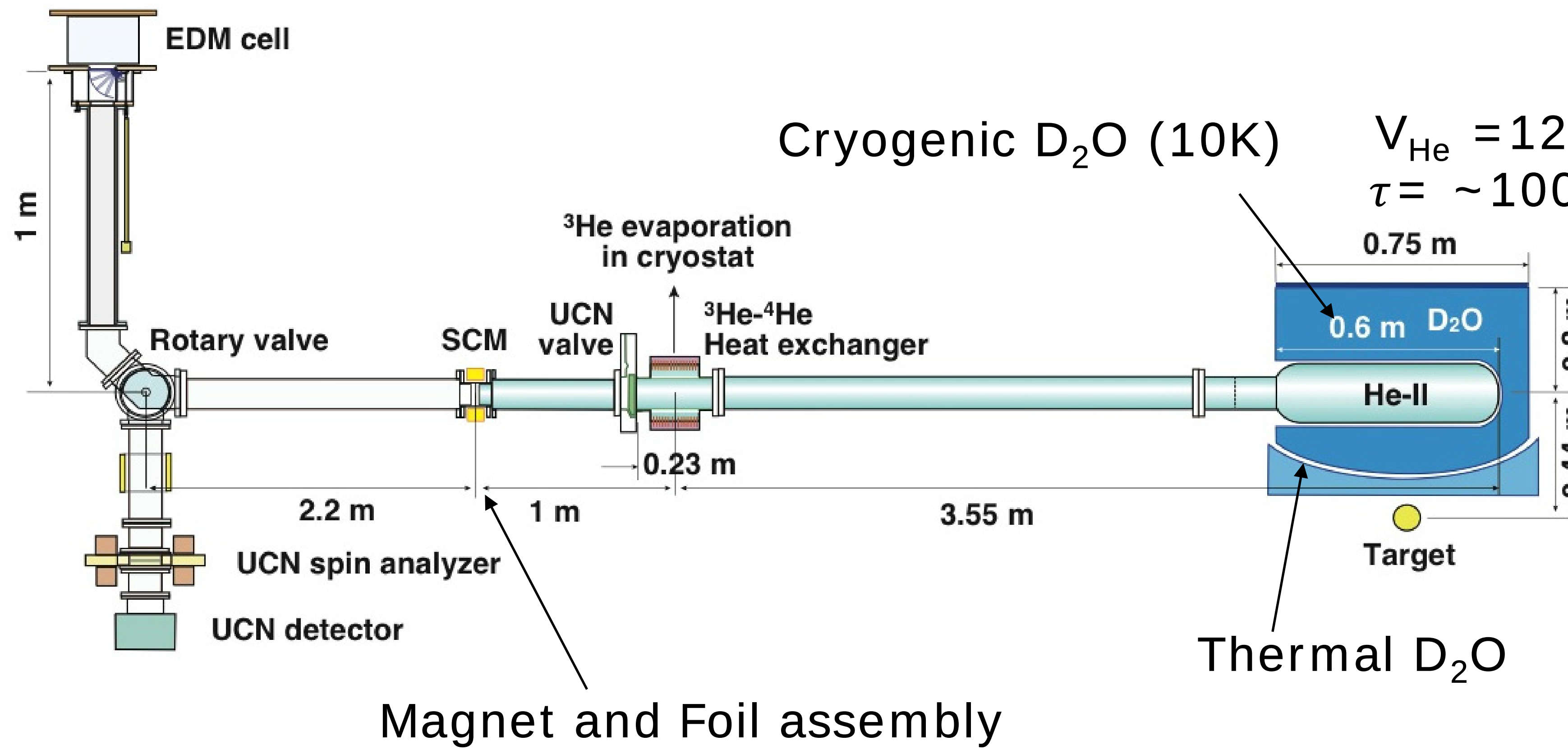


Fig. 3 He-II spallation UCN source

Heat loads – .13 W in source vessel
(predict 1.3 W at TRIUMF)

Prod ≈ 4 UCN/cm^{3}/s

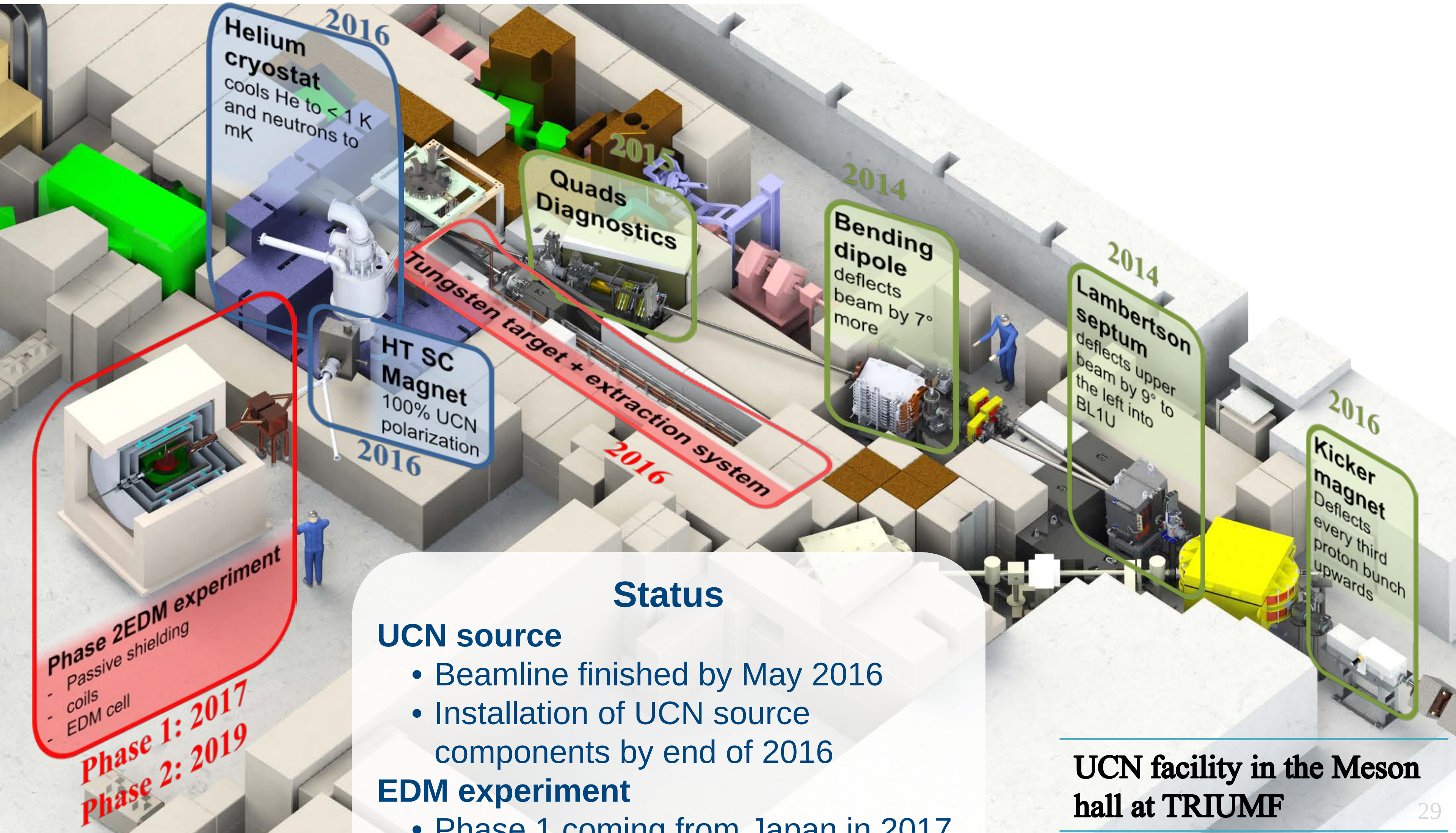
KEK / TRIUMF Source Geometry



V_{He} =12 l,
τ= ~100s

Projected density in cell: 600
Projected current: ~ 1x10^6

Ultra-Cold Neutrons and the Electric Dipole Moment



Status

UCN source

- Beamline finished by May 2016
- Installation of UCN source components by end of 2016

EDM experiment

- Phase 1 coming from Japan in 2017
- Phase 2 developed in Canada (CFI proposal this year) for 2019

UCN facility in the Meson hall at TRIUMF

PNPI Super-source

- Source located in reactor (15 MW) thermal column, behind lead shield – reasonably conservative of neutron flux, very low heating (similar approach taken with PULSTAR source) -- strongest source under construction w/ projected density in a storage cell of 10^4 UCN cm^{-3} and 7×10^7 UCN/s

- Effectively saturated cryogenic cooling power, optimizing design

- Recent tests confirm performance of cryogenic system

- Approach well documented in publications

A. P. Serebrov, Crystallography Reports 61, 144-148 (2016)
A. P. Serebrov and A. K. Fomin, Technical Reports 60, 1238-1242 (2015)

LHe Source in thermal column of WWR-M: MCNP results

$\rho_{ucn}=10^4\ cm^{-3}$ ($\tau=10$ s)

$\Phi=4.5\cdot10^{12}$ n/(cm^{2}s)

$\Phi(\lambda=9$ A$)=3\cdot10^{10}$ n/(cm^{2}sA)

$Q_{He}=6$ W

19 W

Al, $Q_{Al}=13$ W

pump on He bath

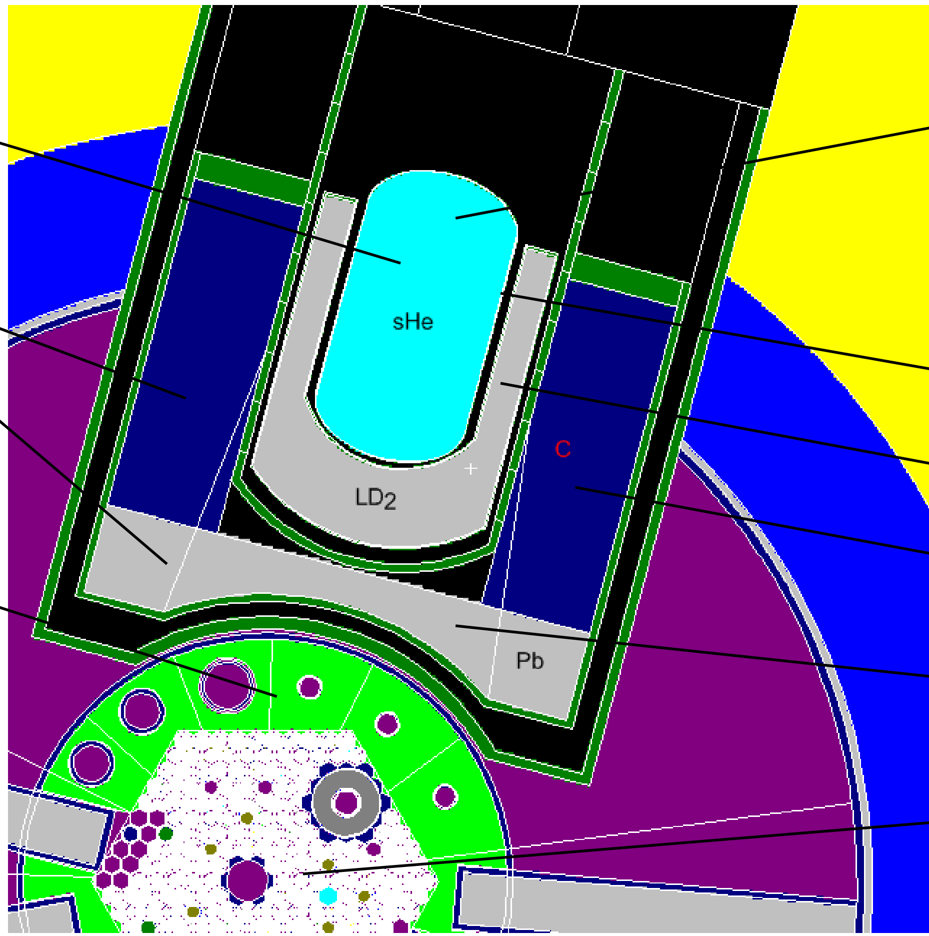
V=100 l

He T=1.2 K

LD_2 T=20 K

C T=300 K

Pb T=300 K



LD_2, $Q_{LD2+Al}=100$ W

C, $Q_C=700$ W

Pb absorbs γ's, passes n's

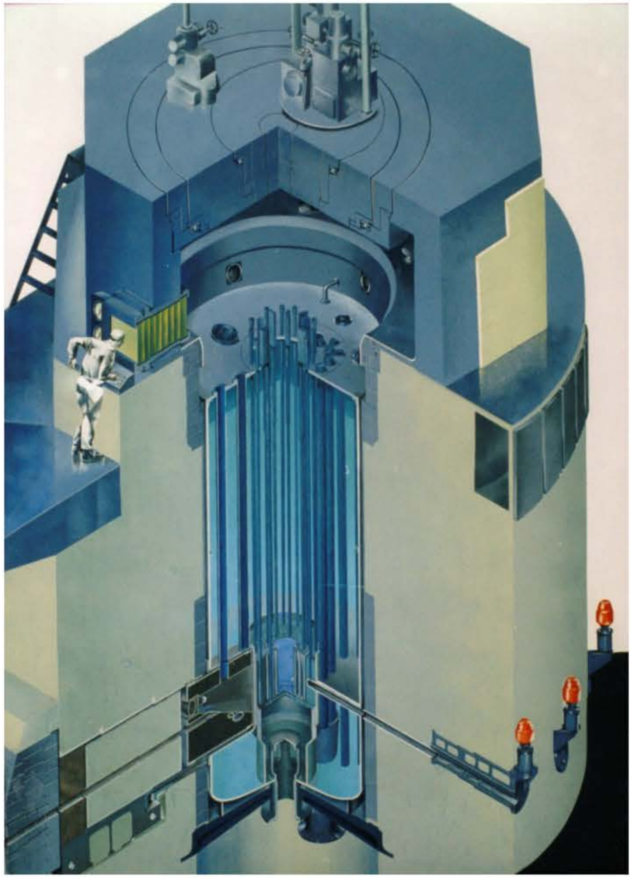
Pb, $Q_{Pb}=15$ kW

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

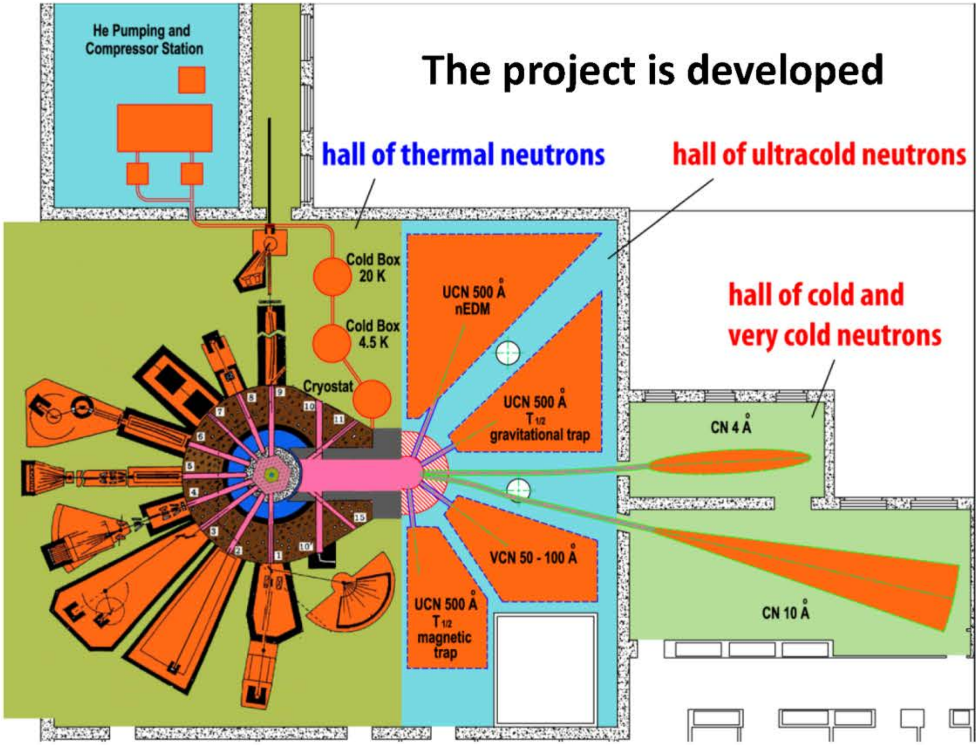
Q=15 MW

Core (15 MW)

Prospects for UCN source at WWR-M reactor



The resource of basic elements of the reactor provides its further operation within 25 years.



The scheme of experimental installations on the WWR-M reactor after installation in a thermal column of the reactor of UCN source with superfluid helium at a temperature of 1.2K.

The full-scale model of UCN source with superfluid helium is tested up to 50 W at 1.3 K

It means that project can be realized. *(Possible UCN density in EDM trap is about* $10^4 cm^{-3}$ *)*

November 2015

Temperature - from heat load

Serebrov. Mainz

Refrigerator 20 K **Cryostat 1 K** **Liquefier 4 K**

Points of Personal Interest...

- Dominance of simple T^7 behavior at higher T ... try analyzing measured scattering law data to understand? Also curious whether losses confirm expectation in sources with larger heat-loads...

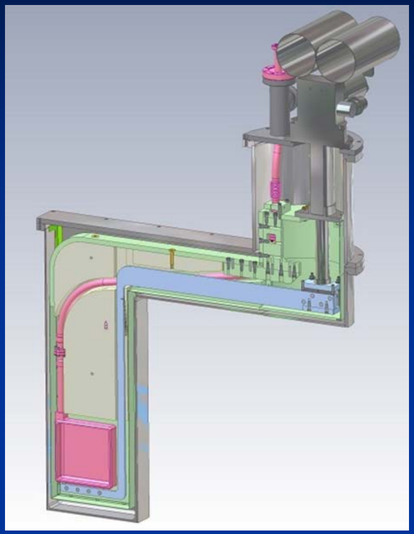
- Planned TRIUMF source upgrade involves shifting from D_2O to LD_2 cold moderator– with potential gain in UCN production of factor of 5, but is this the optimal choice for moderator?

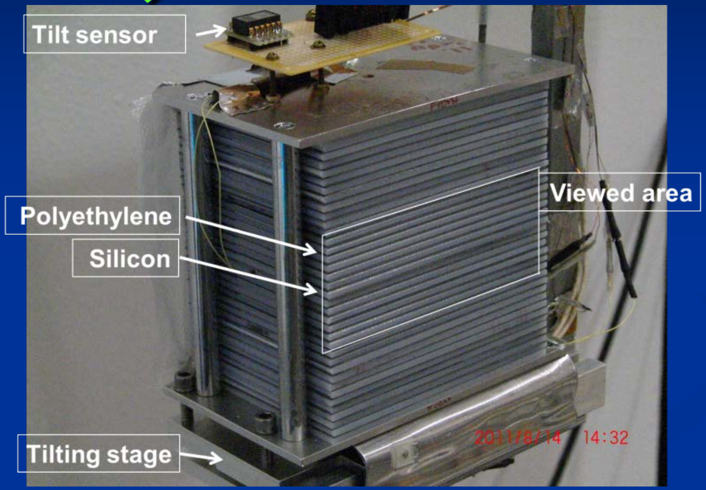
⇒ Moderator Research could have significant impact!

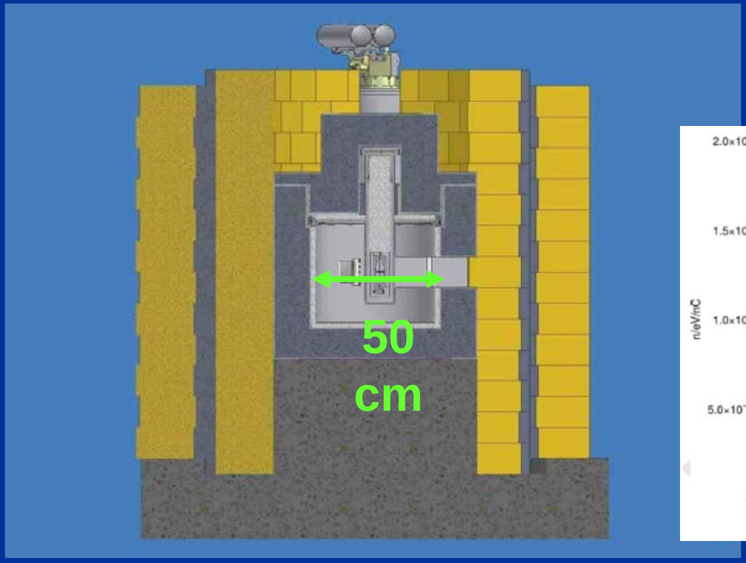
LENS and CoNS collaborations

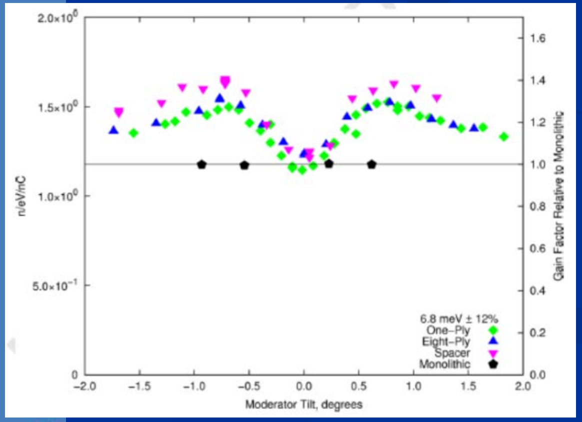
Triphenylmethane, moderating reflectors...

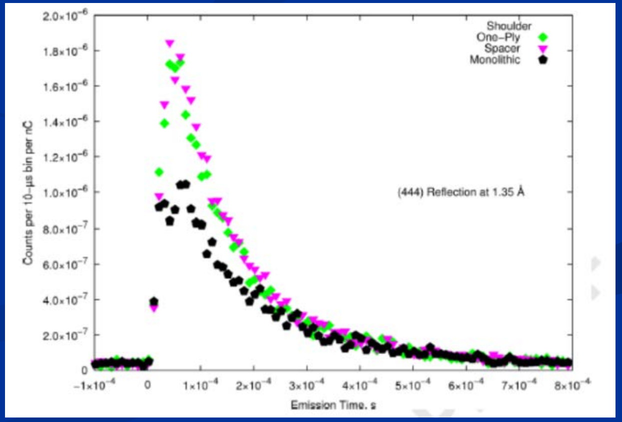
Convoluted moderator tests (TMR)











Optimized LHe Source

- Other ideas to cool and transform CN flux might be important! Talk: **O. Zimmer**

- Source at a low power reactor which “saturates” the cooling power (~1 W for ^{3}He refrigeration) for LHe < 1 K (where moderated neutrons dominate the heat load) has not yet developed

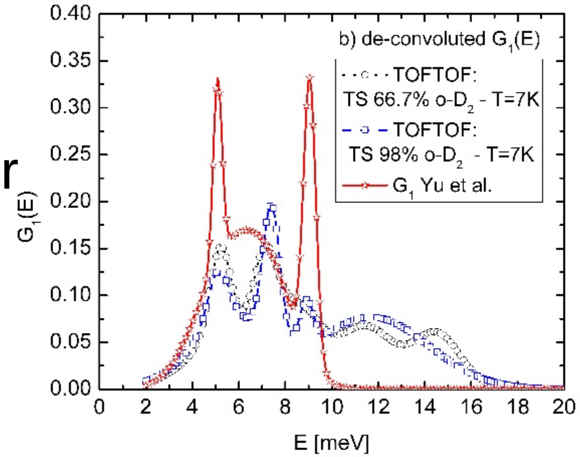
- LHe sources might also be a place where V. Nesvizhevsky’s nano-diamond reflectors useful...

Solid D_2

An early measurement of UCN production was performed at LINP in 1980:

Altarev *et al.*, Physics Lett. 80A, 413-416 (1980).

And the early work analyzing solid D_2 for production and upscattering rates relied on the incoherent approx. (reasonable candidate for a superthermal source)



R. Golub and K. Boning, Zeitschrift fr Physik B Condensed Matter, 51(2):95- 98, 1983.

Z-Ch. Yu, S.S. Malik, and R. Golub. Zeitschrift fr Physik B Condensed Matter, 62(2):137-142, 1986.

There is a significant body of work by Serebrov's group concerning solid deuterium, probing aspects of production, elastic scattering and upscattering (including large UCN production “gain factors” and an indication of importance of para contamination):

A P Serebrov et al., Pis' ma Zh. Eksp. Teor. Fiz. 59, 728-733, 1994.

A P Serebrov et al., Pis'ma Zh. Eksp. Teor. Fiz. 62, 764-769, 1995.

A P Serebrov et al., Pis'ma Zh. Eksp. Teor. Fiz. 66, 765-770, 1997.

A P Serebrov et al, , Nucl. Instrum. in Phys. Res.A, 440:653-657, 2000.

A P Serebrov et al, , Nucl. Instrum. in Phys. Res.A, 440:658-665, 2000.

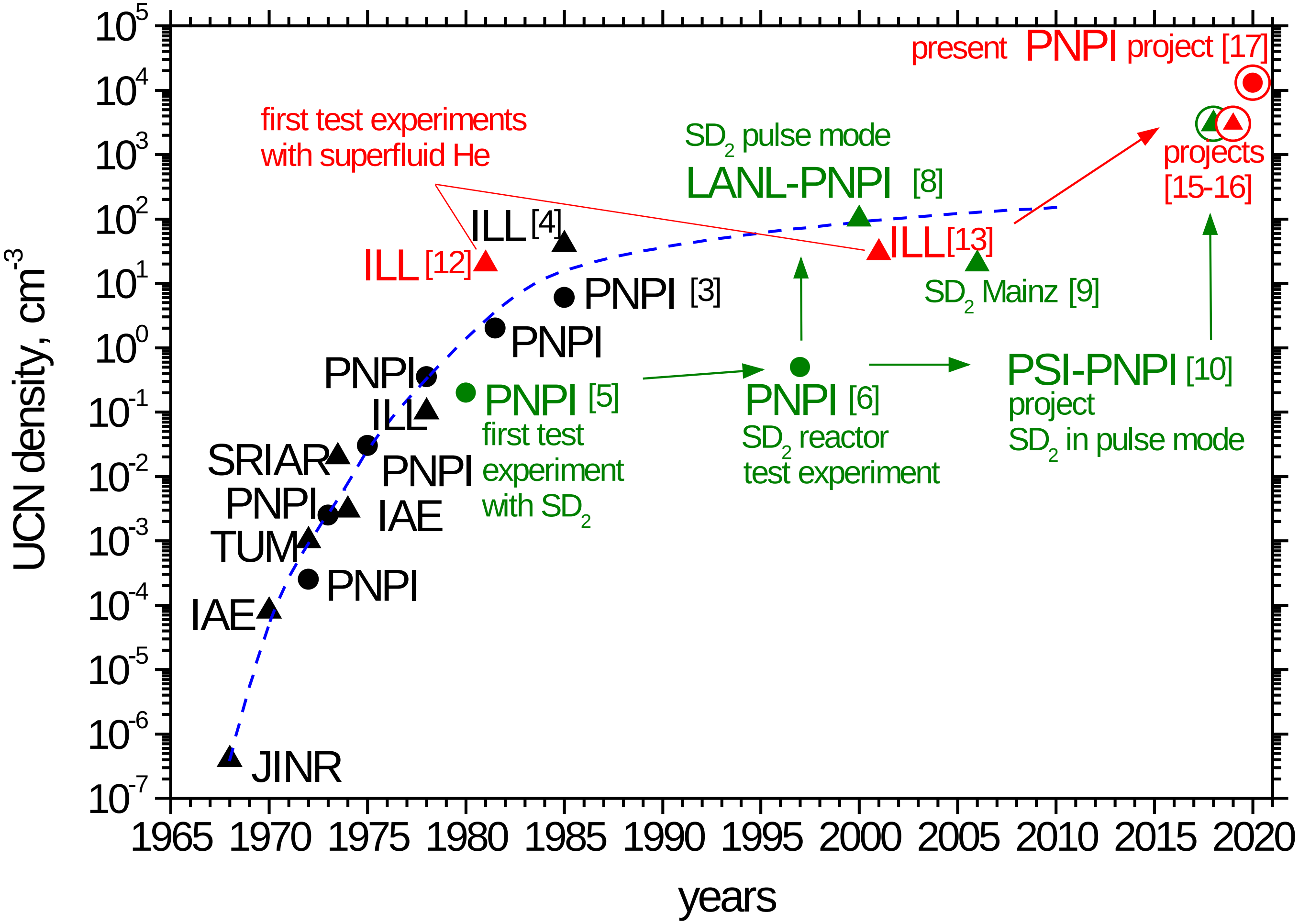
A P Serebrov et al., Pis'ma v. ZhETF 74, 335-338, 2001.

And Yuri Pokotilovskii discussed the use of SD2 in pulsed sources:

Y. N. Pokotilovski, Nucl. Instrum. Methods Phys. Res., Sect. A 356, 412 (1995)

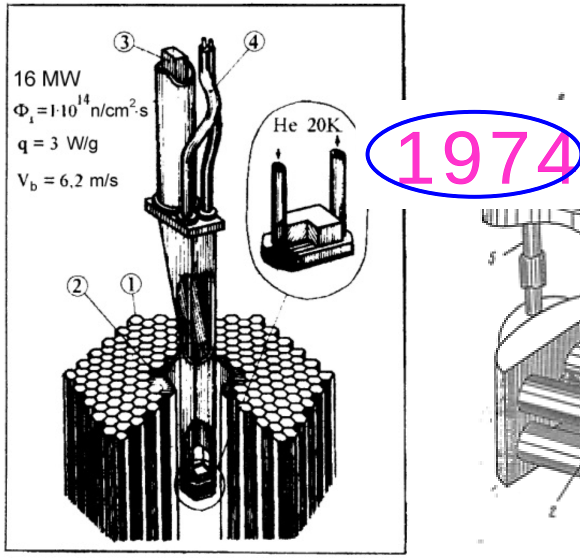
An overview of source development from A. Serebrov, with both Lhe and SD_2 source development is included on the next 2 slides

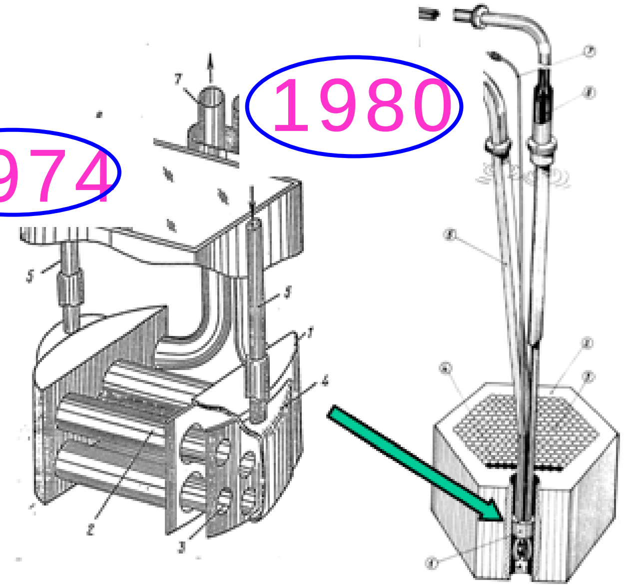
Progress in UCN source development and future prospects

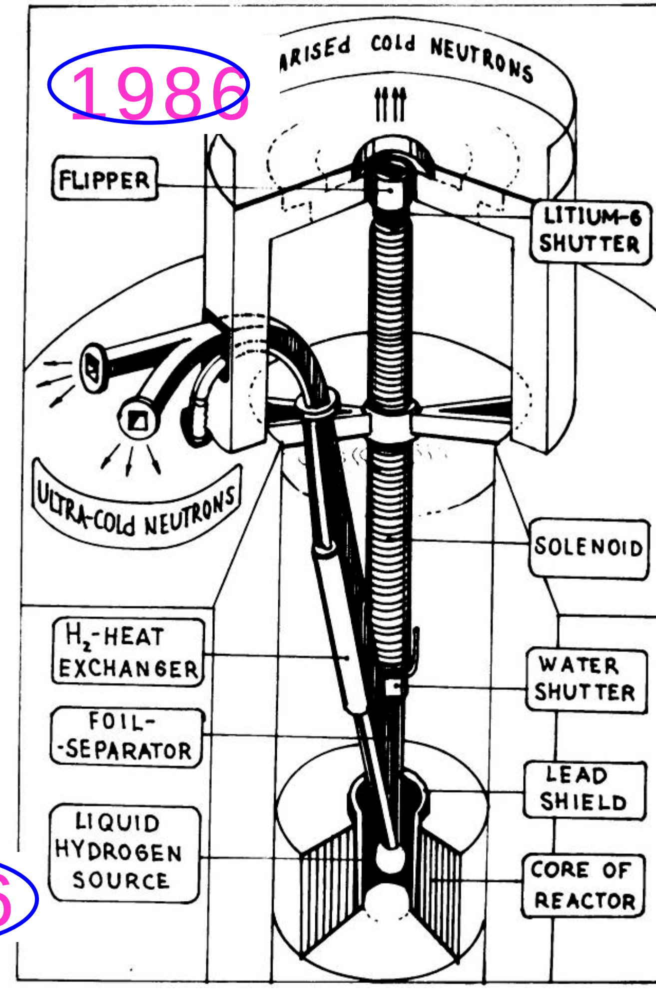


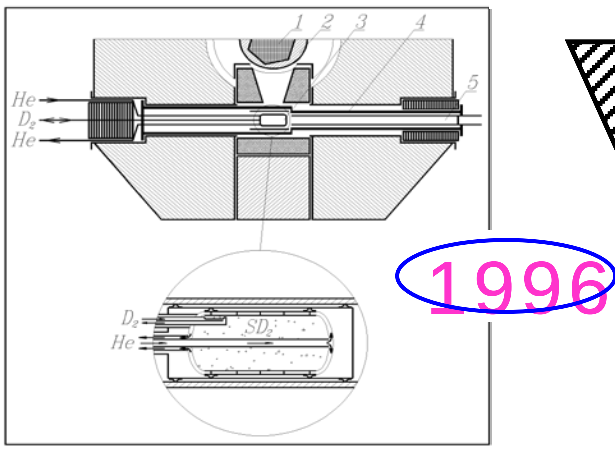
Plot elucidating the progress in UCN source development. The last point in this diagram concerns the designed parameters of the new source in the PNPI WWR-M reactor based on superfluid helium; indicated is the possible UCN density in the trap of the EDM spectrometer.

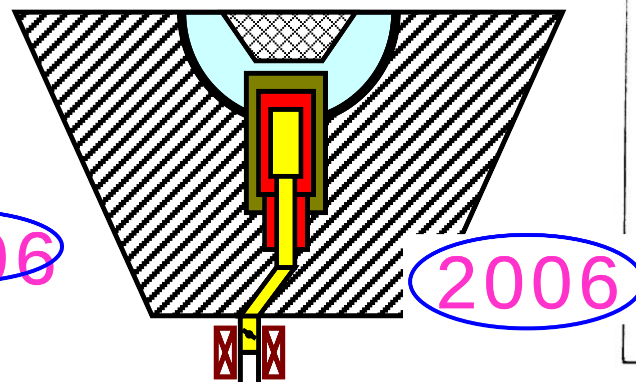
Slide courtesy of A. Serebrov

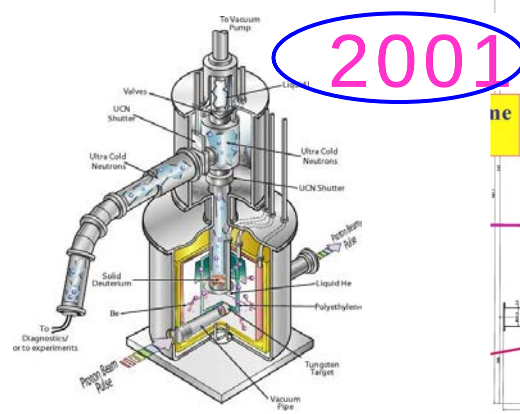


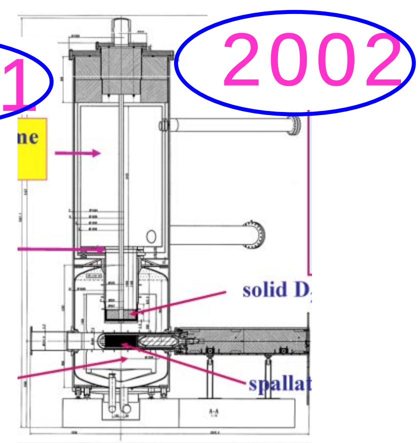








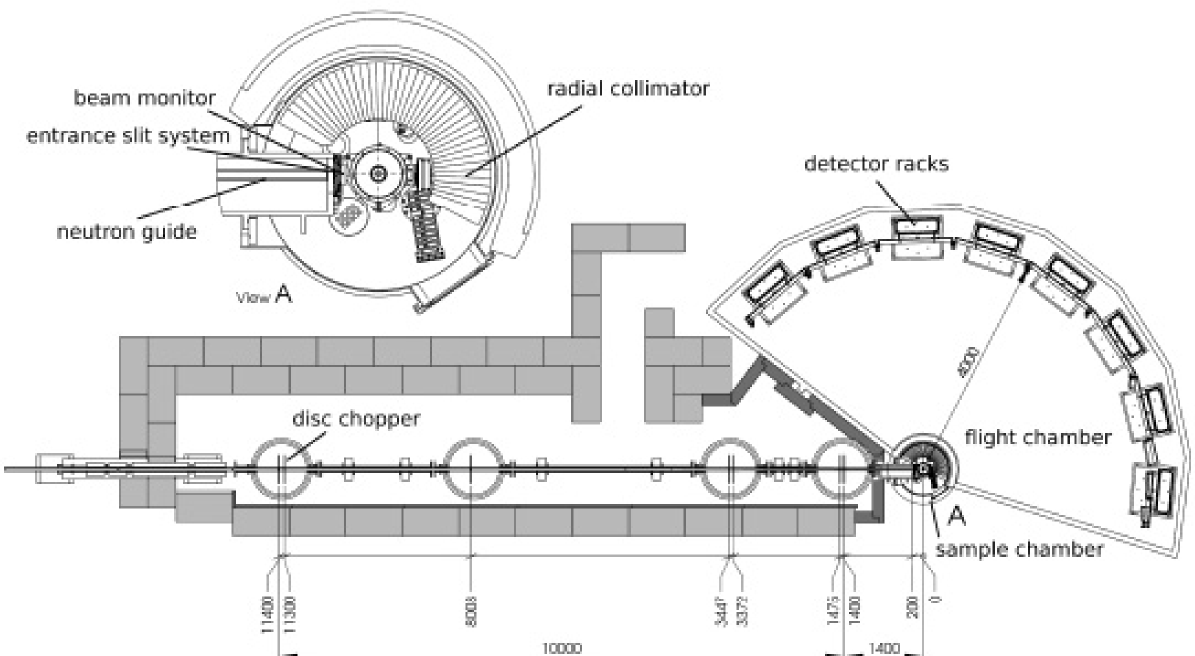




Slide courtesy of A. Serebrov

Scattering studies

IU, Munich and PSI groups led quantitative studies of CN energy dependent scattering and UCN production to pin down production– refining our expectations



TOFTOF

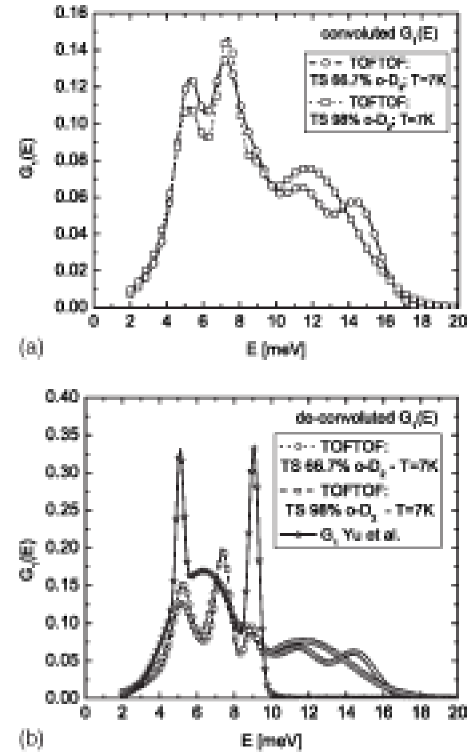
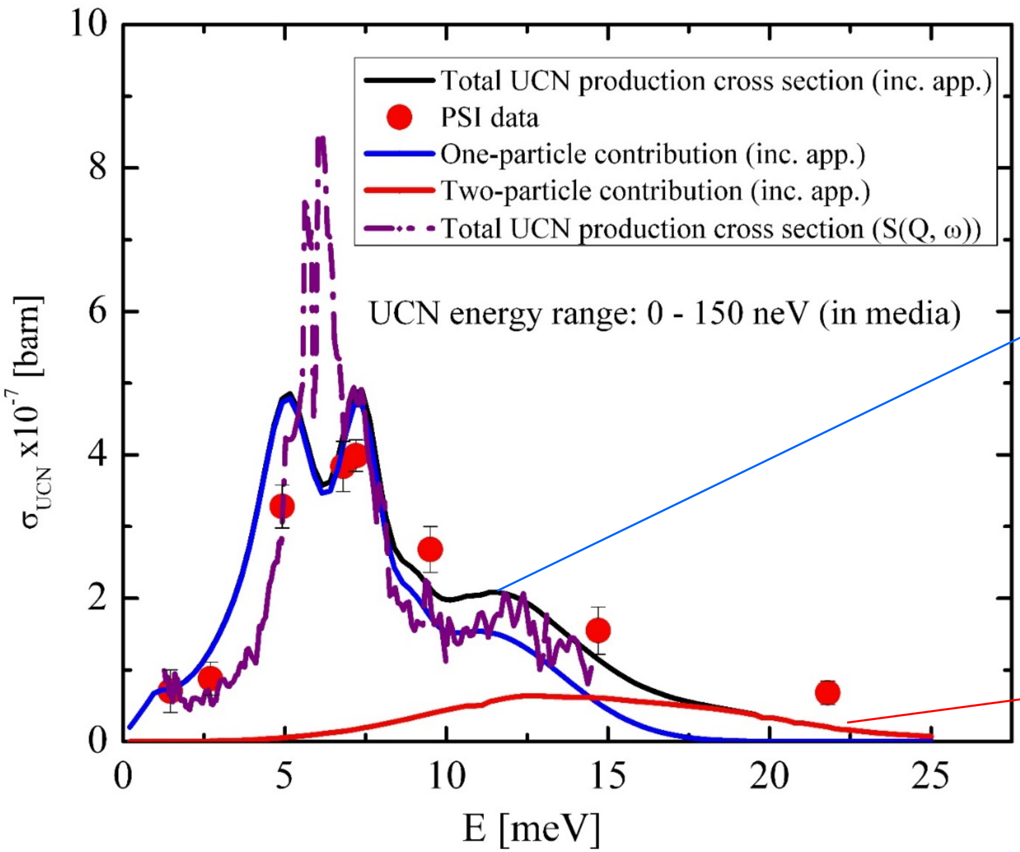


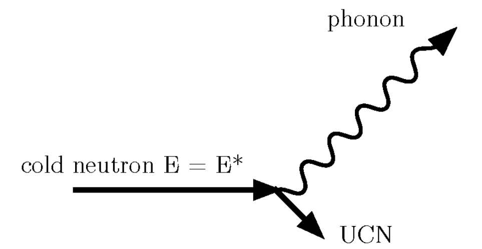
FIG. 10. (a) One-particle density of states of solid D_2 for c_o =66.7% (○); c_o=98% (□) at T=7 K. (b) Comparison of deconvoluted DOS with data (★) from Yu *et al.*(Ref. 24). The DOSs [part b)] are deconvoluted with the full width at half maximum (FWHM) of the elastic peak of $d\sigma/dE$.

A. Frei *et al.*,Phys. Rev. B 064301 (2009)

IN4 and TOFTOF

UCN Production in SD_2





Incoherent ap. when folded
with 40K n's:
80% 1 phonon
20% 2 phonons

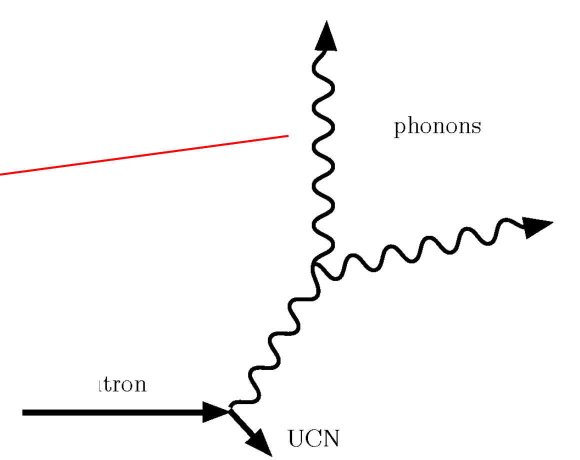
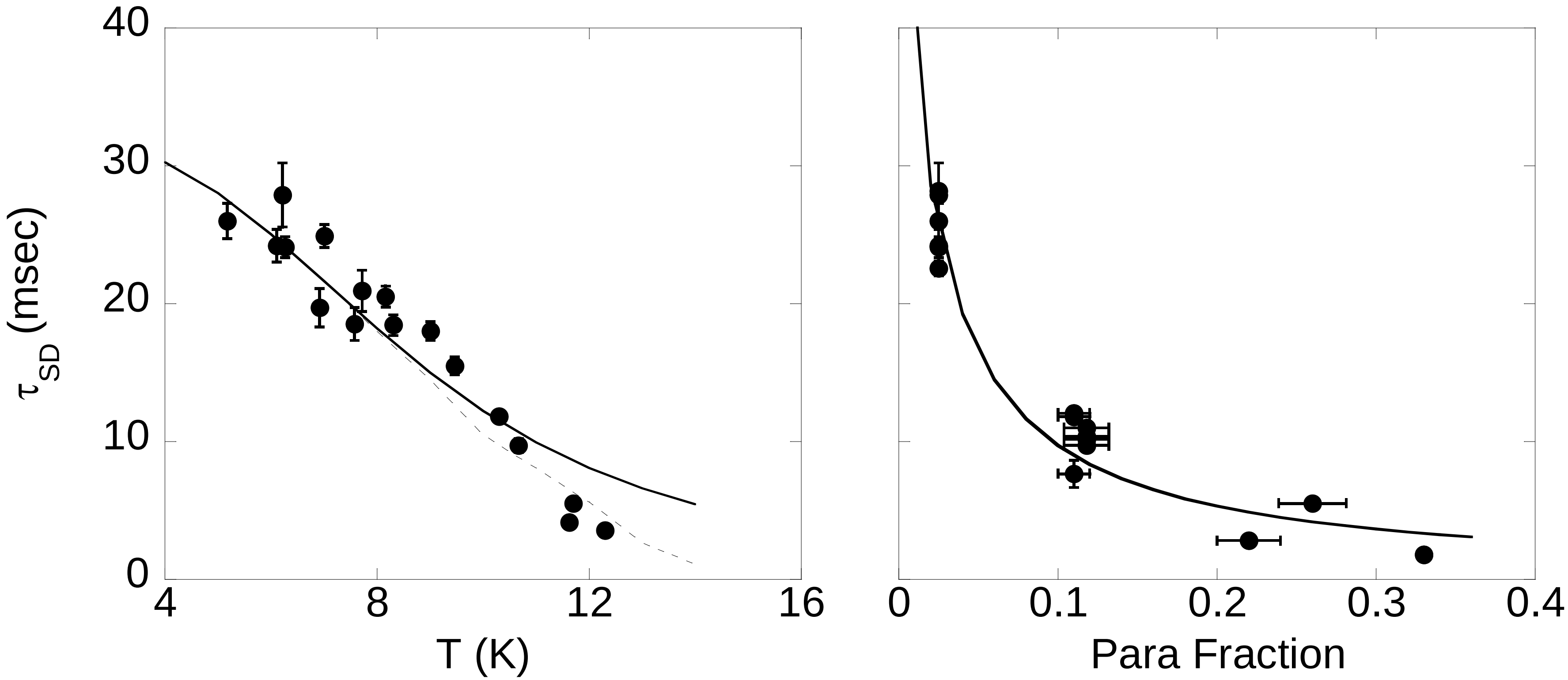


Figure and Calculations courtesy of **E. Gutsmiedl**

UCN lifetime in Solid D_2



$$\tau_{para} = 1.2 \pm .14 \text{ (stat)} \pm .20 \text{ (syst) ms}$$

C. L. Morris *et al.*, Phys. Rev. Lett. **89**, 272501 (2002)

confirmed: F. Atchison et al., Phys. Rev. Lett. **95**, 182502 (2005)

The SD_2 sources – Overview

Name	Density in cell	Useful average current (10^4 s^{-1})	Source storage time (s)
ILL Turbine	39	100-200	Few s
Talk: **P. Geltenbort**			
LANL	~50 (gatevalve mon) ~25 polarized	10-20 5-10 polarized	40
Talk: **R. Pattie**			
PSI	Peak ~23	Peak ~70 20M/300s = 6.7	~90 s
Talks: **B. Lauss, D. Ries**			
Mainz	10	3.2	Few s
Talks: **I. Sobolev**, **A. Hollering**			
FRM II	~5000	6000	Few s
Talk: **A. Frei, S. Wlokka**			
PULSTAR	>30	>10	Few s
Talk: **E. Korobkina**			

Available Now

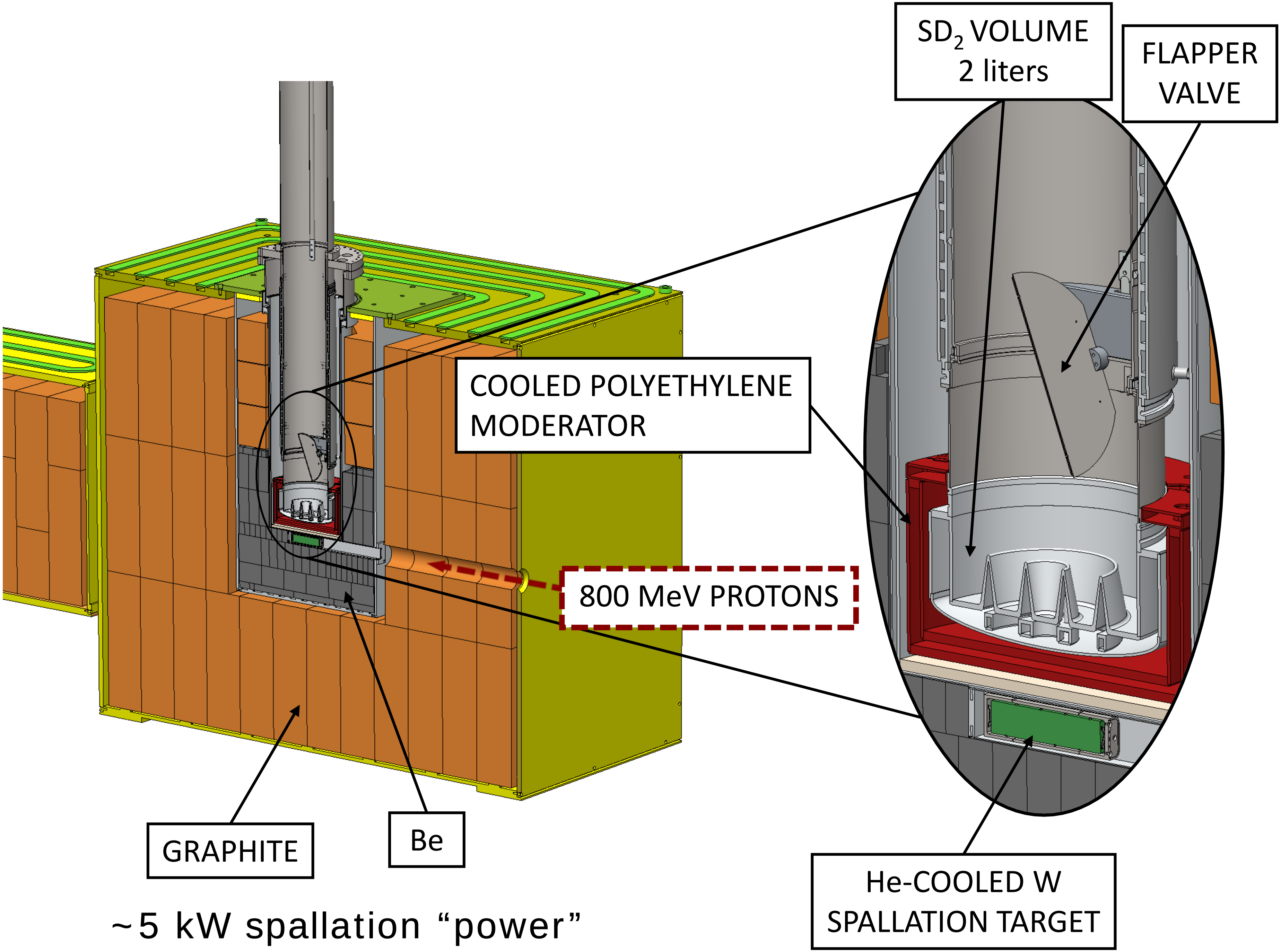
Los Alamos SD_2 source

- Originally running with 5uA (time-averaged), 800 MeV proton beam incident on a He-cooled, W target. Run mode is quasi-CW, with production pulses currently spaced about 30s apart

- Utilizes flapper valve to isolate UCN from SD2 after proton beam pulse. Storage $\tau \approx$ 40s

- UCNA running begain 2008. Peak performance for UCNA in 2010, when measured 2 UCN cm^{-3} in 40 l experimental volume (decay trap and guides with storage time 20 s) and 50 UCN cm^{-3} at gate valve (agreeing with expectation)

- Major upgrade planned for this year – over order of magnitude gain in intensity! Takeyasu Ito is leading the source upgrade effort, reported on in the talk by **R. W. Pattie**



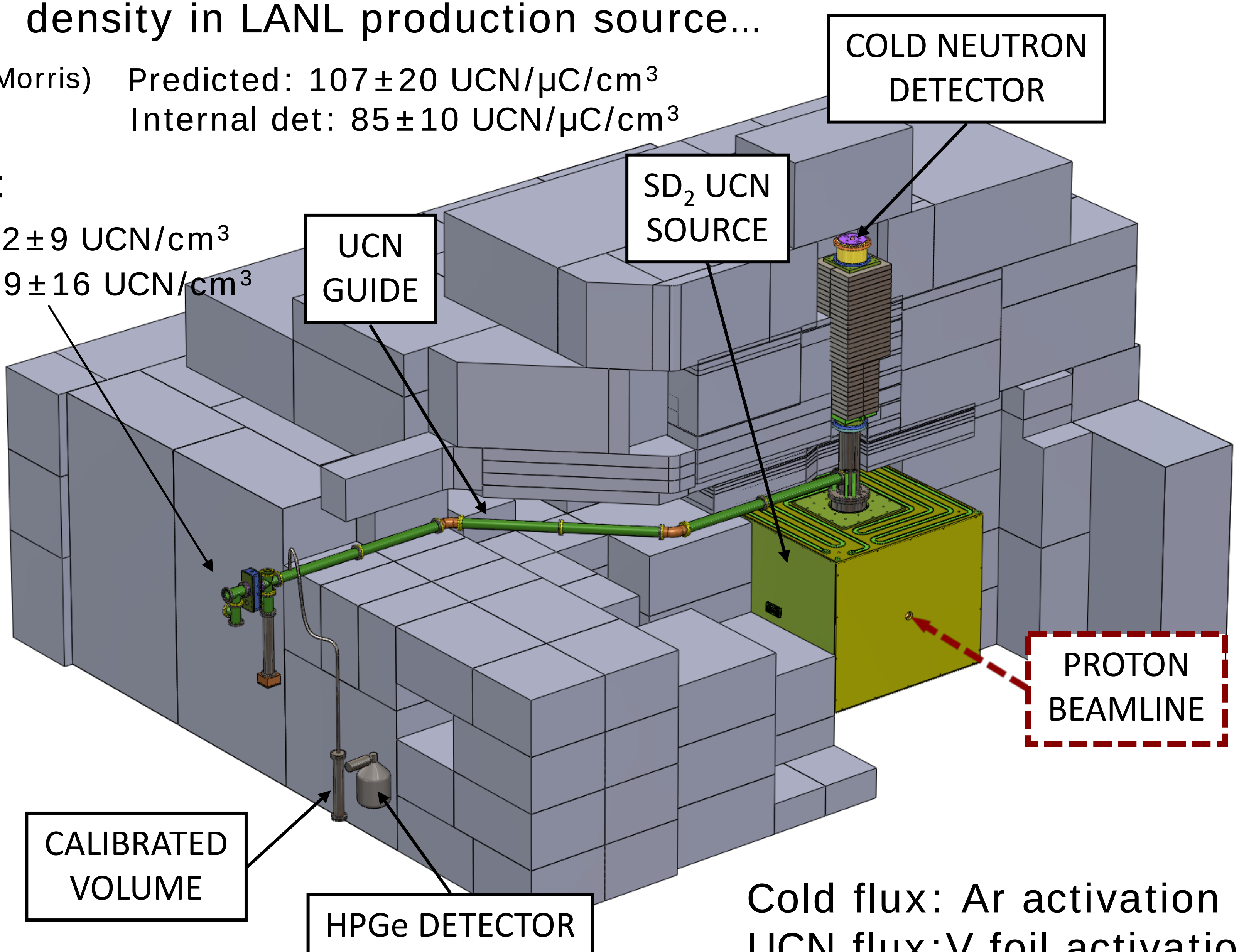
~5 kW spallation "power"

Consistent interpretation of extracted UCN density in LANL production source...

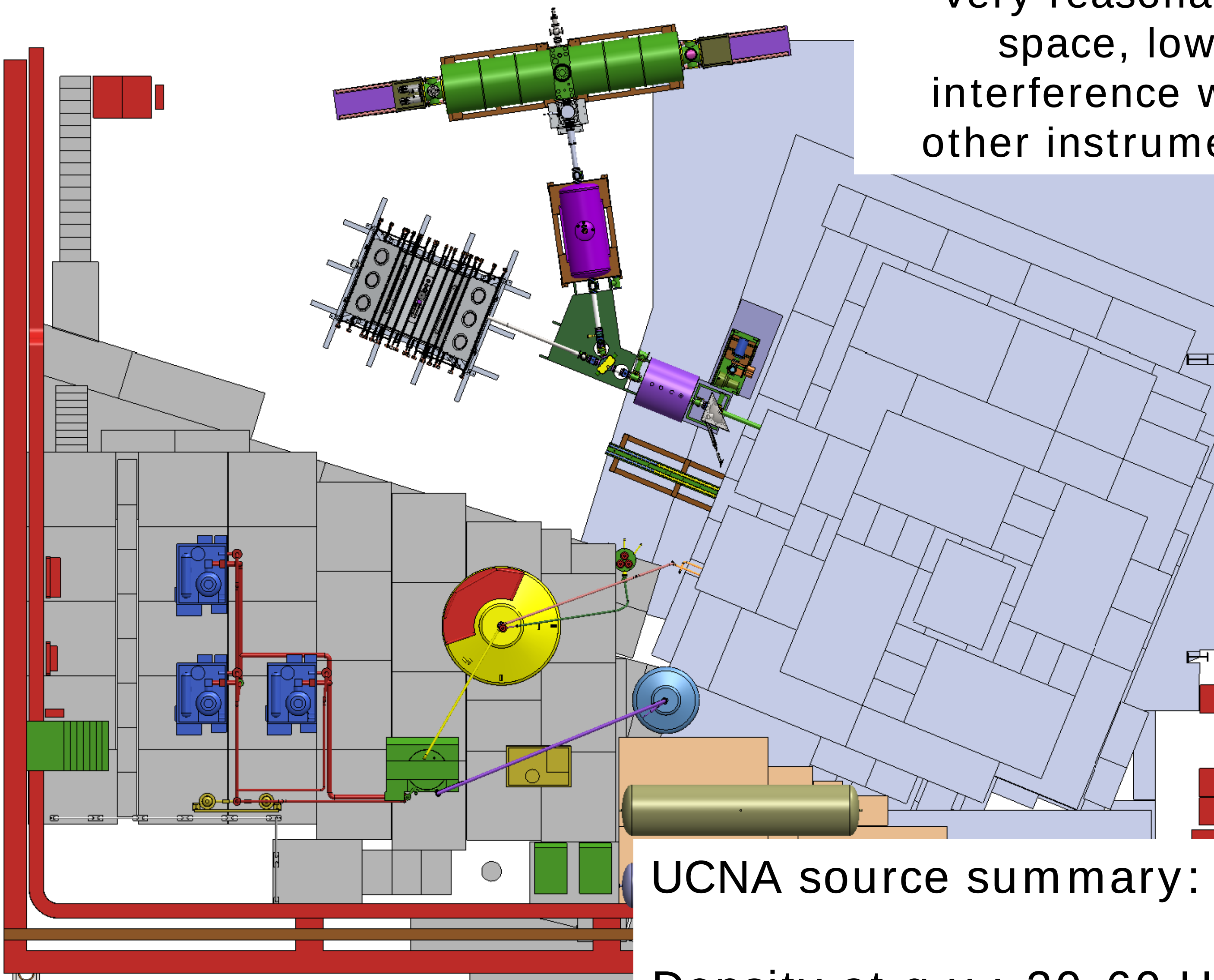
(C. Morris) Predicted: 107±20 UCN/μC/cm^3
Internal det: 85±10 UCN/μC/cm^3

2010:

V: 52±9 UCN/cm^3
Mon: 79±16 UCN/cm^3



Cold flux: Ar activation
UCN flux: V foil activation



Very reasonable space, low interference with other instruments

UCNA source summary:

Density at g.v.: 30-60 UCN/cm^3

Eff. Current 1-2×10^5 UCN/s

Source effective τ ~ 40 s

Load through 3” guide

Not precisely determined because of losses in D2 and transport above flapper → (Eff. Current)

When flapper closed → (Source effective τ)

The PSI Source

- 600 MeV proton beam, 2.2 mA (3 s on, 300 s off) incident on a Pb/Zr target. Uses 30 l of SD_2 both as moderator and UCN converter, surrounded by D2O thermal moderator

- Uses a flapper isolation valve to limit losses between beam pulses, $\tau \approx 90s$ and a volume of ~2 m^3.

- Operating as a production source since 2012 with on-going EDM experiment, with a peak density of 23 UCN cm^{-3} and a peak current of 7×10^5 UCN/s. Also serves general experimental area...(Area West)

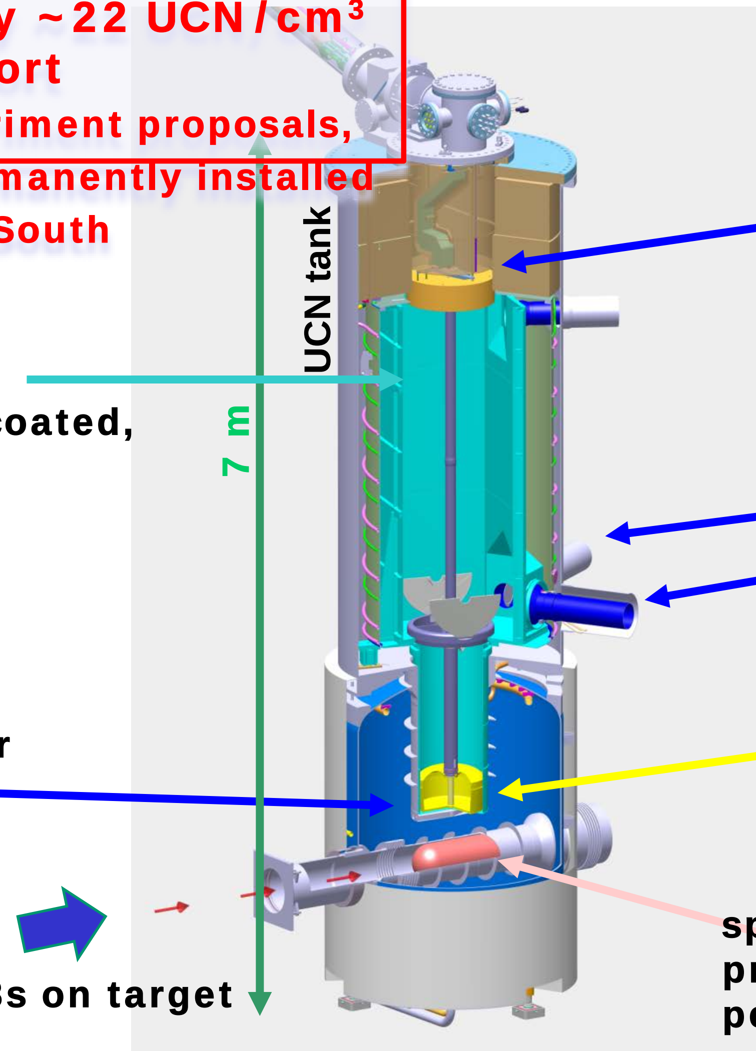
- Extensive characterization program for all aspects of source operation

PAUL SCHERRER INSTITUT PSI

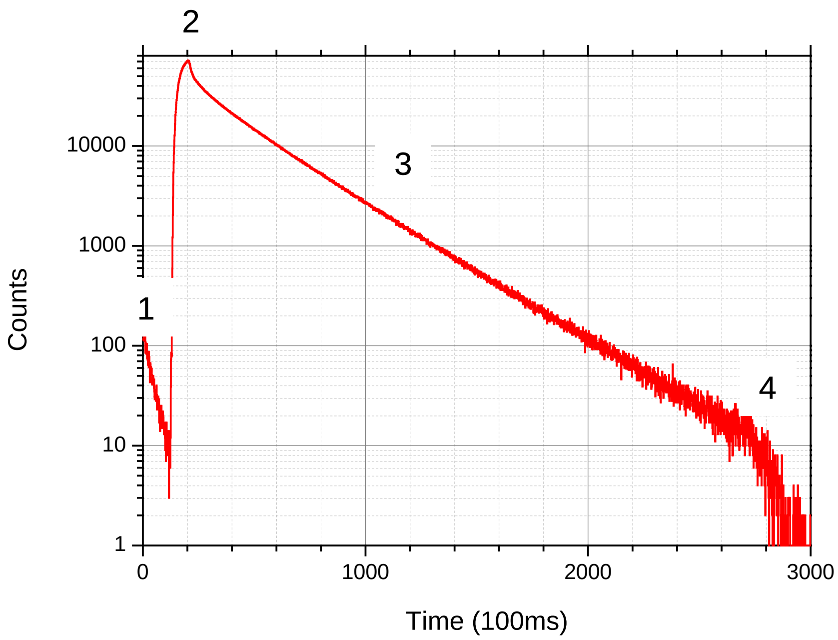
the ultracold neutron source at the Paul Scherrer Institute

UCN Ultra Cold Neutron Source

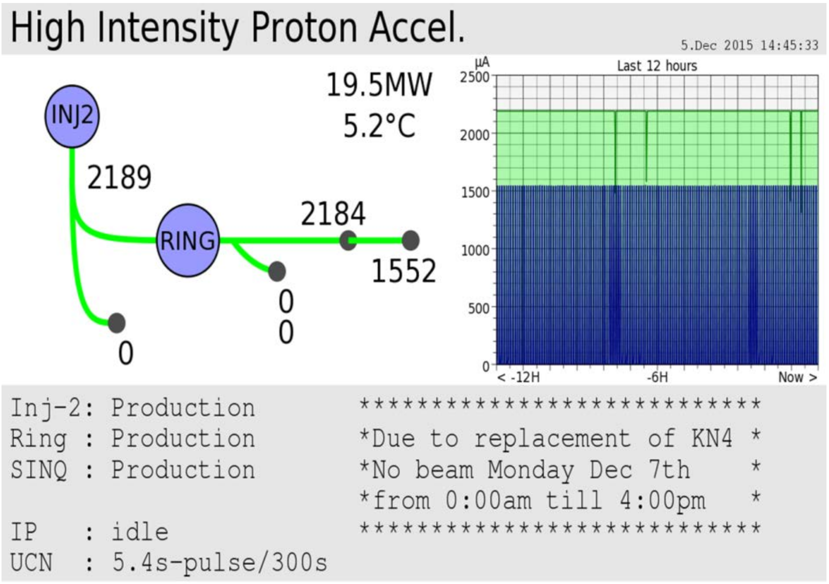
regular UCN source performance in 2015:
- **20 million UCN every 300s delivered**
- **provided UCN density ~22 UCN / cm^3 at beamport**
- **open for external experiment proposals,**
- **nEDM experiment is permanently installed at beamport South**



UCN delivery to beamport



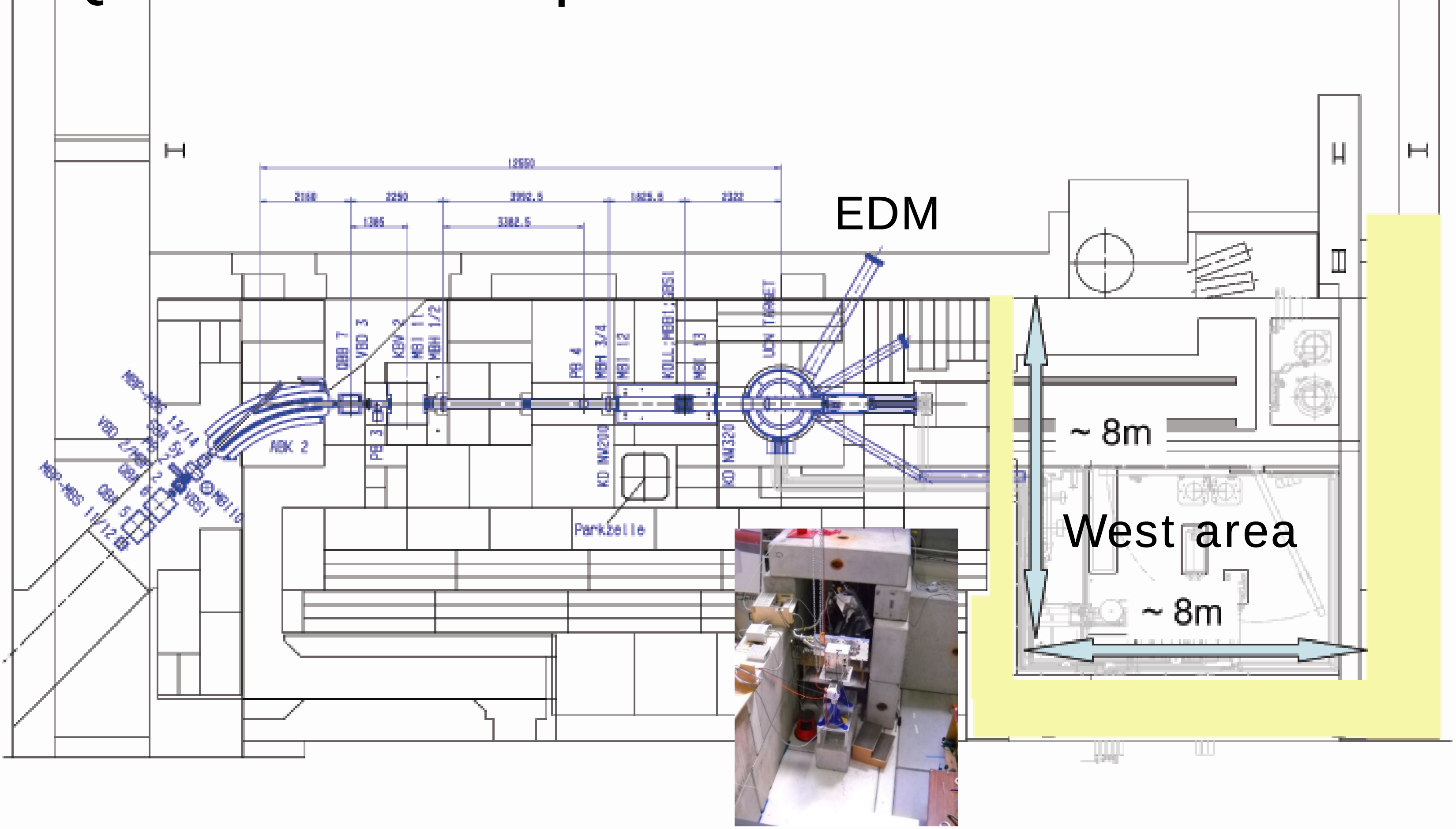
UCN counts as measured with a B10 coated CASCADE GEM counter on beamport West-1.
1 - 7ms Pilotpulse to check proton beam geometry
2 - full proton beam for up to 8s onto target, then closing of UCN shutter
3 - delivery of UCN towards beamport
4 - after 280s the UCN shutter opens again and awaits next proton beam pulse



Accelerator status display for standard nEDM data taking operations in Dec. 2015 - 12 hours of constant pusling are displayed - UCN operations went 24/7.

UCN source and area West

Quite a bit of space...



Mainz Source

- First group to operate source at a low power university reactor and newest production source – great opportunity to develop source technology and do experiments

- SD_2 converter with V = 160 cm^3, exposed to a thermal neutron fluence of 4.5×10^{13} n/cm^2, delivers up to 240000 UCN ($v \leq 6$m/s) per pulse and UCN densities of ≈ 10/ cm^3 are obtained in stainless-steel bottles of $V \approx 10$ L.

- Pulsed operation permits the production of high densities for storage experiments (tauspect)

- Upgrade of guide system complete (hear about that today in the talk of **Hollering**) New ideas under consideration

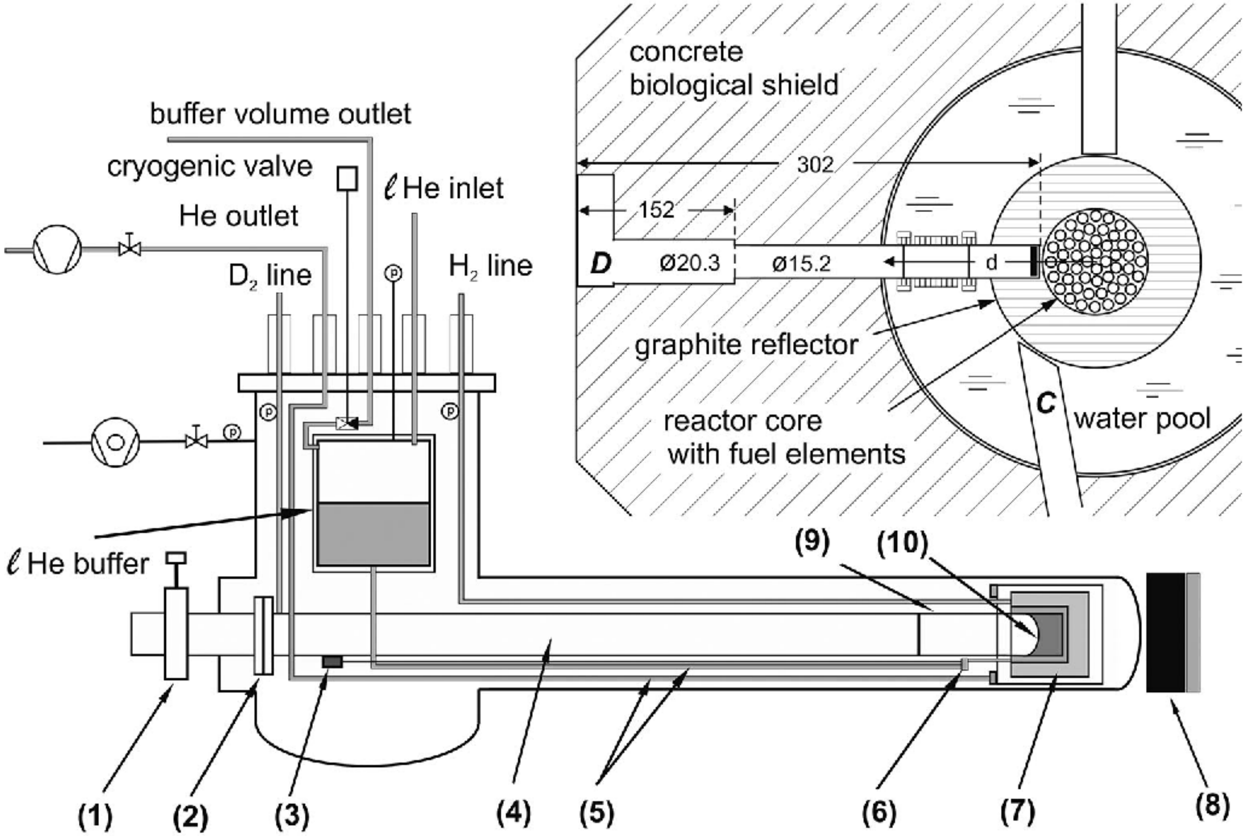
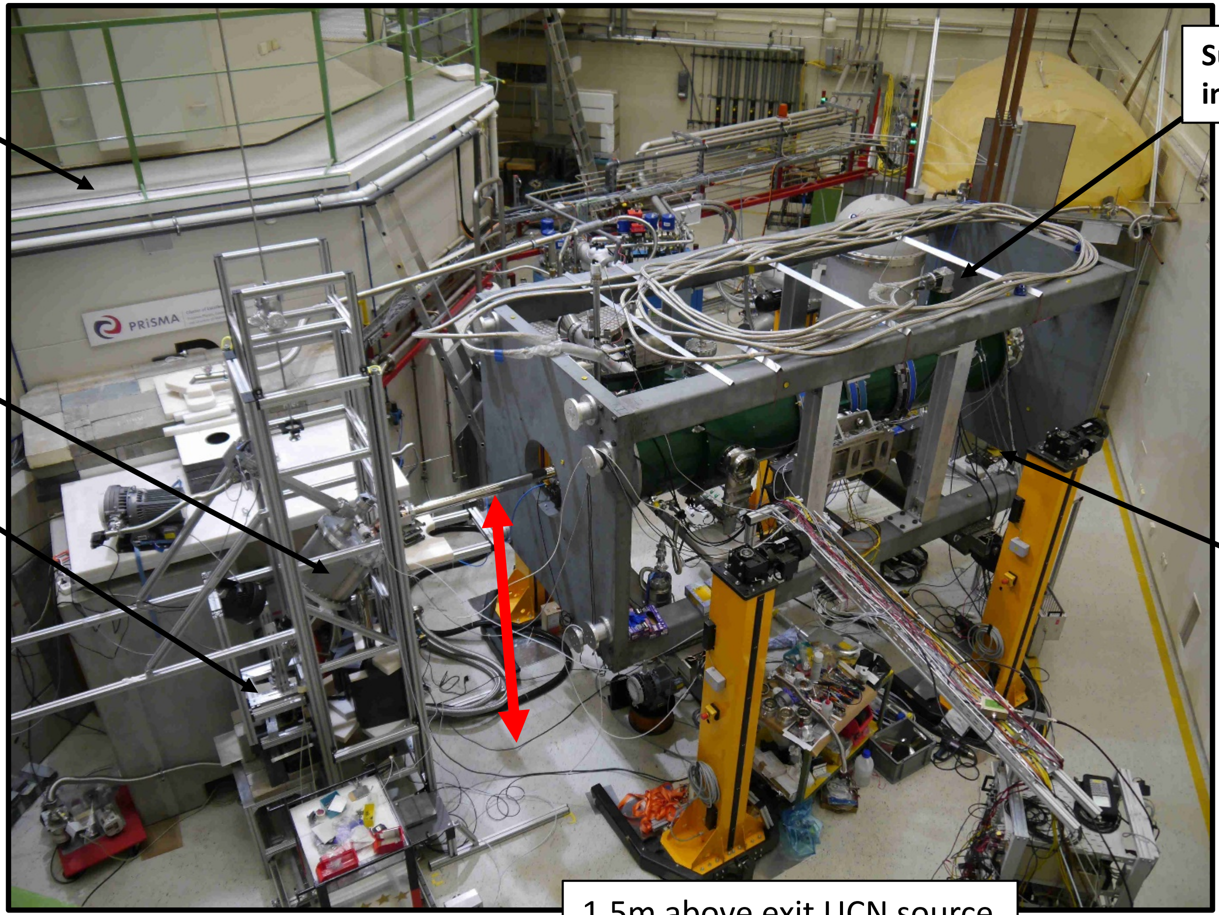


Fig. 1. Schematic drawing of the UCN source at beamport D, showing the vertical cryostat outside the biological shield and the in-pile part which ends close to the reactor core: (1) safety shutter, (2) $AlMg_3$ foil, (3) driver for Joule-Thomson valve, (4) neutron guide, (5) lHe supply lines, (6) Joule-Thomson valve, (7) premoderator (H_2, D_2 or CH_4), (8) graphite/bismuth stopper, (9) thermal bridge, (10) nose with sD_2 converter. With d, we define the distance from the center of the reactor core to a given point along the axis of the radial beamtube D. Inset: Scale drawing (measures in cm) of the horizontal section at reactor TRIGA Mainz with focus on the radial beamport D.

J. Karch et al., Eur. Phys. J. A (2014) **50**: 78

Installation of τ-SPECT (n-lifetime) at beamport D



PhD: Jan Peter Karch

The FRM II Source

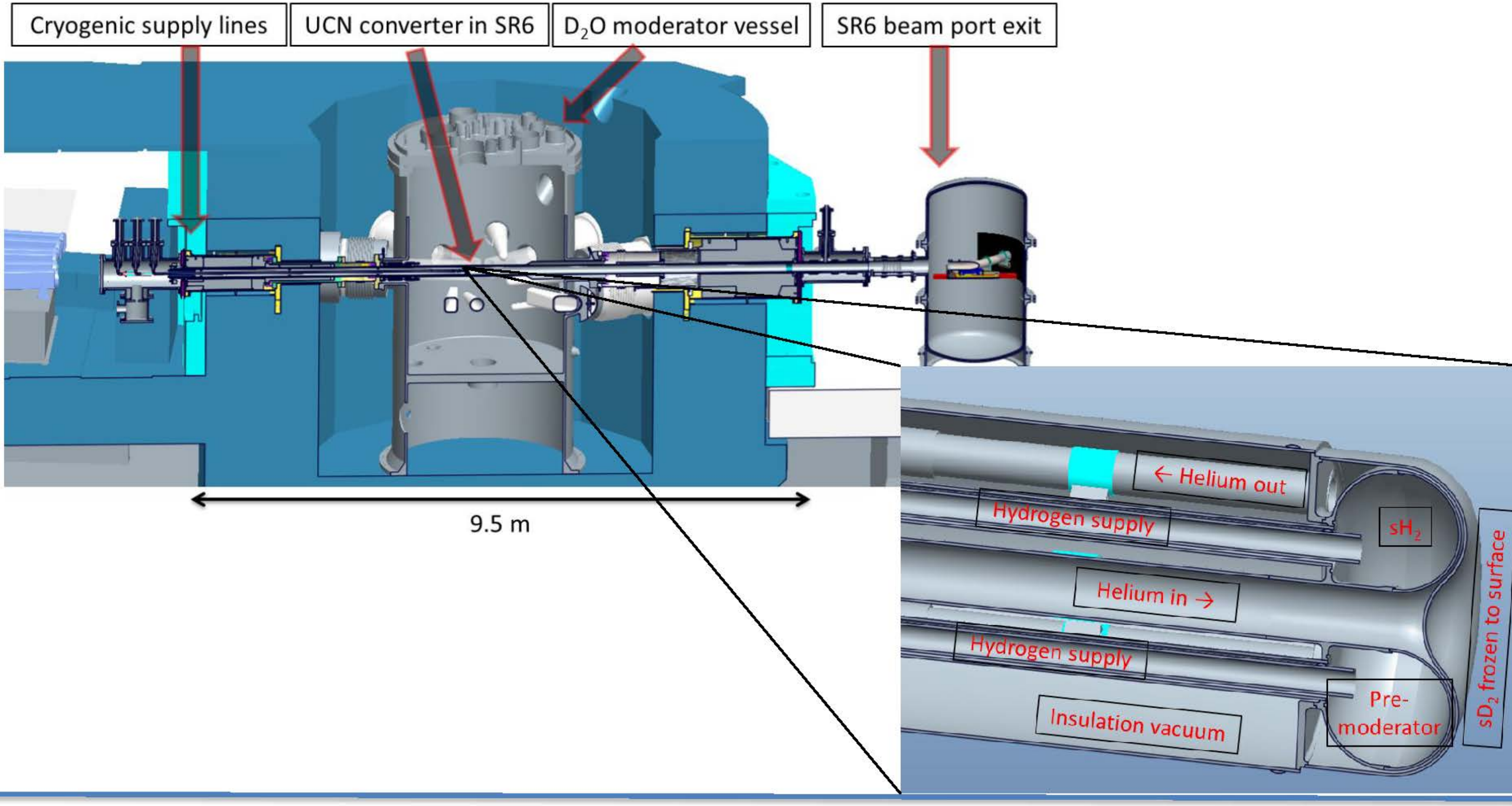
- Unique concept: 250 cm^3 converter frozen to the outside of the cold moderator – moderator and converter close-coupled and thickness of converter small enough (~1 cm) to minimize transport issues

- CW production in D2O moderator outside reactor (in through-going beam-tube) – large currents and densities (7×10^7 UCN/s and 5000 UCN cm^{-3})!

- Non-nuclear tests underway – installation discussed by **A. Frei**

- Extensive characterization program and detailed analysis of scattering studies by team (Talk of **Wlokka** for the latest)

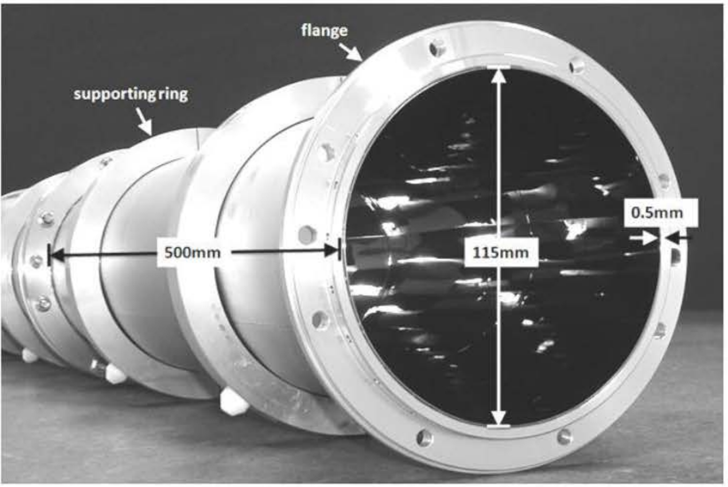
UCN source design



Some pictures

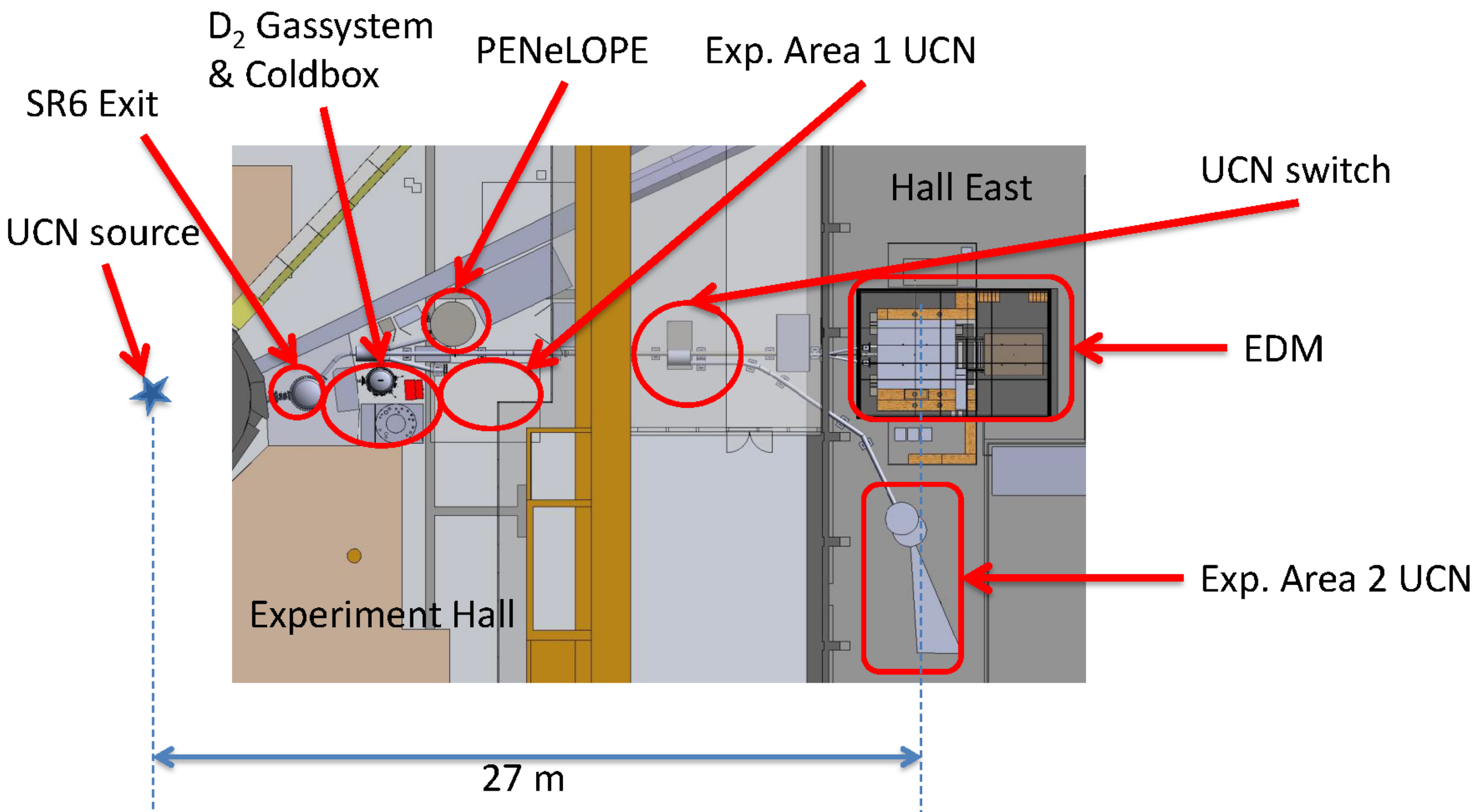
Converter vessel

Coldbox



UCN guide
Transmission:
(0.990±0.006)m^{-1}

The UCN-Lab @ FRM II



The PULSTAR Source

- Source placed in thermal column, with a special port and lead shielding box coupling D2O thermal moderator with reactor – reactor gamma heating negligible. Low heat load permits methane moderator (optimal T ~ 40-60 K)

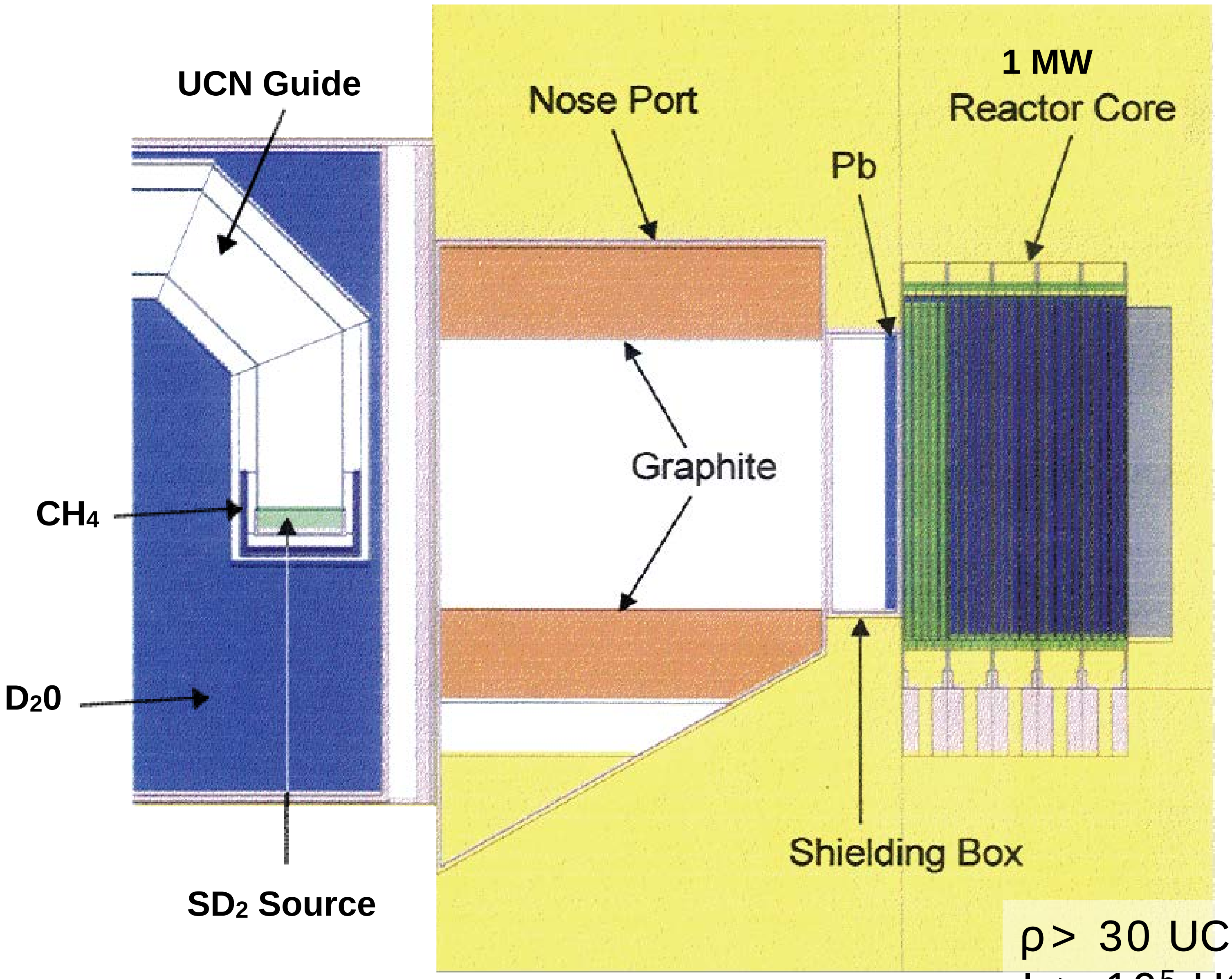
- CW production 1 l converter in vertical configuration

- 58Ni-coated quartz guides in source

- Project in Safety Review for about 4 years...

- **Currently exploring crystal growth procedures in crystat instrumented to view crystal, with temperature sensors and pressure monitoring in the D2 volume**...

- Primary project will be the nEDM test apparatus



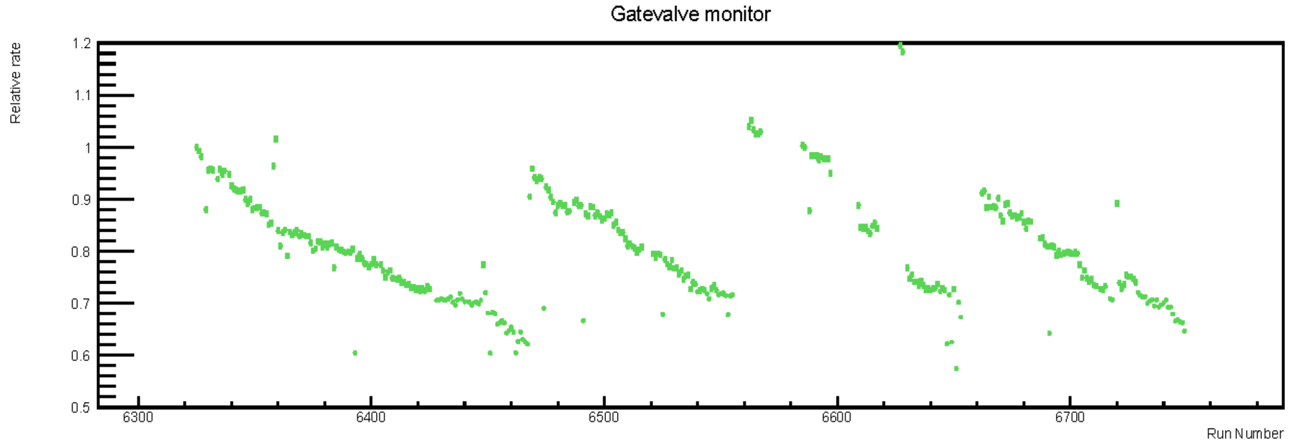
Re-assessing now (based on meas) →

$\rho > 30$ UCN/cm^3
I > 10^5 UCN/s (3" gd)
τ short (few s)

Points of Personal Interest

- Loose End: UCN transport effects poorly controlled in SD_2:

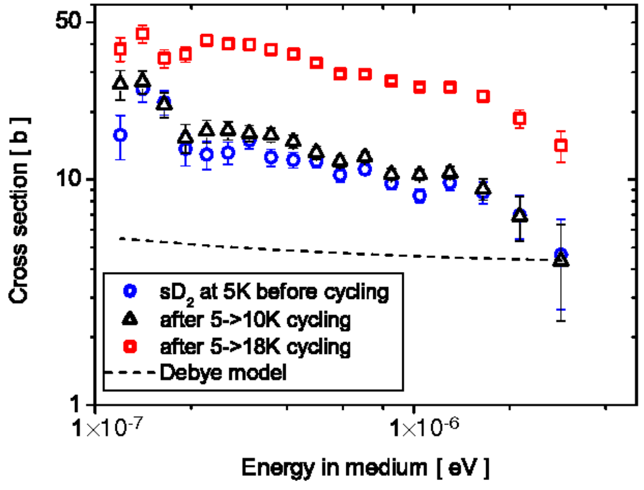
  - Routine operation of spallation source (LANL, PSI) requires a melt-and-refreeze at LANL, and annealing at PSI to recover source output:



Source output and melt-and-refreezes over 11 days at LANL (every couple of days)

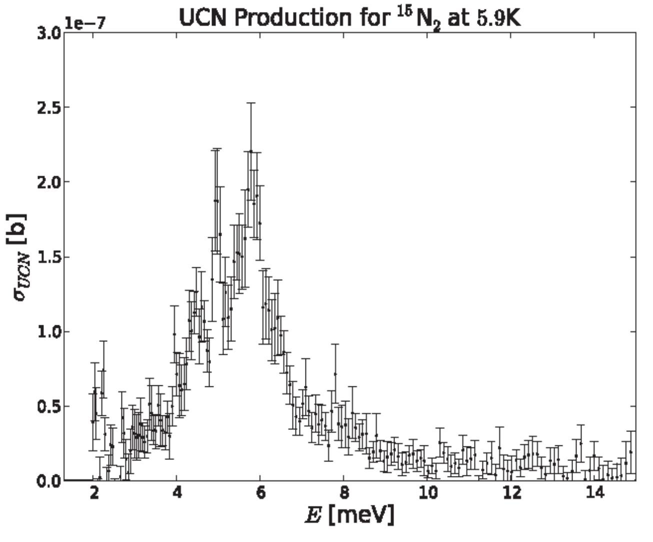
- Elastic scattering mean free path at least a factor of 2 smaller than expected from incoherent scattering cross section, even for carefully grown crystals (seen by all groups) – may be responsible for rate discrepancy with the PSI source...

F. Atchison et al., PRL **95,** 182502 (2005)



Probably due to crystal imperfections (voids, cracks, surface roughness) but would be useful to confirm and learn how to control!

- A number of alternatives to D_2 and He now investigated...^{15}N might be a winner! "Peak" cross-section (for CN dist at 40K) down about 5 relative to D_2, but losses a factor of 20 less! Need to check elastic scattering properites and might be a bit expensive…



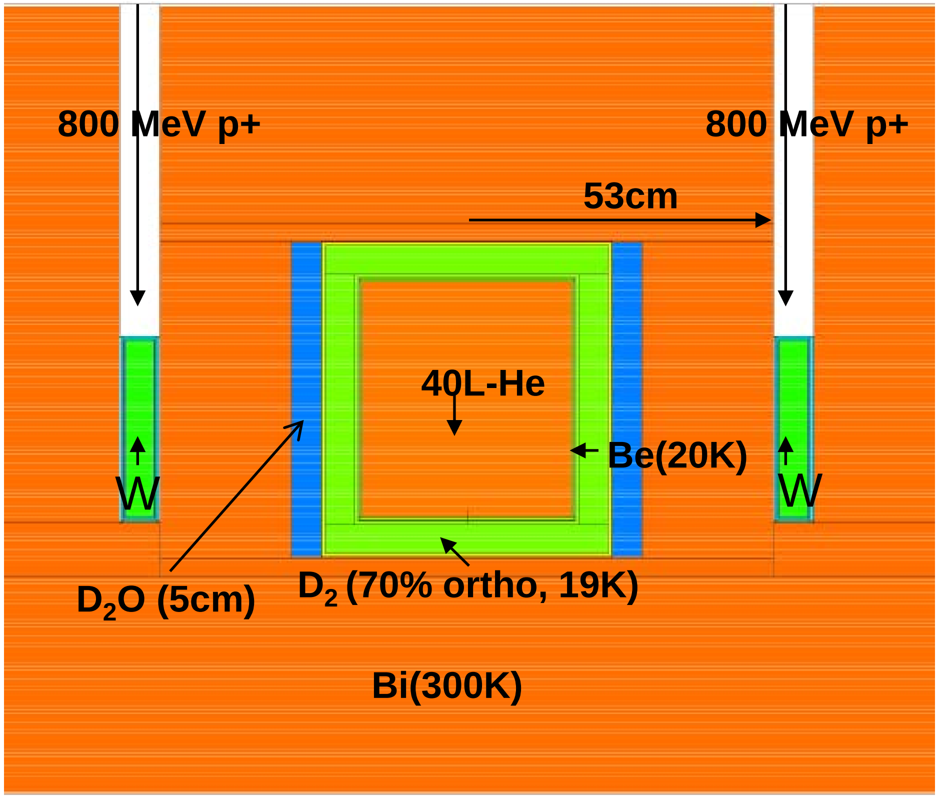
D. J. Salvat, E. Gutsmiedl, C.-Y. Liu, P. Geltenbort, A. Orecchini, S. Paul and H. Schober, EPL, 103 (2013) 12001

- Why should the upscatter rate for SD2 match so well to a calculation made with the incoherent approximation when para-D2 concentration low (mostly coherent scattering – modes frozen out where coherent scattering is allowed)?

- Interesting possibilities if one saturates cooling power of sub-cooled He station (many used at CERN) to cool LHe source coupled to a spallation target with an optimized geometry to remove gamma and proton heating...very high currents possible (> 10^8 UCN/s for beam power at 800 MeV > 100 kW -- refining estimates...)

G. Muhrer et al...

ICG (5): D_2 moderator



$1.0*10^8$ UCN/s/100μA

Heat load @ 100μA ≡ 80KW

Total heat: 13.9 W

Neutron heat: 10.8 W

Photon heat: 2.4 W

Proton heat: 0.7 W

$7.14*10^8$ UCN/s/100W (heat in the He)

Obtained factor of 2+ x production in latest design...

Conclusions

- There has been incredible progress in the past 10 years in the construction and availability of UCN sources

Thanks to all those who contributed slides!

- We are in an excellent position to create “feeder” programs to develop the excellent experiments and then move them to where “maximum smoke” is available

- It also seems there are a few outstanding issues for source technology we can address...