

CryoEDM

Instrument to measure the Electric Dipole Moment of the neutron using a superthermal UCN source

Maurits van der Grinten (*talk given by P. Geltenbort*)

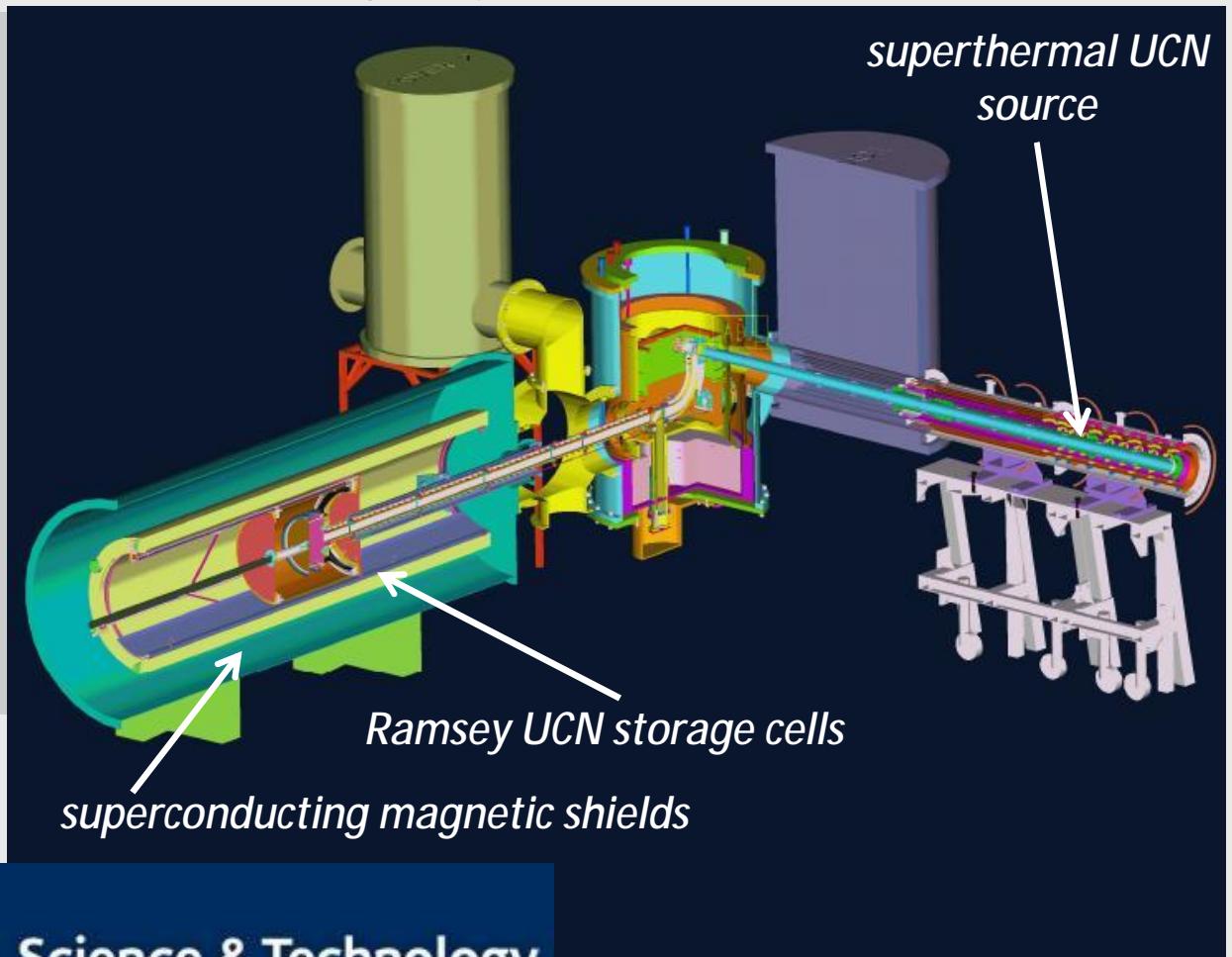
outline:

- why are we measuring
- set-up of CryoEDM
- how are we doing, essential parameters
- comparison other projects
- outlook for years to come

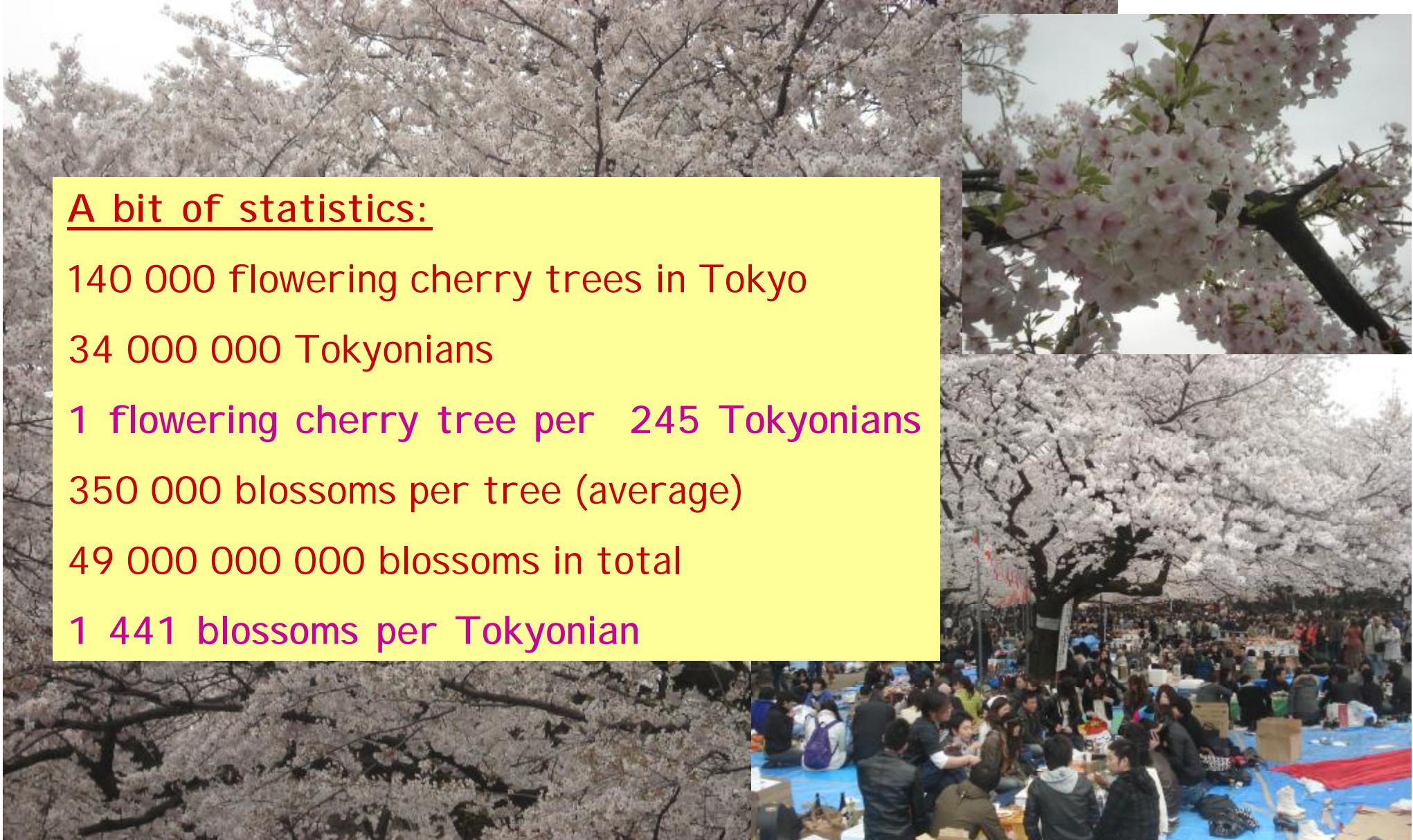
Rutherford Appleton Laboratory
University of Sussex
University of Oxford
Institut Laue-Langevin
University of Kure



Science & Technology
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"Saakuuuura, Saakuuuura! "



A bit of statistics:

140 000 flowering cherry trees in Tokyo

34 000 000 Tokyonians

1 flowering cherry tree per 245 Tokyonians

350 000 blossoms per tree (average)

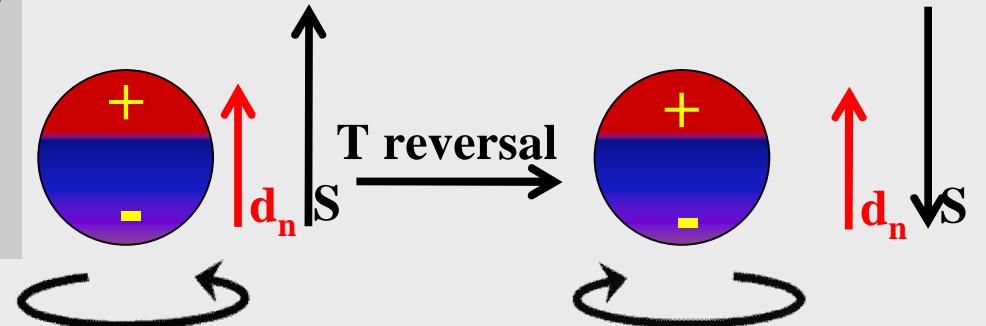
49 000 000 000 blossoms in total

1 441 blossoms per Tokyonian

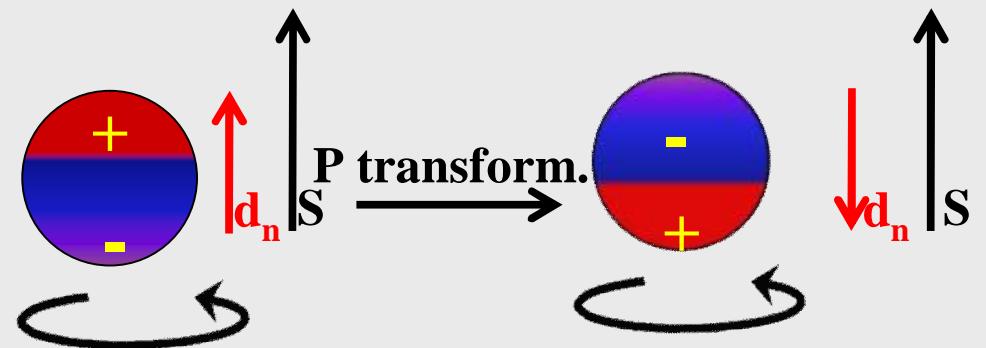
nEDM: why

neutron electric dipole moment: d_n

$d_n \neq 0$ P and T violation



electric dipole moment d_n
spin S



P & T violation

CPT conservation è CP violation

Baryon asymmetry:

Big Bang should have produced equal quantities of matter and anti-matter.

This is not what we observe in our Universe

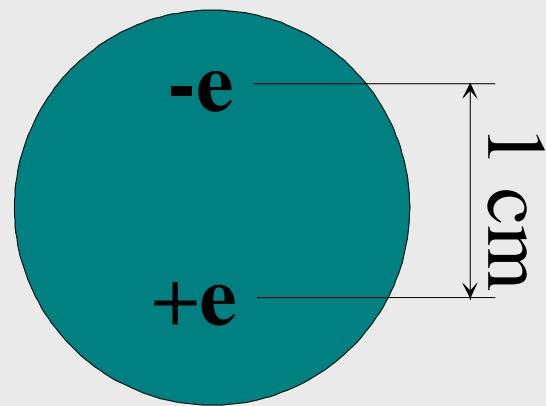
CP violation required for this asymmetry...

CP violation present in Standard Model but:

- The CP violation in the Standard Model is too small by many orders of magnitude to explain the observed matter-anti-matter asymmetry of the Universe
- There must be CP violations in laws of physics we don't know yet!
- We have to keep looking...

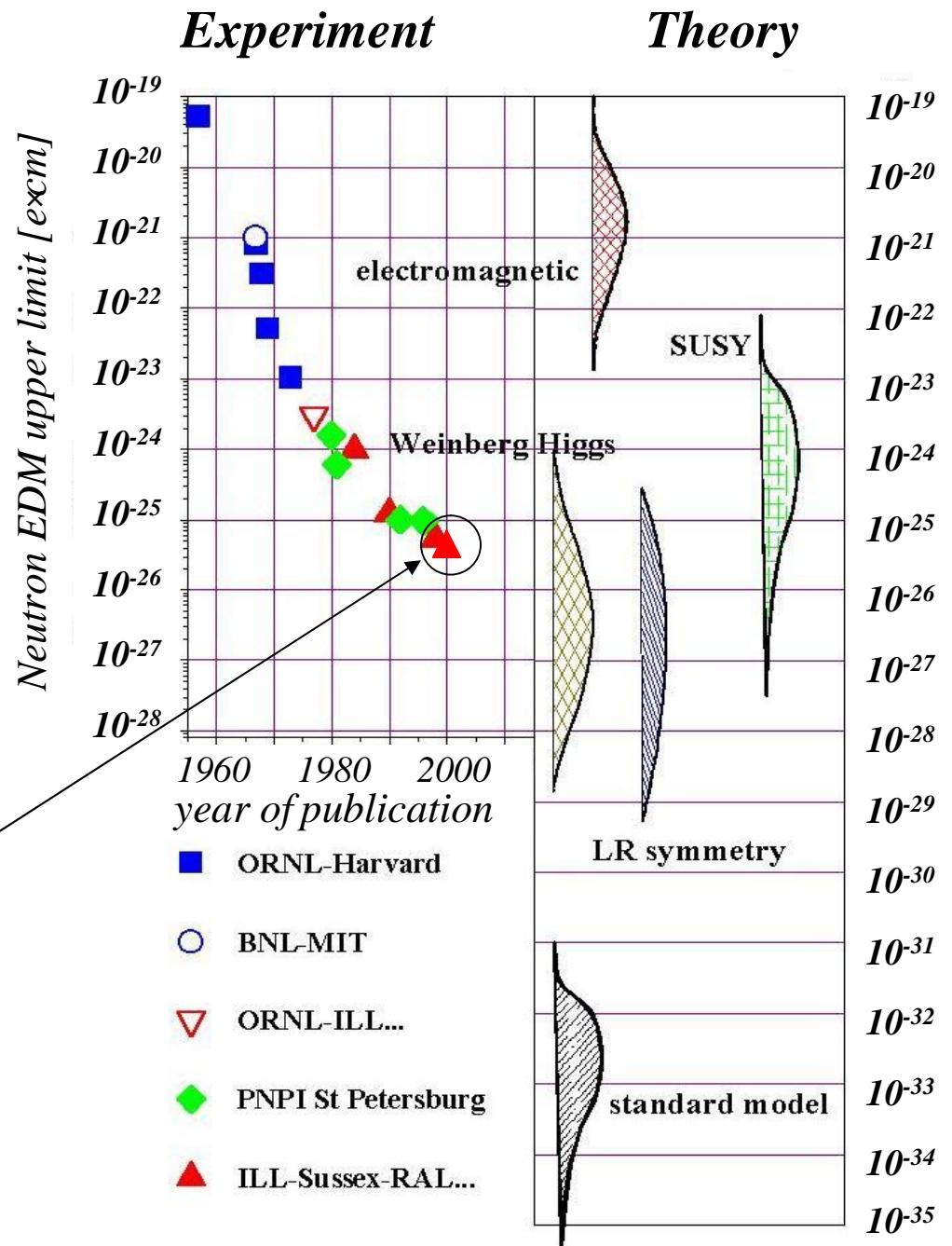
nEDM: experiment vs theory

Progress at \sim order of magnitude per decade
 Standard Model out of reach
 Severe constraints on *e.g.* Super Symmetry



$$d_n = 1 \text{ e}\times\text{cm}$$

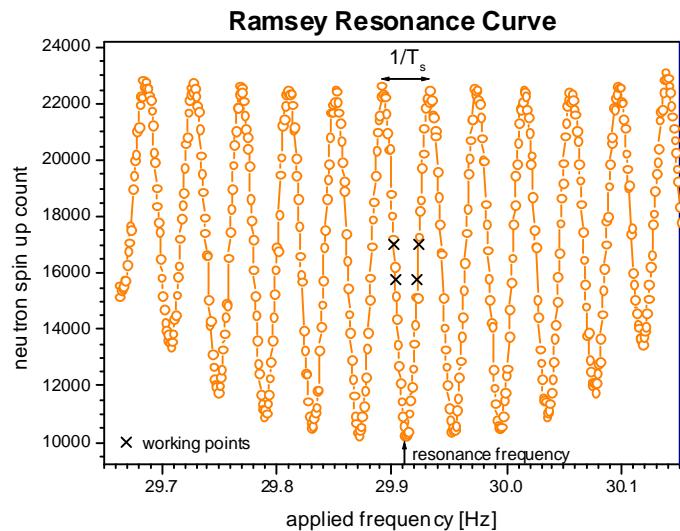
$$|d_n| < 3 \times 10^{-26} \text{ e}\times\text{cm}$$



nEDM: measurement principle

Experiments:

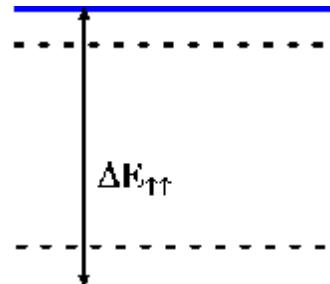
Measurement of Larmor precession frequency of polarised neutrons in a magnetic & electric field



$$S(d_n) = \frac{h}{2aET\sqrt{N}}$$

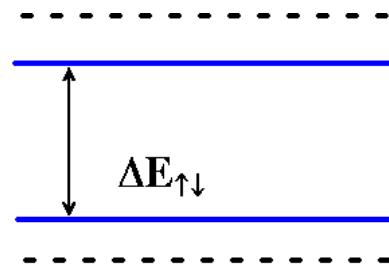
α : polarisation product
 E : electric field
 T : observation time
 N : number of neutrons

Compare the precession frequency for parallel fields:



$$\nu_{\uparrow\uparrow} = \Delta E_{\uparrow\uparrow}/h = [-2B_0\mu_n - 2Ed_n]/h$$

to the precession frequency for anti-parallel fields



$$\nu_{\uparrow\downarrow} = \Delta E_{\uparrow\downarrow}/h = [-2B_0\mu_n + 2Ed_n]/h$$

The difference is proportional to d_n and E :

$$h(n_+ - n_-) = 4E d_n$$

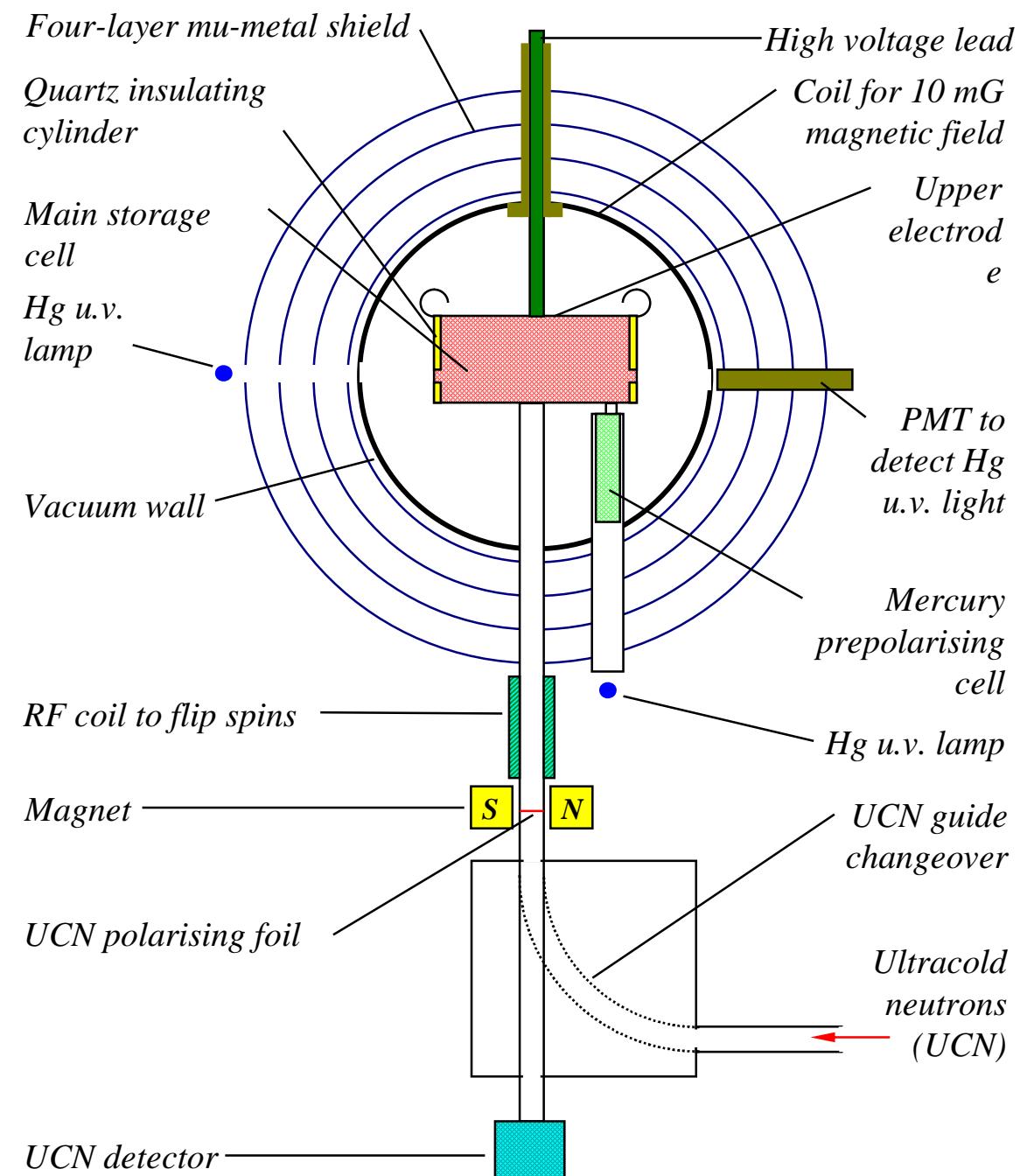
Ultra-cold neutrons for nEDM: ILL

- PF2 UCN source
(user facility)
- superthermal UCN source



nEDM past room temperature experiment

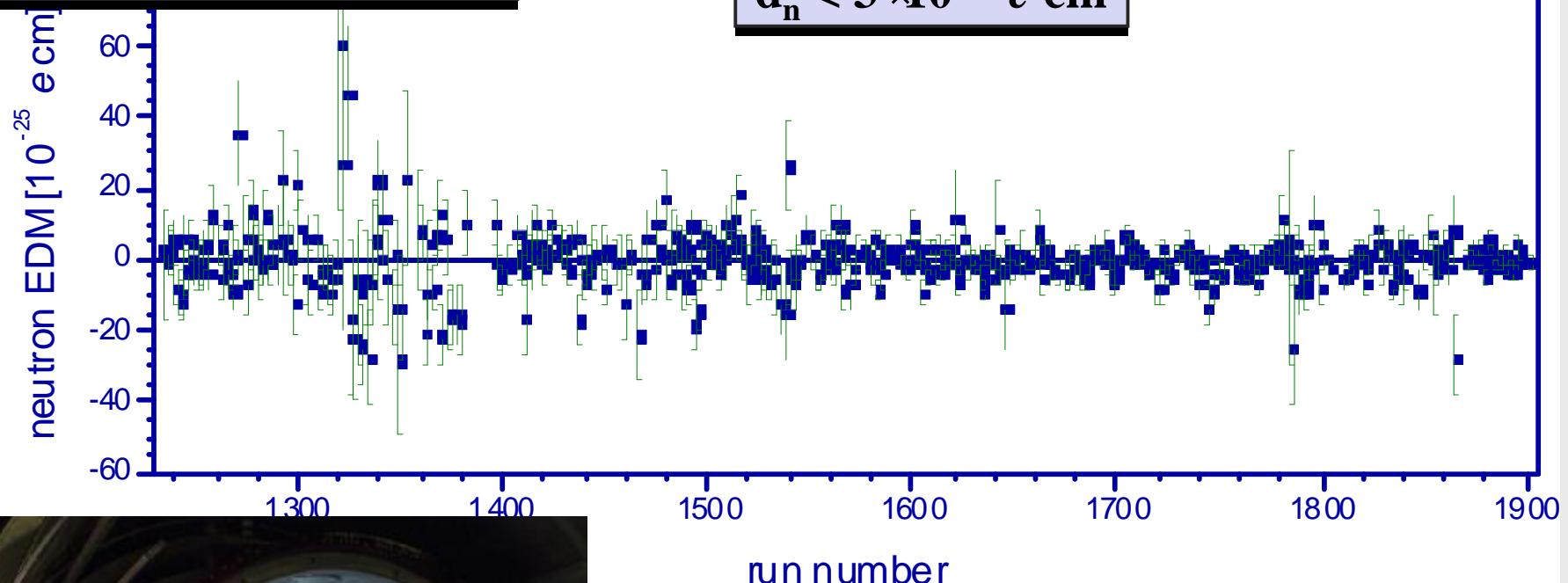
ran on PF2 UCN source at ILL
Hg co-magnetometer
4-layer mu-metal shields



nEDM past room temperature experiment

ran on PF2 UCN source at ILL
Hg co-magnetometer
4-layer mu-metal shields

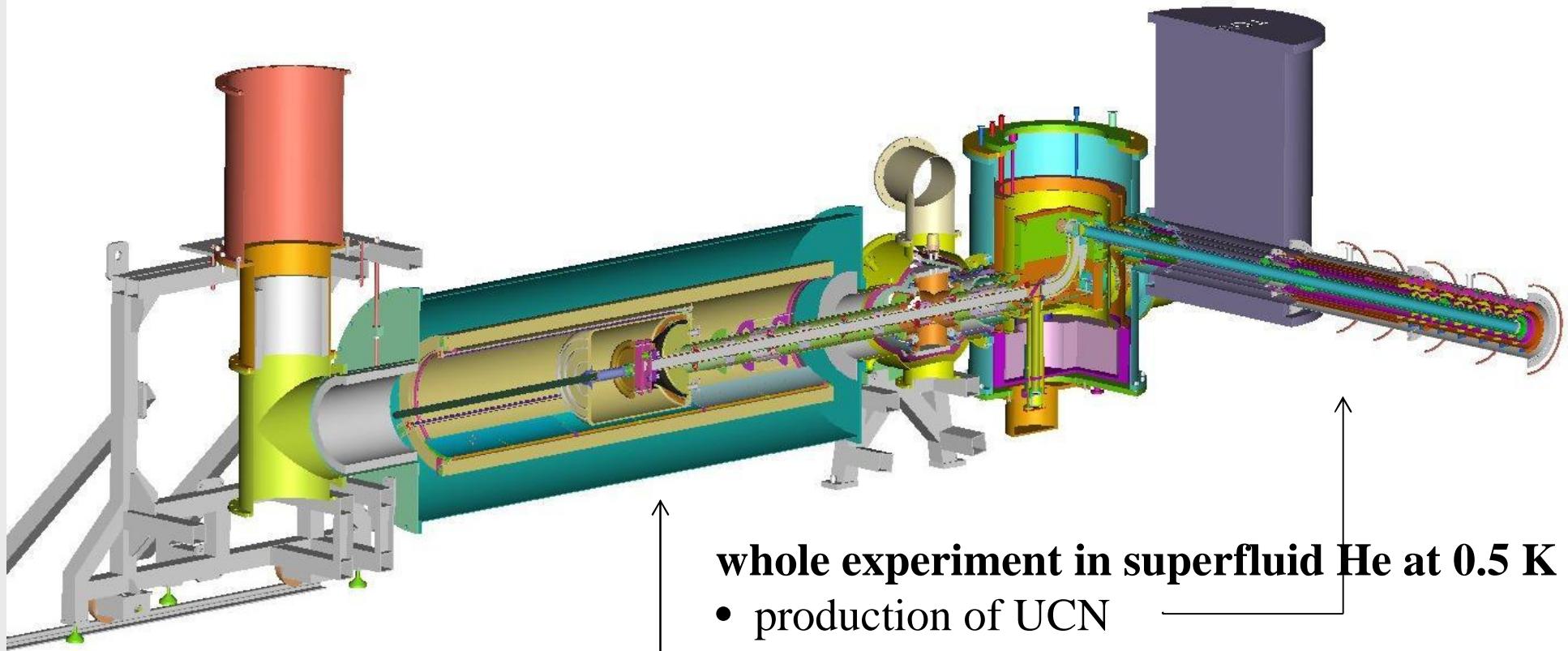
$$d_n < 3 \times 10^{-26} e \text{ cm}$$



CryoEDM: optimising sensitivity further

$$S(d_n) = \frac{h}{2ETP^2 \sqrt{N}}$$

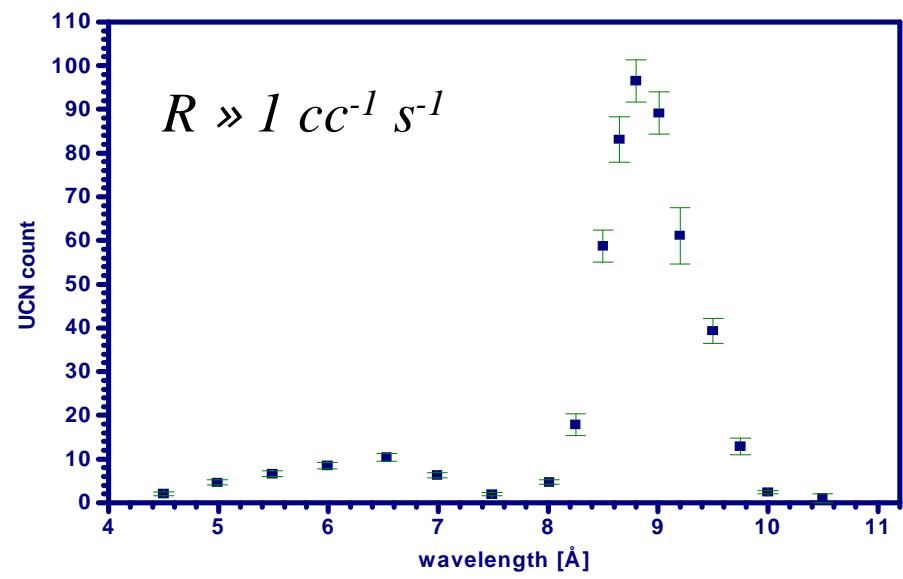
new superthermal UCN source
higher electric fields in $l\text{He}$



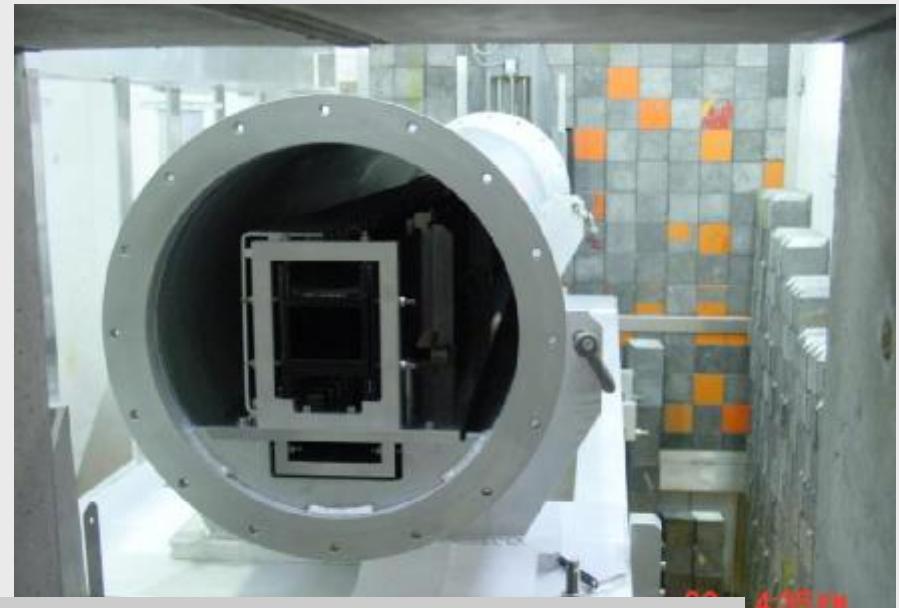
whole experiment in superfluid He at 0.5 K

- production of UCN
- storage & Larmor precession of UCN
- magnetometry
- detection of UCN

CryoEDM

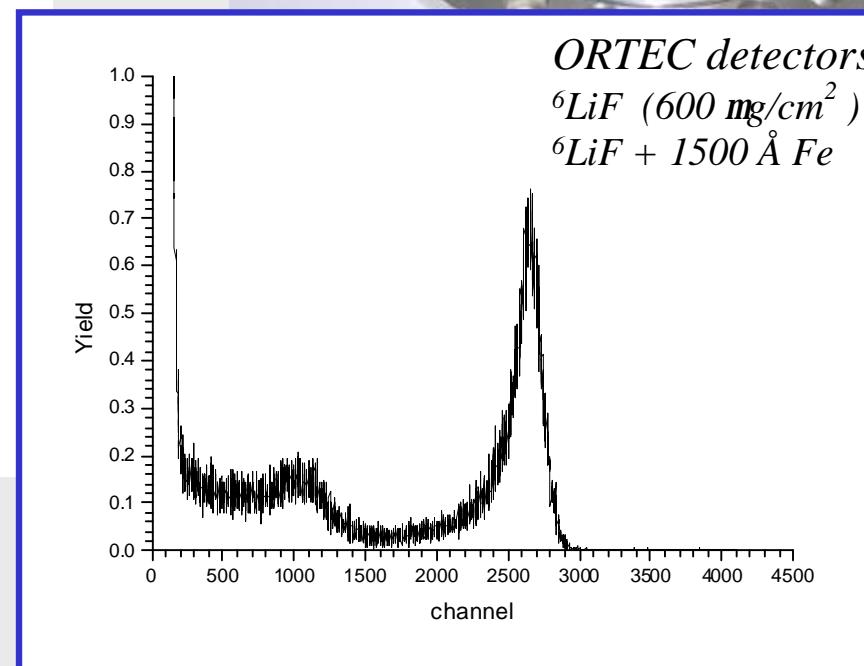
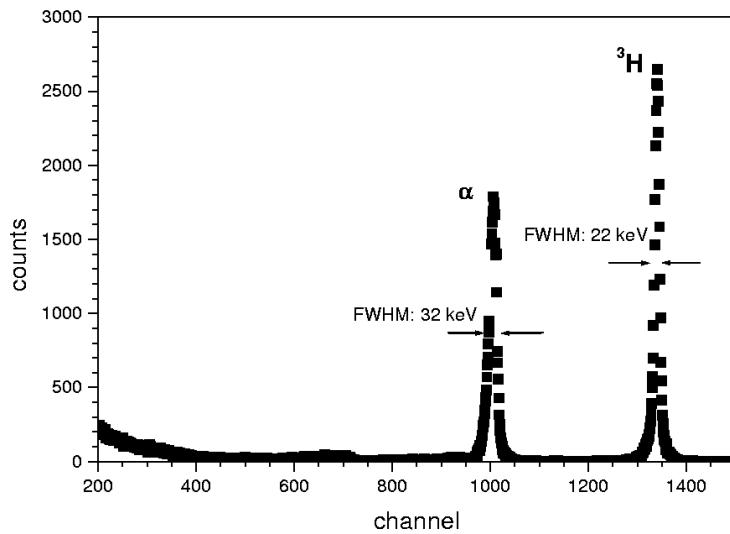
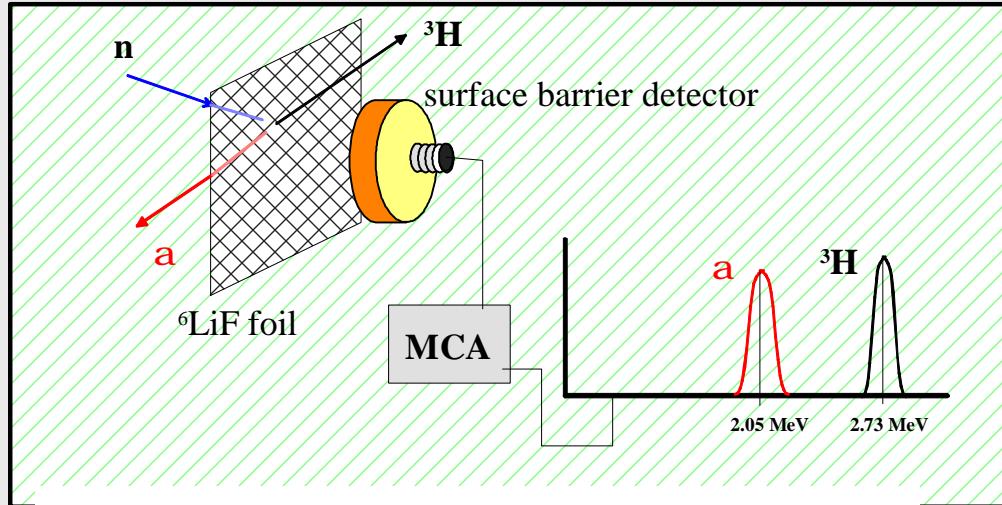


CryoEDM: primary beam polarisation

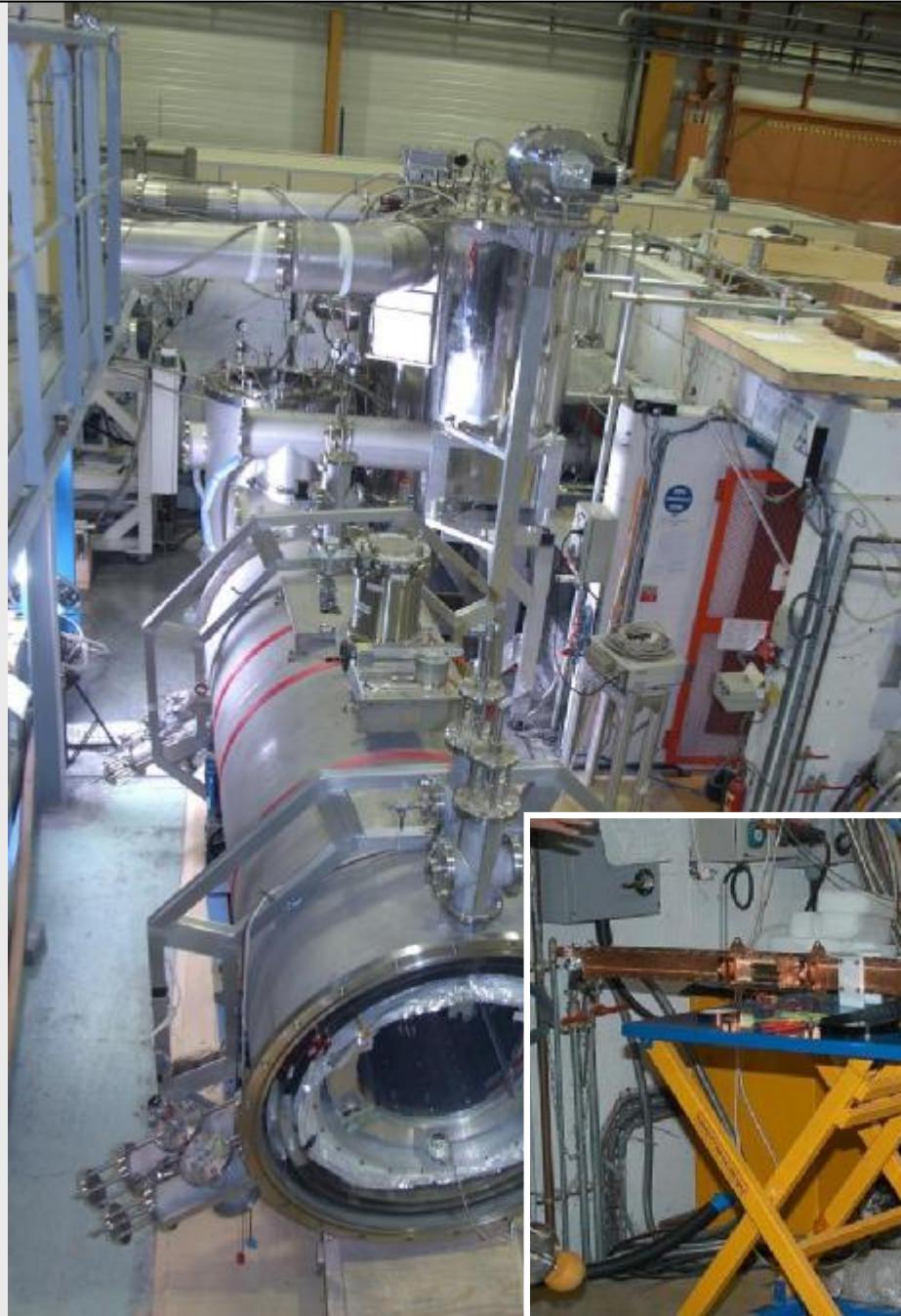


"Monochromating" polariser on primary cold beam (Ken Andersen)

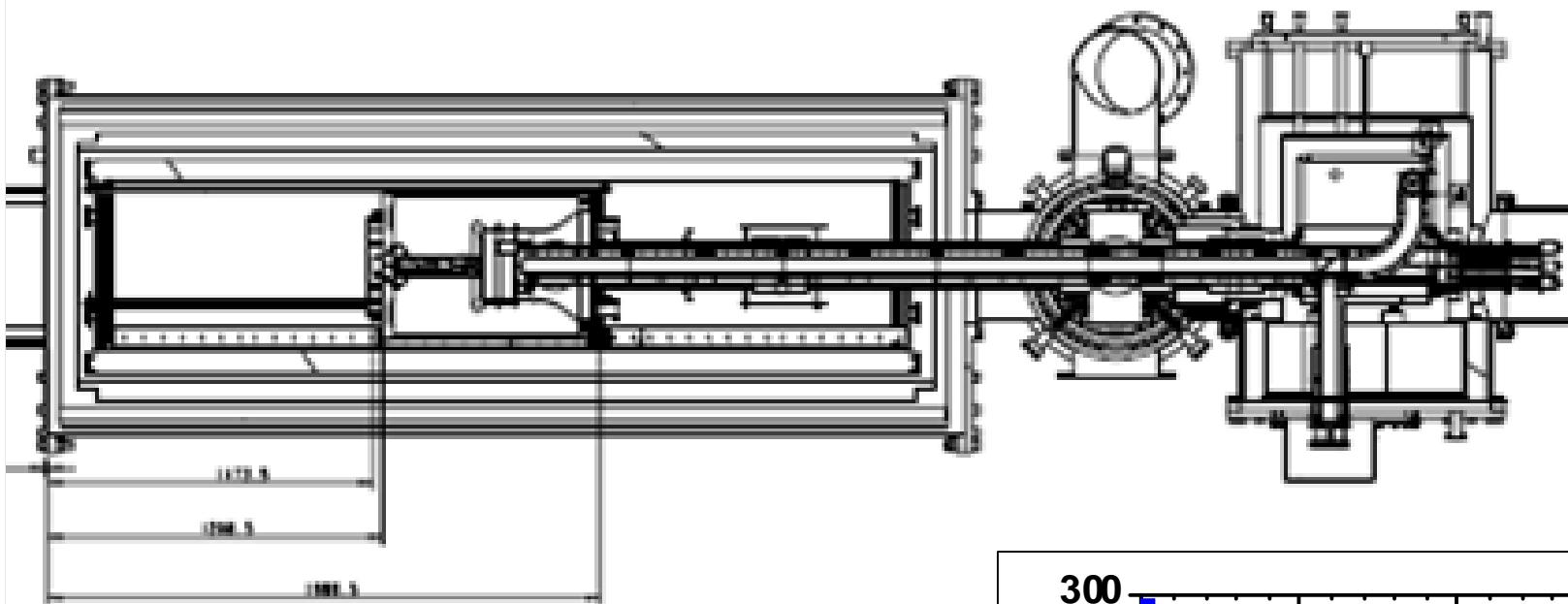
CryoEDM: *in situ* UCN detection



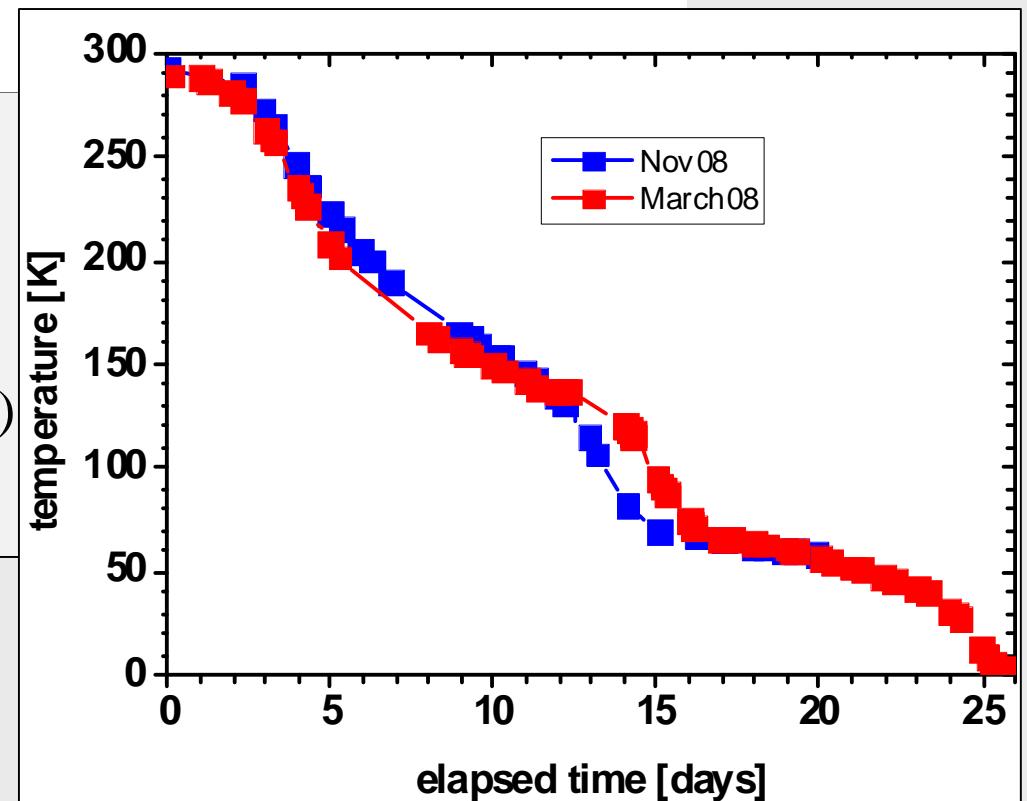
CryoEDM: storage chambers, Be/BeCu underway



CryoEDM: cool-downs



- 250 l of pure superfluid at 0.65 K
- cool-down times ~25 days, then superleak filling
- kept entire system (~800 l liquid helium) operational for sustained periods



CryoEDM: how are we doing, essential parameters

Experiment constructed and commissioning:

cryogenic performance:

- 250 l isotopically pure ^4He produced and kept at 0.65 K
- entire apparatus (~800 l liquid helium) being run cold for sustained periods

neutron parameters:

- UCN produced in high densities
- UCN transportation parameters between source and storage cells and storage cells and detectors good
- UCN polarisation good and polarisation holding times high

electric fields:

- high electric fields demonstrated in LIHe - separate test
- non-magnetic superfluid HT feed-through operational though tested to ~30kV so far.

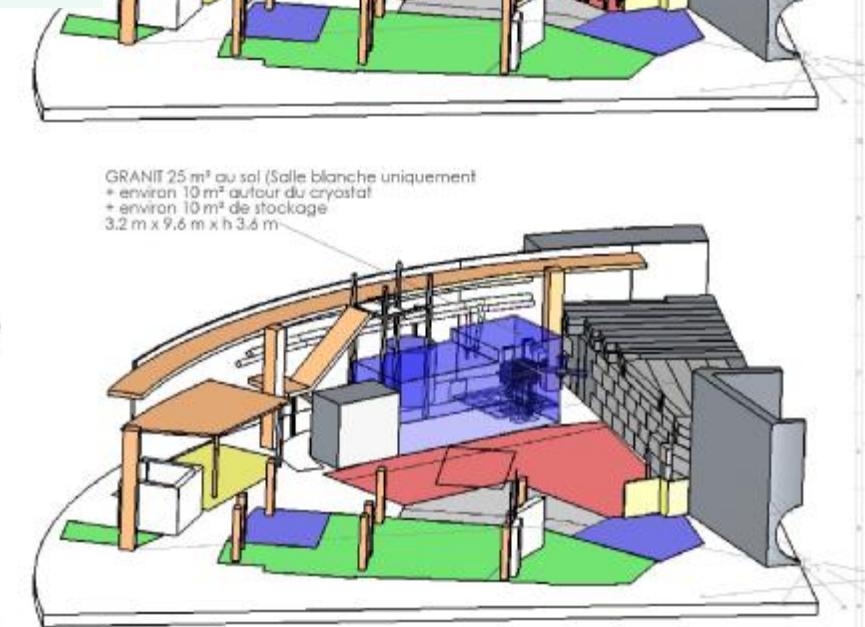
magnetic field:

- homogeneity in storage region sufficient for EDM measurement
- rebuilding storage chambers: Be/BeO/BeCu structure
- shielding operational, further improvements on the way

*take data with new storage chambers Autumn10,
increase sensitivity to $\sim 10^{-27}$ excm at H53 in first instance (2010 – 2012)*

H17-2 beamline:

- A factor of 20 higher cold flux incident on monochromator
- Magnetic environment of acceptable level
- Configuration of set-up ongoing
- aim year of move in 2013/14 (during reactor closure)
- exploit apparatus to design sensitivity of 10^{-28} e·cm



POINTS DELICATS :

- Implantation des centrales de traitement d'air de la salle blanche
- Protection Cryo EDM (charge ou sol)
- Différence Cryo / Tropose accès niveau B
- Protection stérile contre le virus
- Installation de la colonnette D9 en zone DRE
- Modification et implantation du monite charge pour les vases
- Zone de travail D9 (EURAN 8)
- Répartition des coûts
- Second décalage canameric
- Cabine pour GRANIT (zone limitée)

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H17-2
CRYO EDM+GRANIT

Implantation générale

725-03-00-501

SECRET LAURE LAROCHE S.A. - Génie Civil et Ingénierie - Paris - France
Tél. : +33 1 40 20 00 00 - Fax : +33 1 40 20 00 01

CryoEDM



- been constructed and now commissioning/
start of exploitation
- still requires tuning to deliver
a competitive EDM measurement

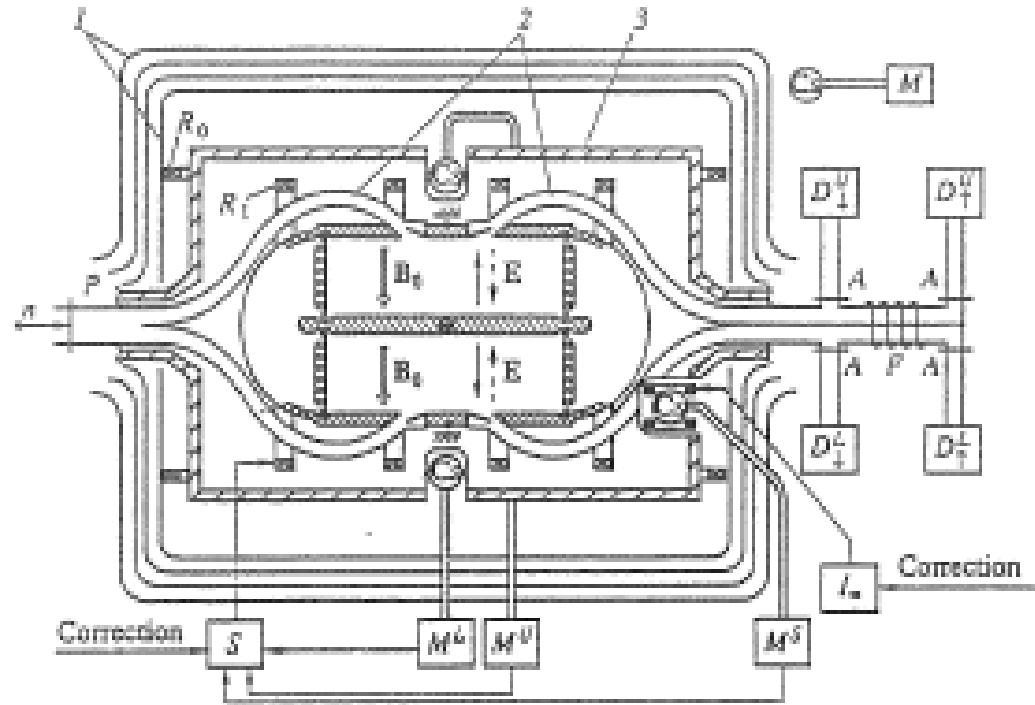
On H53 beam: sensitivity $\sim 10^{-27} e \text{ cm}$
2010 - 2012

On new beam: sensitivity $\sim 10^{-28} e \text{ cm}$
2013 – 2015

an EDM *discovery* in this region ?

nEDM projects worked on elsewhere

Russian EDM



PNPI – St Petersburg liquid D₂ UCN source

- double storage cell
- 3 cesium magnetometers
- 4-layer mu-metal magnetic screen

ultimate sensitivity of $10^{-25} e \text{ cm}$ 1996

ILL- level D PF2 UCN source

- double storage cell
- 8 cesium magnetometers
- 4-layer mu-metal magnetic screen

possible to aim for $10^{-26} e \text{ cm}$
in a couple of years running



Ongoing and near future

Neutron Lifetime Experiments

at the Institut Laue-Langevin in Grenoble, France

Peter Geltenbort

thanks to

*L. Bondarenko, A. Harrison, K. Leung, (M. van der Grinten), A. Serebrov, A. Steyerl, and O. Zimmer
for using some of their beautiful slides*

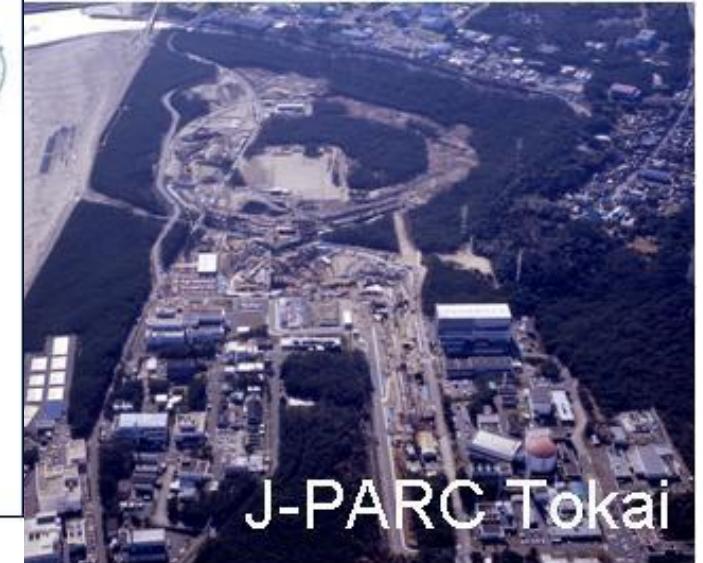
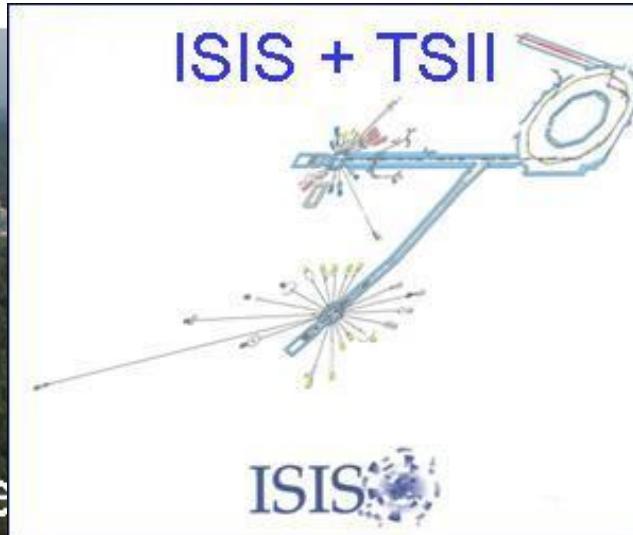
The changing facilities landscape

But we're not doing this in isolation...

Although ILL is THE leader in its field for almost 40 years now
and tries to keep its lead further



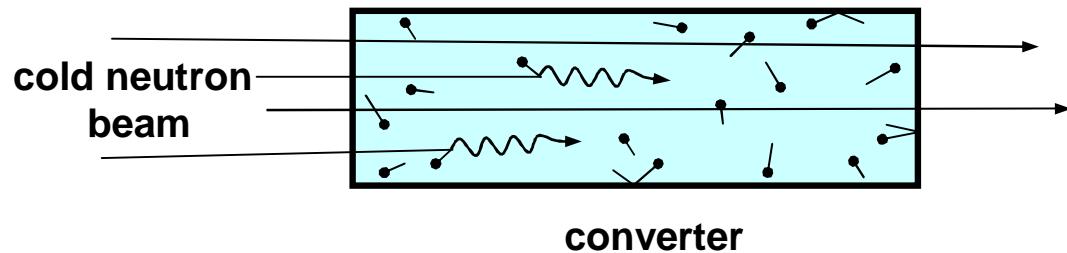
The changing facilities landscape



NCNR Gaithersburg, MD

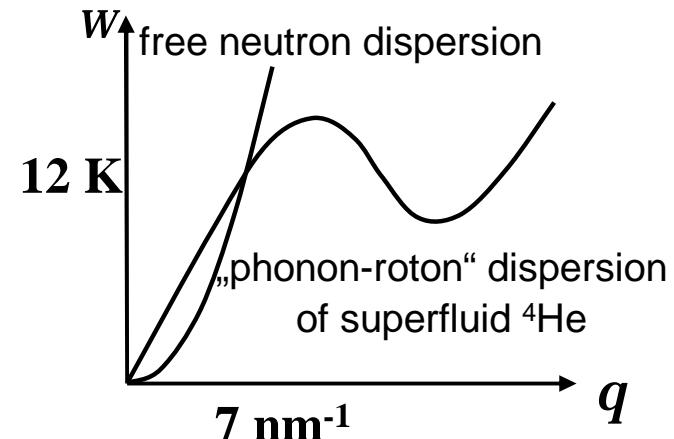
... and UCN at
Mainz, PSI, (TUM), (PNPI)
RCNP, (J-PARC)
LANL, NI ST, (NCSU, SNS), (TRIUMF)

UCN production in He-II at a cold neutron beam



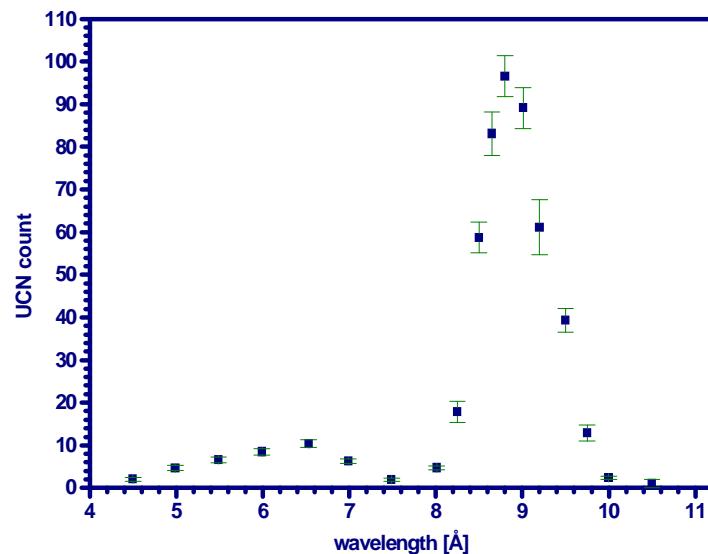
$$r_{\text{UCN}} = Pt_{\text{storage}}$$

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



- absorption cross section $S_{\text{abs}} = 0$
- 0.7 K: $t_{\text{storage}} \gg 500$ s (due to phonon absorption)
- 0.5 K: $t_{\text{storage}} \gg 800$ s
- $P = 14 \text{ cm}^{-3}\text{s}^{-1}$ at H172a / H172b

$r_{\text{UCN}} = \text{several } 1000 \text{ cm}^{-3}$ possible
at beam positions H172a / H172b

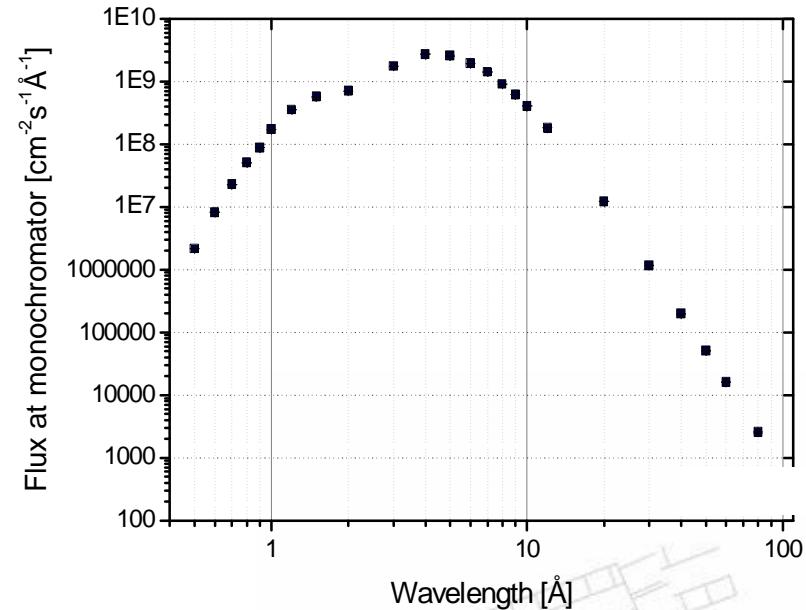


C.A. Baker et al., PLA 308 (2003) 67

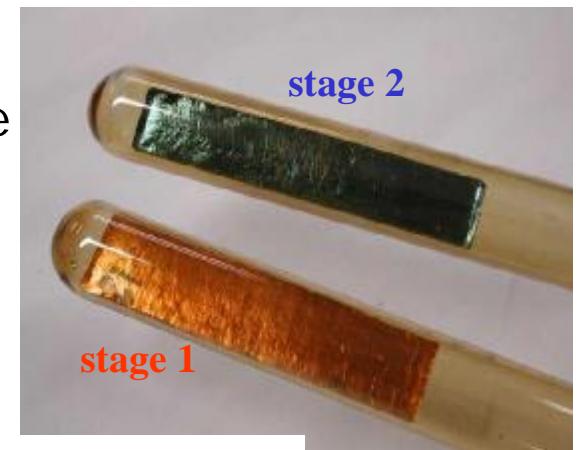
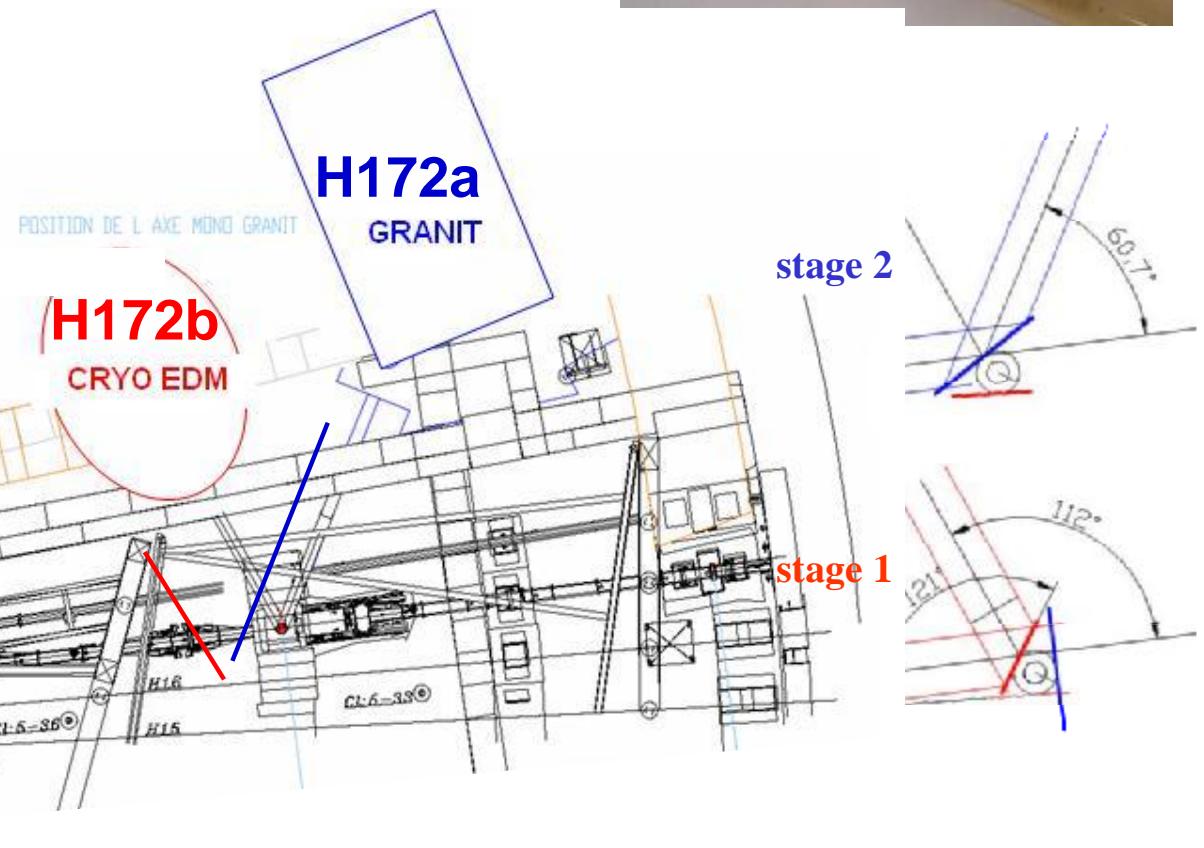
Implementation of 2 He-II UCN sources at H172

Two secondary 0.89 nm beams at H172:

- Bragg reflection from stage-I / -II intercalated graphite

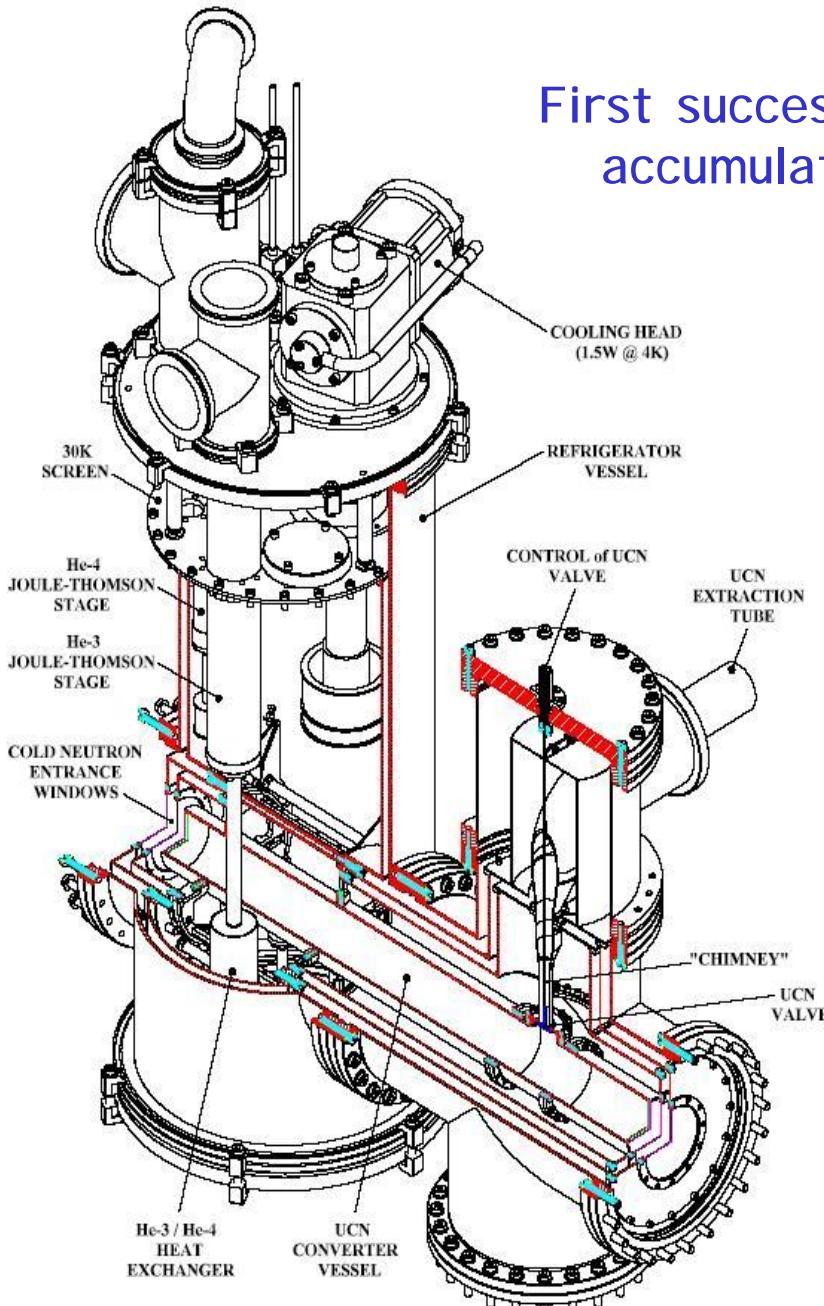


average flux (at mono.pos.)
 $3.9 \times 10^{10} \text{ n/cm}^2/\text{s}$

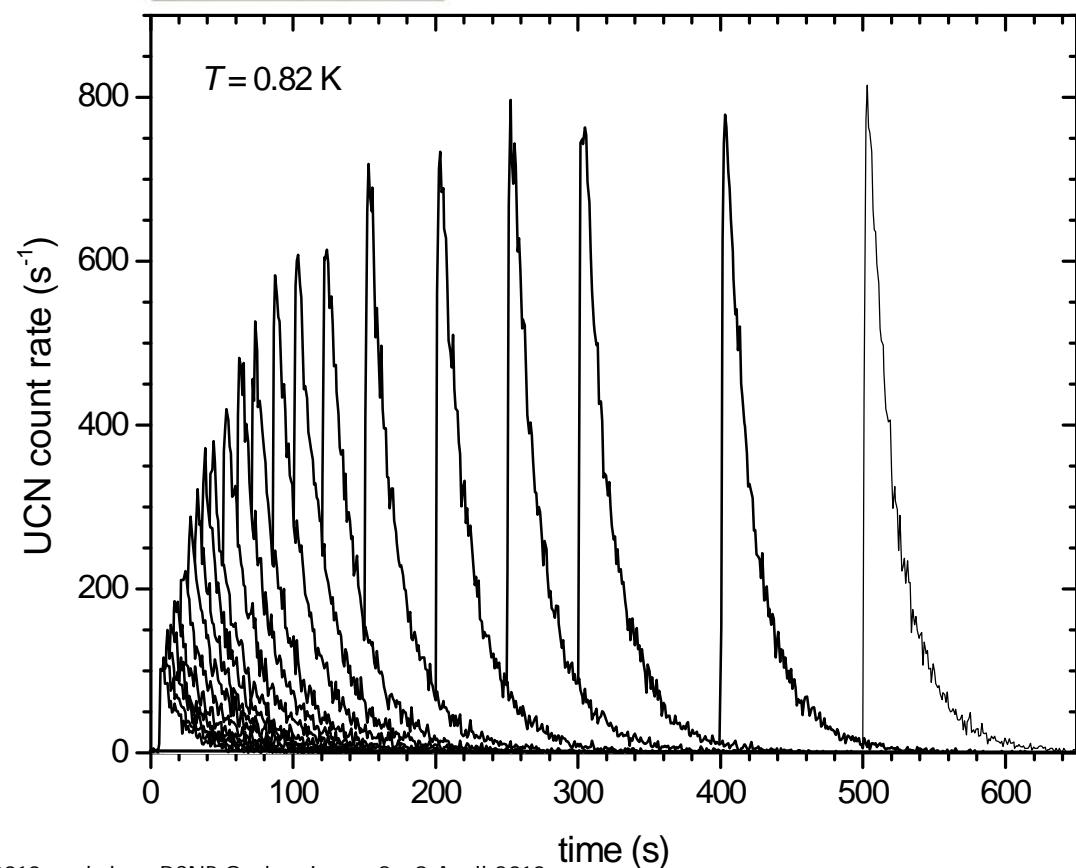


Prototype converter to be implemented at H172a

O. Zimmer *et al.*, Phys. Rev. Lett. 99 (2007) 104801

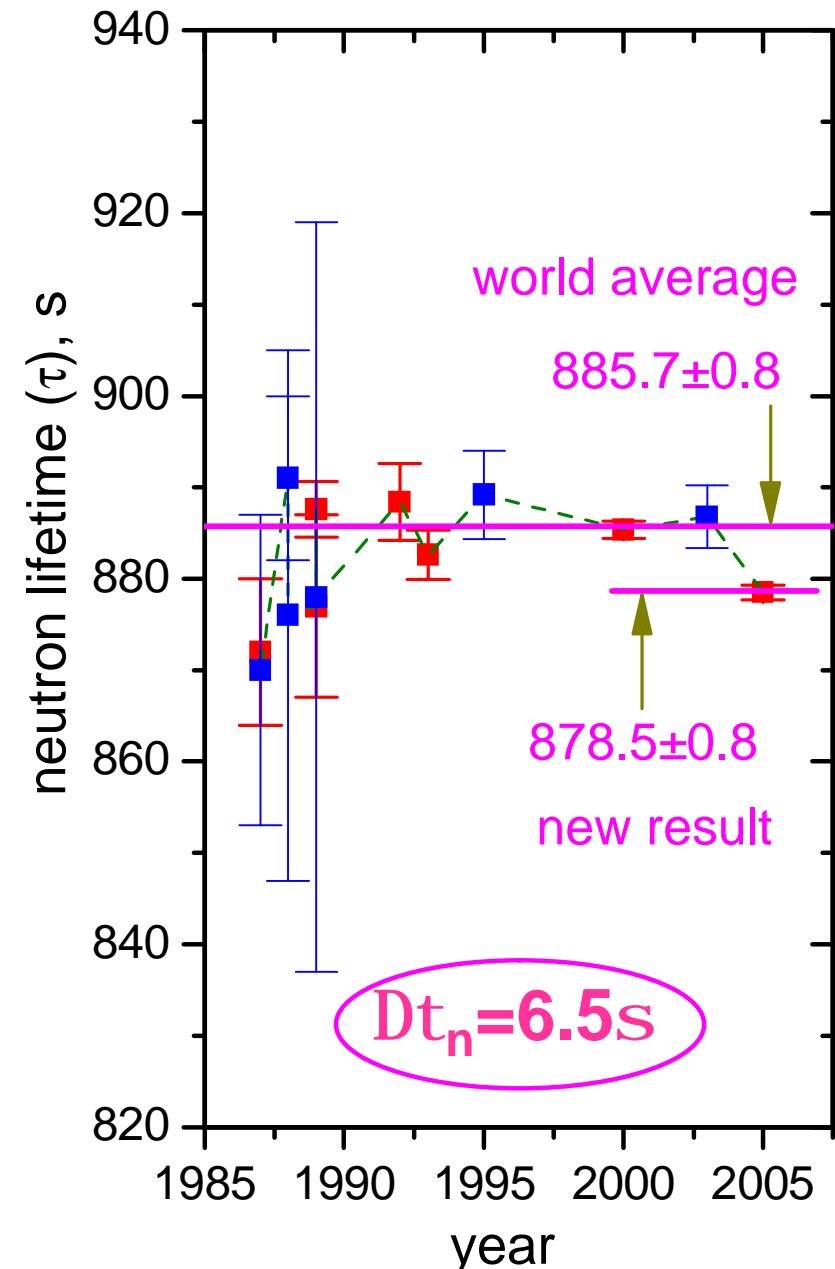


First successfull extraction of UCN
accumulated in superfluid helium



Neutron lifetime: world average and new result

Lifetime τ [s]	Method	Ref./Year
878.5 ± 0.8	Storage of ultra-cold neutrons	Serebrov et al. 2005
$878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{sys}}$		PLB 605(2005)72
886.8 ± 3.42	Neutron beam experiment	M.S. Dewey et al. 2003
885.4 ± 0.95	Storage of ultra-cold neutrons	S. Arzumanov et al. 2000
$885.4 \pm 0.9_{\text{stat}} \pm 0.4_{\text{sys}}$		PLB 483(2000)15
889.2 ± 4.8	Neutron beam experiment	J. Byrne et al. 1995
882.6 ± 2.7	Storage of ultra-cold neutrons	W. Mampe et al. 1993
$888.4 \pm 3.1 \pm 1.1$	Storage of ultra-cold neutrons	V. Nesvizhevski et al. 1992
$878 \pm 27 \pm 14$	Neutron beam experiment	R. Kosakowski 1989
887.6 ± 3.0	Storage of ultra-cold neutrons	W. Mampe et al. 1989
877 ± 10	Storage of ultra-cold neutrons	W. Paul et al. 1989
$876 \pm 10 \pm 19$	Neutron beam experiment	J. Last et al. 1988
891 ± 9	Neutron beam experiment	P. Spivac et al. 1988
872 ± 8	Storage of ultra-cold neutrons	A. Serebrov et al. 1987
870 ± 17	Neutron beam experiment	M. Arnold et al. 1987
903 ± 13	Storage of ultra-cold neutrons	Y.Y. Kosvintsev et al. 1986
875 ± 95	Storage of ultra-cold neutrons	Y.Y. Kosvintsev et al. 1980
937 ± 18	Neutron beam experiment	J. Byrne et al. 1980
881 ± 8	Neutron beam experiment	L. Bondarenko et al. 1978
918 ± 14	Neutron beam experiment	C.J. Christensen et al. 1972
885.7 ± 0.8	world average 2004	PDG 2004



Proton counting experiments at KI in Moscow

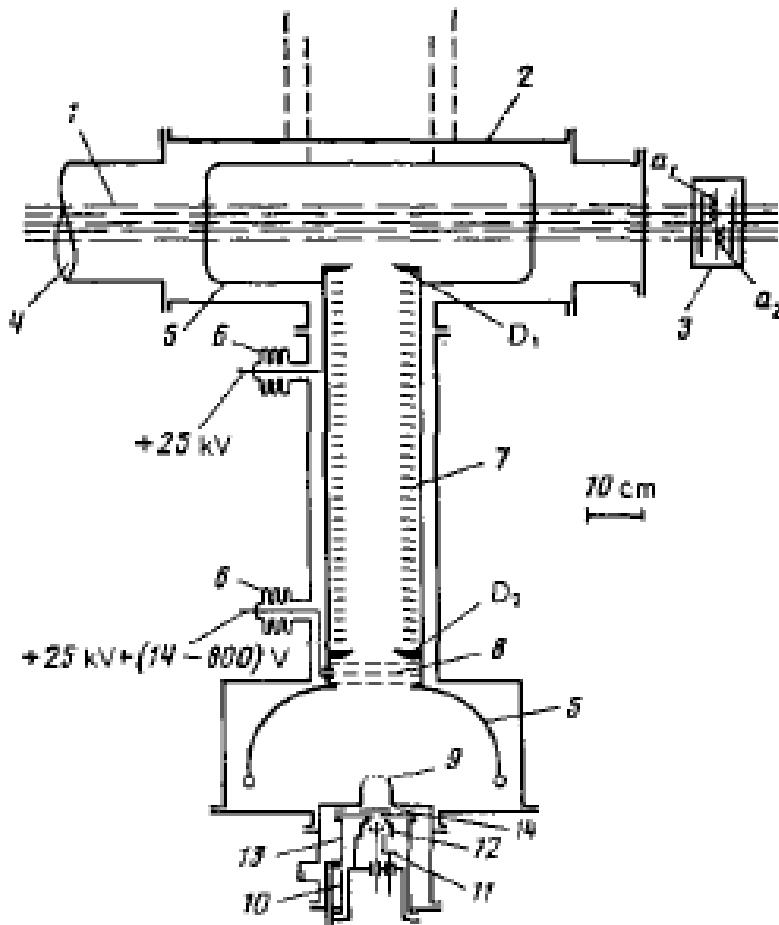


Figure 8. The IAE neutron lifetime experiment counting decay protons [13, 20]. 1, neutron beam; 2, vacuum chamber; 3, monitor chamber (a_1 and a_2 are ^{233}U layers); 4, channel for passage of extracted neutron beam to a trap and to a vacuum post; 5, electrodes; 6, ceramic insulators; D_1 , D_2 , diaphragms; 7, aluminium-foil rings; 8, electrostatic filter grids; 9, hemispherical grid; 10, detector vacuum chamber; 11, detector gas-filled volume; 12, detector comprising a proportional counter with a drift grid; 13, film-covered detector port; 14, valve separating the volumes of chambers 2 and 10.

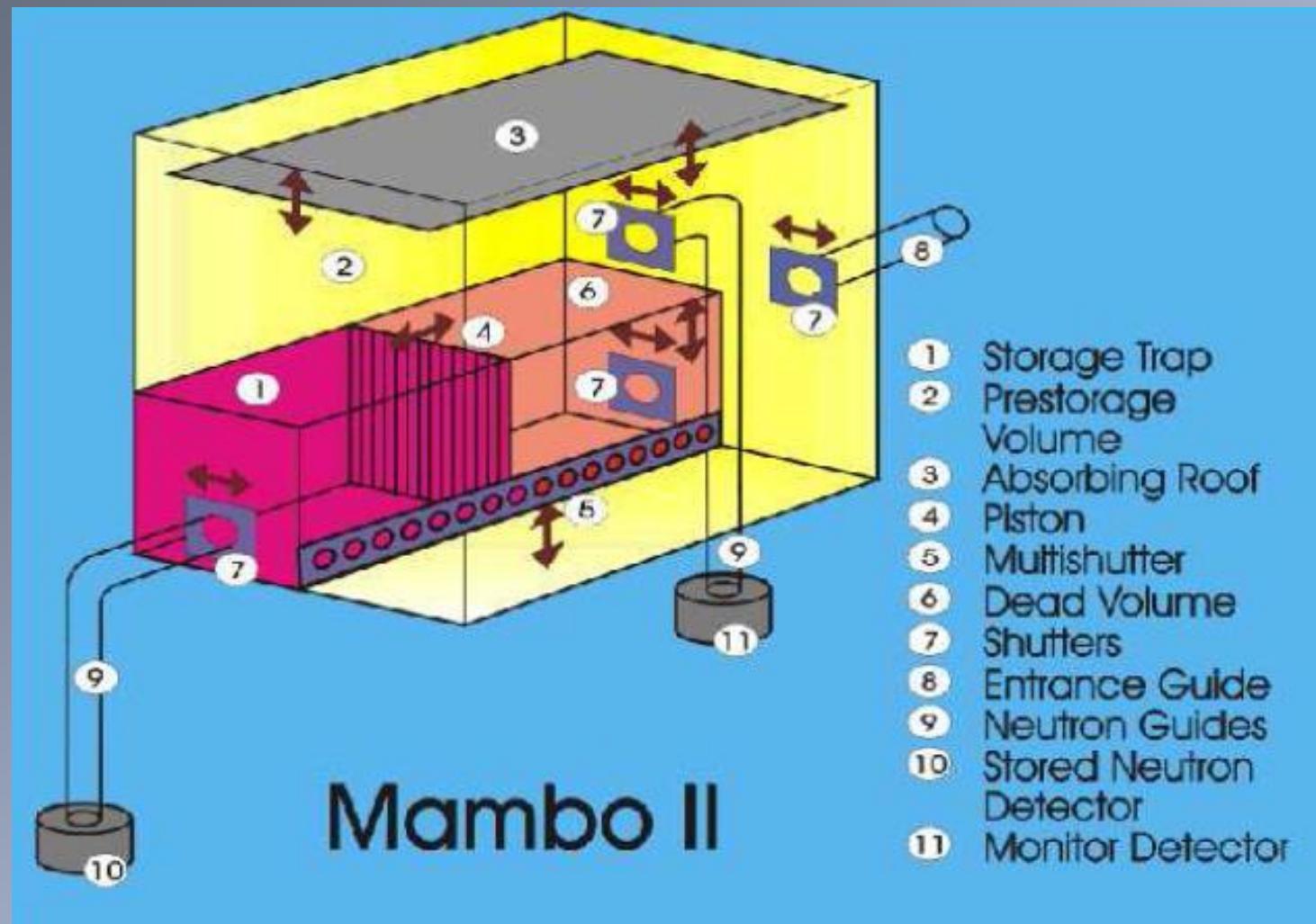
First version in 1958: $T_n = 1013$ (26) s

1978 result: $T_n = 877$ (11) s

In 1988 slightly revised: $T_n = 891$ (9) s

In 1980 Byrne et al. found $T_n = 937$ (18) s [withdrawn in the meantime]. They concluded in a Letter to Nature 310, 212 (1984)
“... a third direct measurement has given the value $T_n = 877$ (11) s, which is totally at variance with all other evidence. We suggest here that ... exclude values of T_n outside the range 911 (10) ...”

2nd generation storage experiment at ILL - MamBo II



A. Pichlmaier (now at TUEV)
 PhD thesis, unpublished
 TUM/ILL/PNPI collaboration

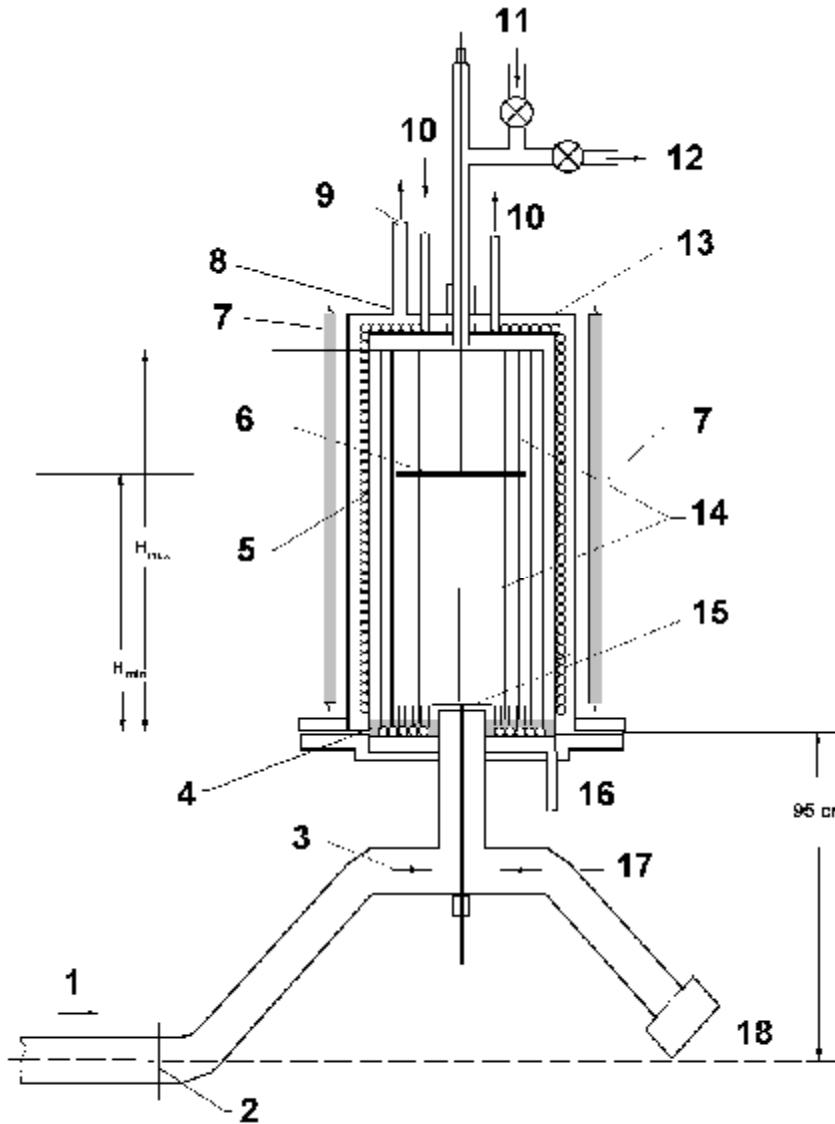
numerous experimental parameters checked!

Preliminary result
 $T_n = (881 \pm 3) \text{ s}$

Collaboration is working on a paper on this result!

Presented method consists of

- storage of ultracold neutrons (**UCN**) with
- concurrent monitoring of UCN losses by registration of inelastic scattered neutrons,
- has guarantee of storage of **weak heated UCN** (the stored UCN spectrum is lower than E_{lim} : $E_{\text{max}} \leq 0.5E_{\text{lim}}$ and main part of weakly heated neutrons has $E_{\text{wh}} \leq 2 E_{\text{max}}$)
- storage under **low temperature** $T=-40^{\circ}\text{C}$ that allows achieve **$h @ 4\text{-}6 \cdot 10^6$**



Experimental installation has

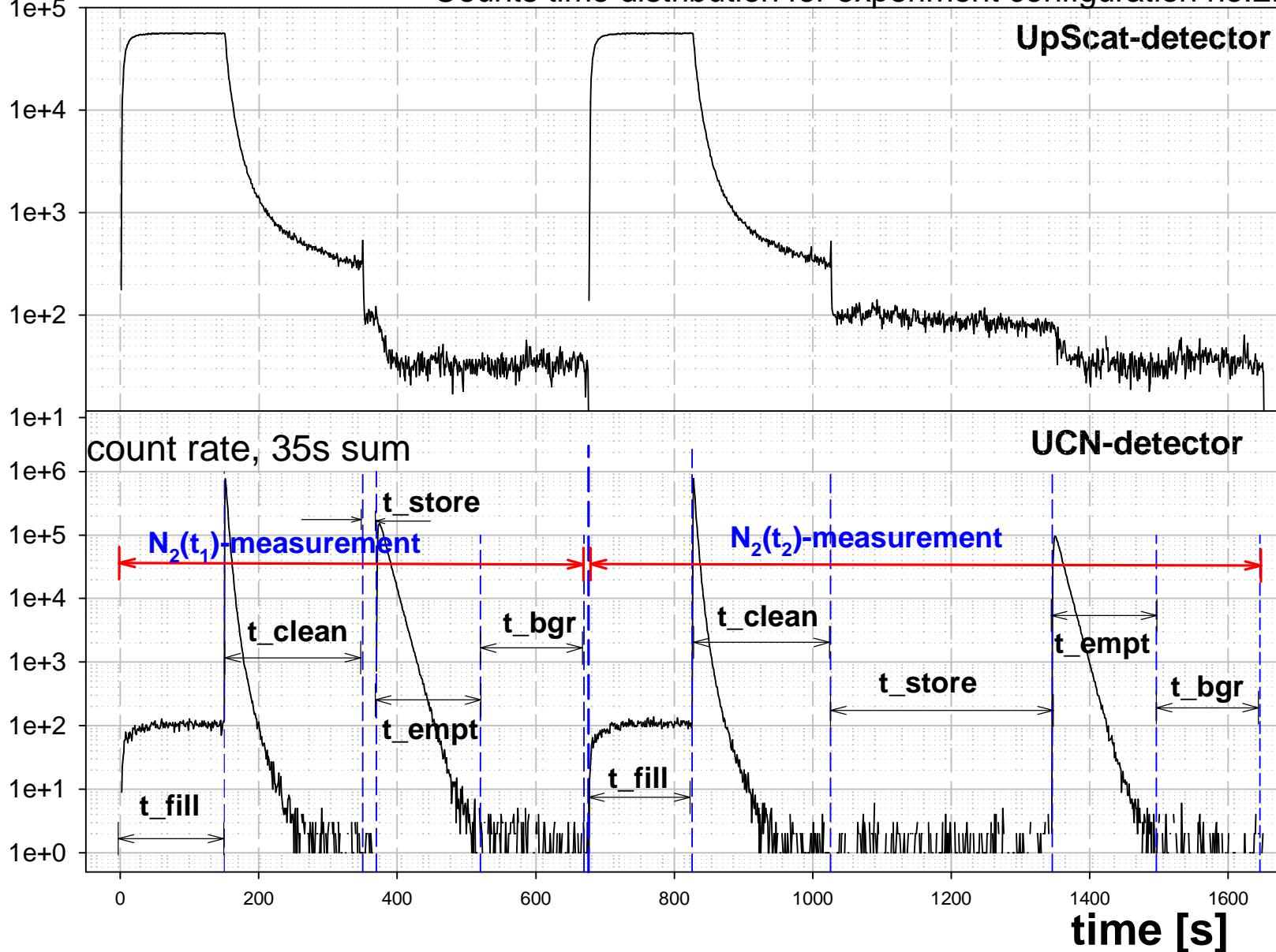
- **detector** to register amount of stored **UCN** (18),
 - 26 **thermal neutron counters** to measure flux of **up-scattered neutrons** (7),
 - **cooling system** that allows to support the temperature of storage vessel in the range $-50 \div 25^{\circ}\text{C}$ with precision of $\pm 0.5^{\circ}\text{C}$ (10),
 - **two** separated vacuum systems (9,16),
 - device to operate with **absorber** (6),
 - neutron guides with a set of UCN **shutters** (3,15,17),
- Inner **surface** of storage vessel and **additional surface** will be coated by thin layer of fluorine polymer **YL VAC18/8**.

At temperature -40°C the polymer layer remains entire, parameter **h** is about $5\text{-}8 \times 10^{-6}$ and weak heating is lower than $2 \cdot 10^{-6}$ per one collision.

count rate, 35s sum

Counts time distribution for experiment configuration no.2.

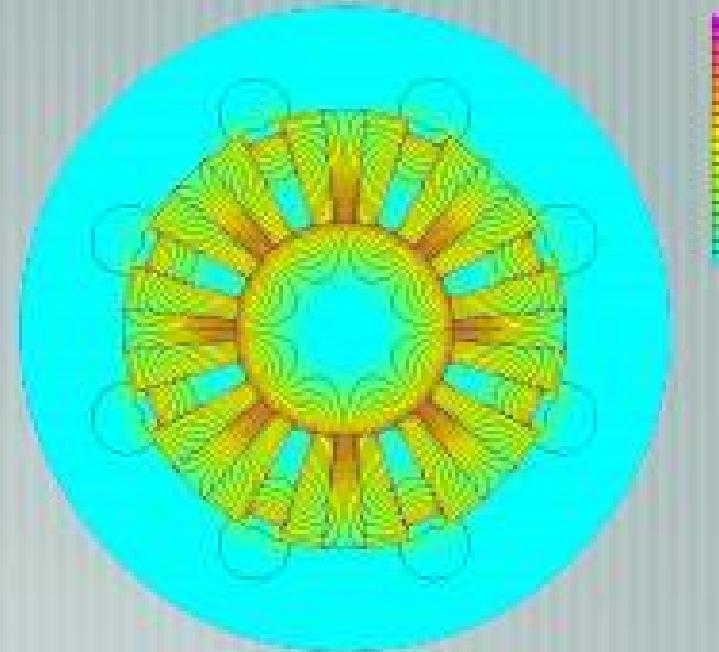
UpScat-detector



$$I = \frac{1}{t} \ln \frac{N(0)}{N(t)} = I_b + I_l$$

Correction	τ_β [s]	Correction values [s]	Standard deviation [s]
Uncorrected value (at room temperature)	885.69		± 2.02
UCN c/rate loss		-1.1 \pm 0.2	
Emptying correction		-3.0 \pm 0.3	
Up-scattered neutron detector efficiency (calculations)		0 \pm 0.8	
Residual gas influence on λ_{ie}		-0.1 \pm 0.3	
UCN leakage under the input valve of storage vessel		< 0.03	
Total		-4.20 \pm 0.23	
preliminary neutron lifetime	881.49		± 2.5

Halbach Octupole Permanent (NdFeB) magnets: 1.3 T at surface.



Inner bore diameter 9cm, each segment 10cm, 12 segments => 1.2 m long trap. $V_{\text{physical}} = 8L$. $V_{\text{effective}} = \text{quadrupole with } 1.8x \text{ field strength}$

Mutual repulsive force of 1 Ton

K. Leung, K. Fraval, O. Roberts, O. Zimmer

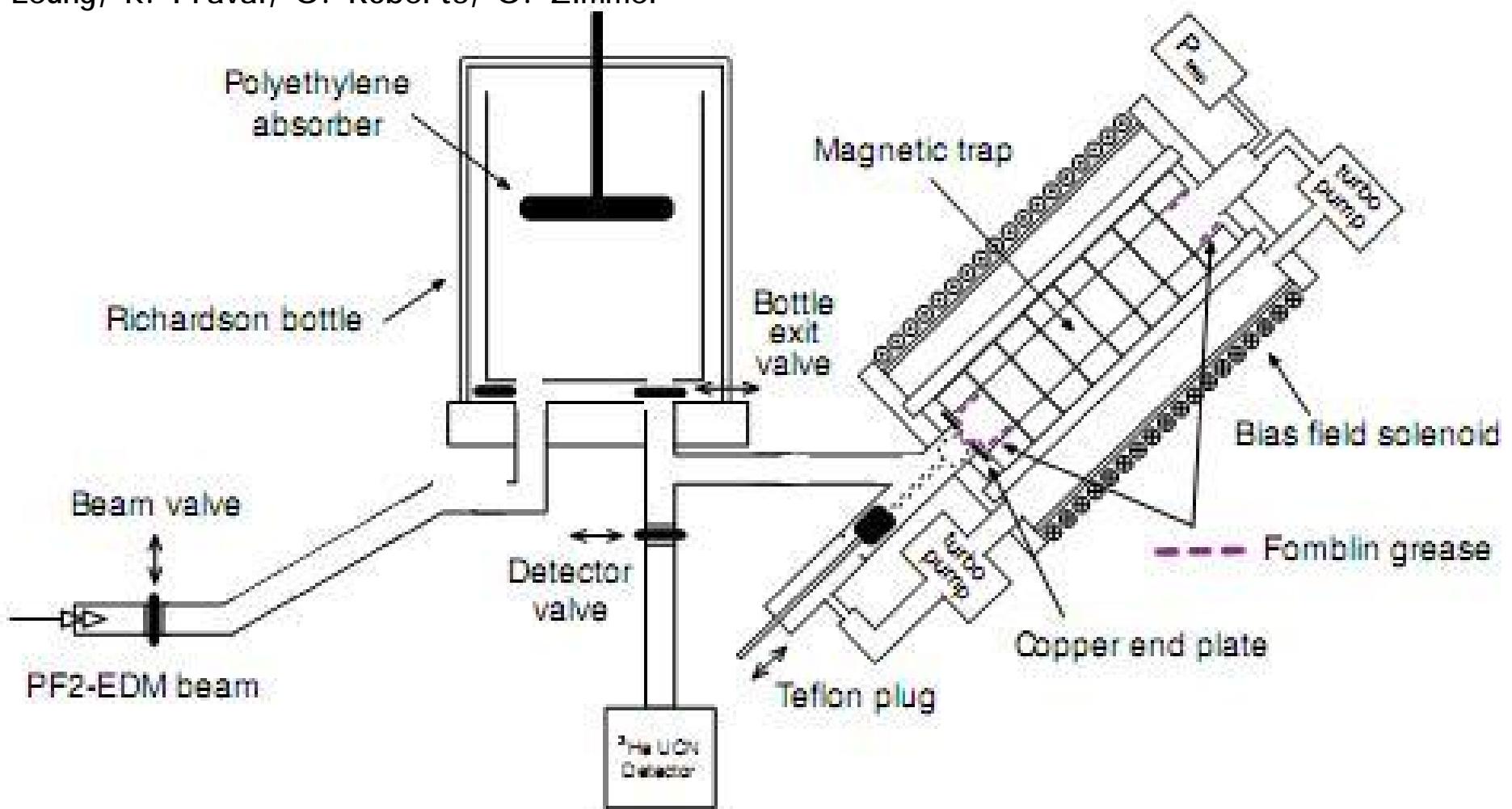
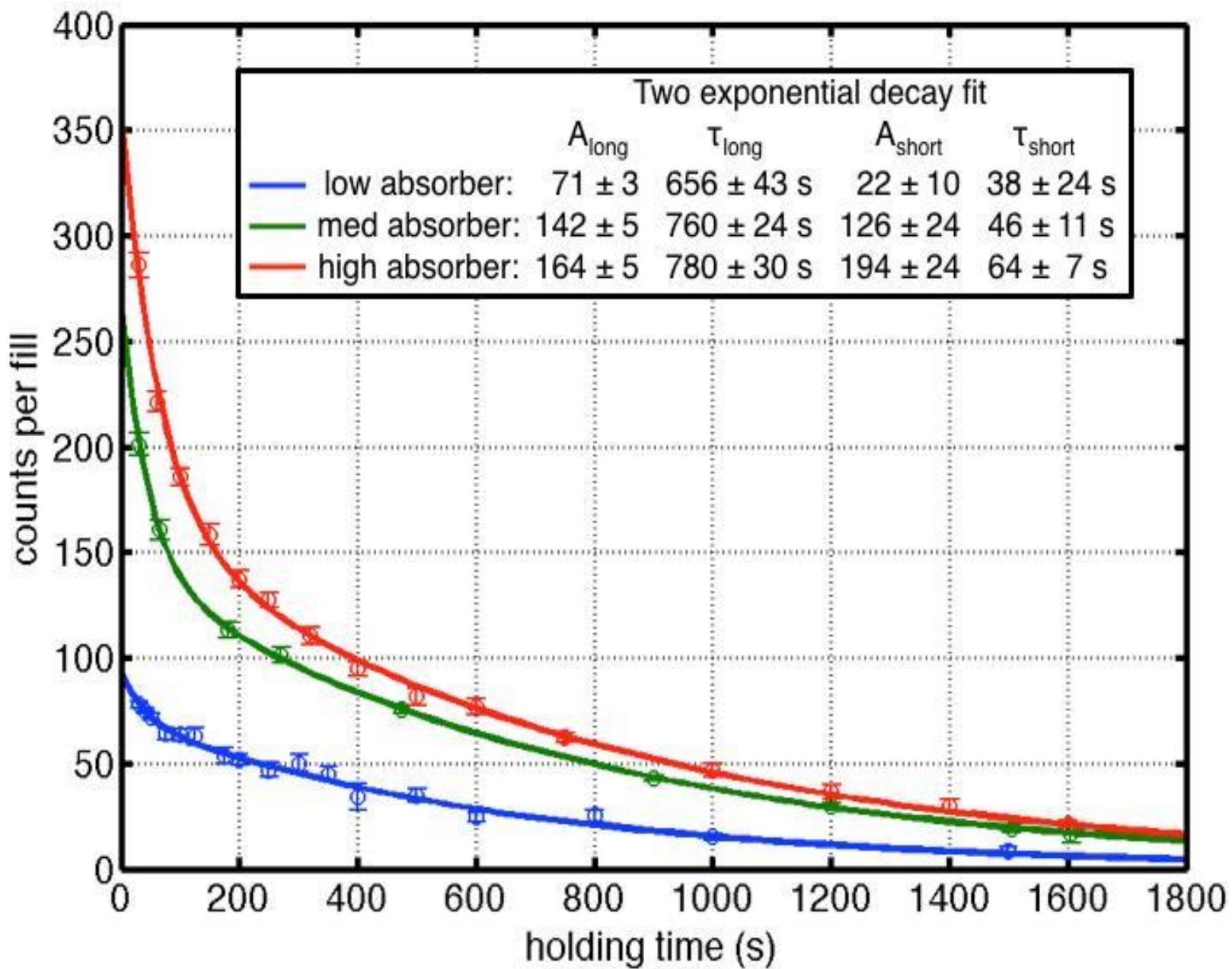


Figure 1: Schematic of experimental setup. See text for more details. Double-ended arrows (↔) indicate movable plugs or valves. Fomblin grease was used on the inside of the Richardson bottle as well but is not shown.





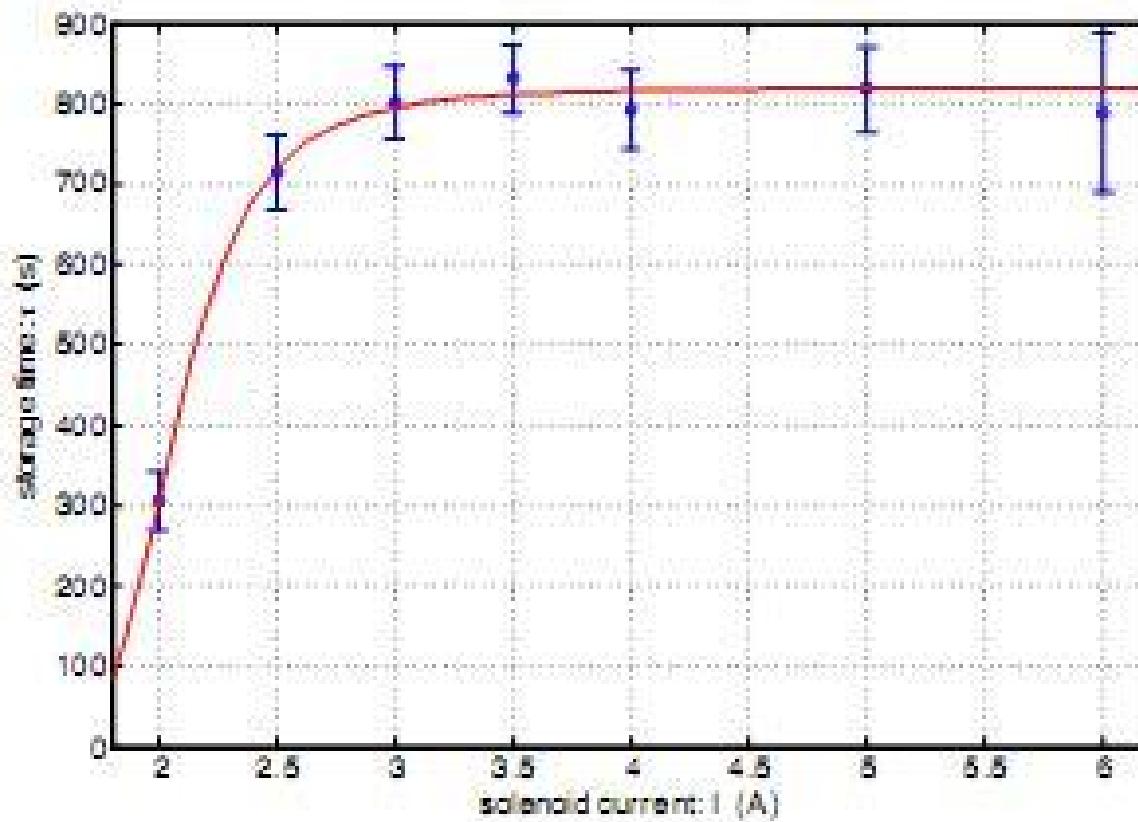
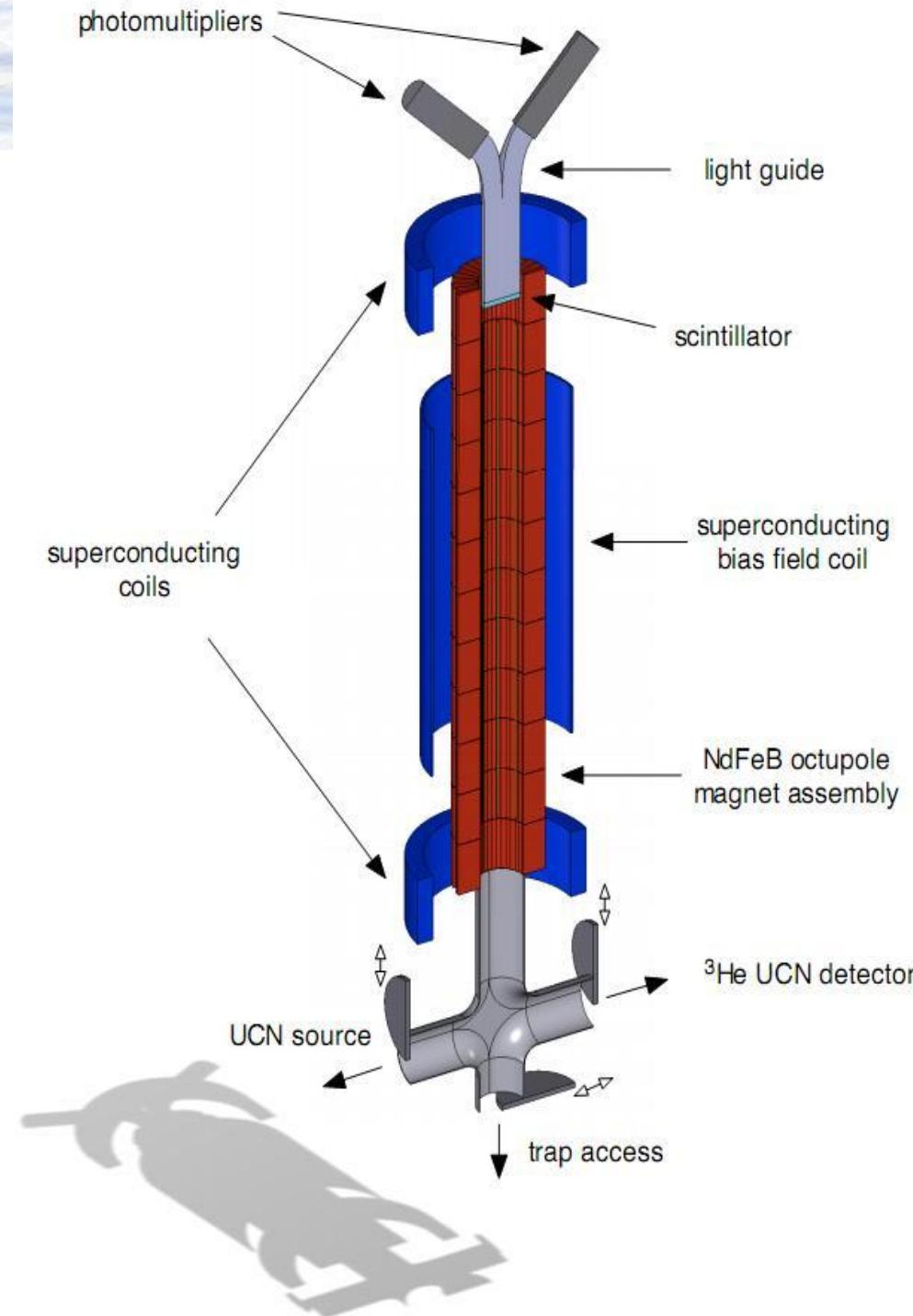
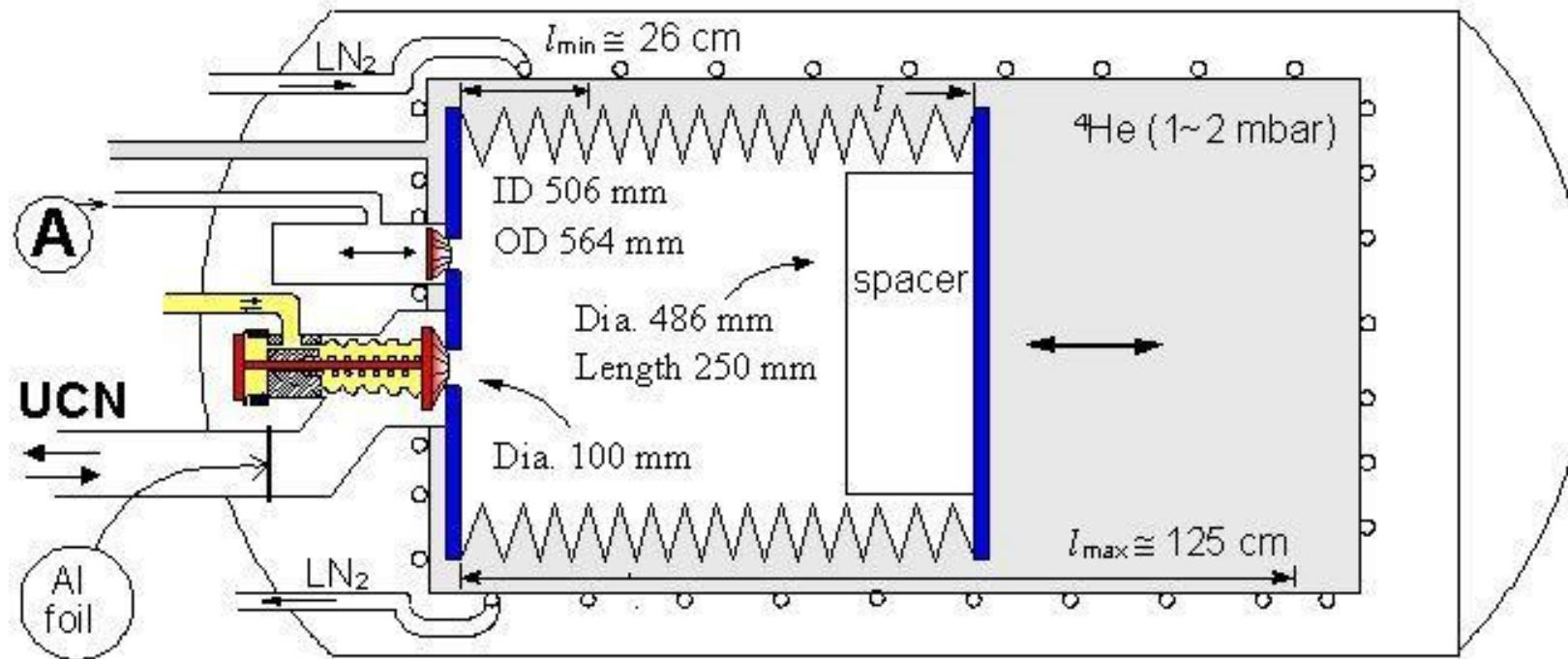


Figure 3: Changes in the storage time of the magnetic trap with different bias solenoid current. Saturation occurs at around 3.0 – 3.5 A. The red line, a fit with the analytic function $[1/\tau_1 + 1/(\tau_2(I - I_0)^4)]^{-1}$, is there for visual purposes only.



An 'accordion-like' UCN storage system

A. Steyerl, A. Desai, S.S. Malik, B. Yerozilimski, W. Furman, V. Shvetsov, A. Strelkov, N. Achiwa, P.G.



- Features:**
- (a) Use a bellows with horizontal axis.
 - (b) Volume V variable within a large factor of ~ 10 .
 - (c) Surface area and its distribution over height are constant.
 - (d) Times for loading, holding, emptying are scaled $\sim V$
 \Rightarrow Spectral development is the same for different V
 - (e) Provide up-down symmetry and ensure that all UCN have enough energy to reach roof \Rightarrow cut spectrum from below

“Lifetime Conclusion” of Boris Yeruzolimsky:

*“If you try to improve the t_n -value to the level $\sim 10^{-3}$ or better
you will run against a brick wall of exponentially growing problems.”*

Thank you for your attention ...

