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The New Ultracold Neutron Source at PSI

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on behalf of the PSI UCN Project Team

Paul-Scherrer-Institut, Villigen, Switzerland

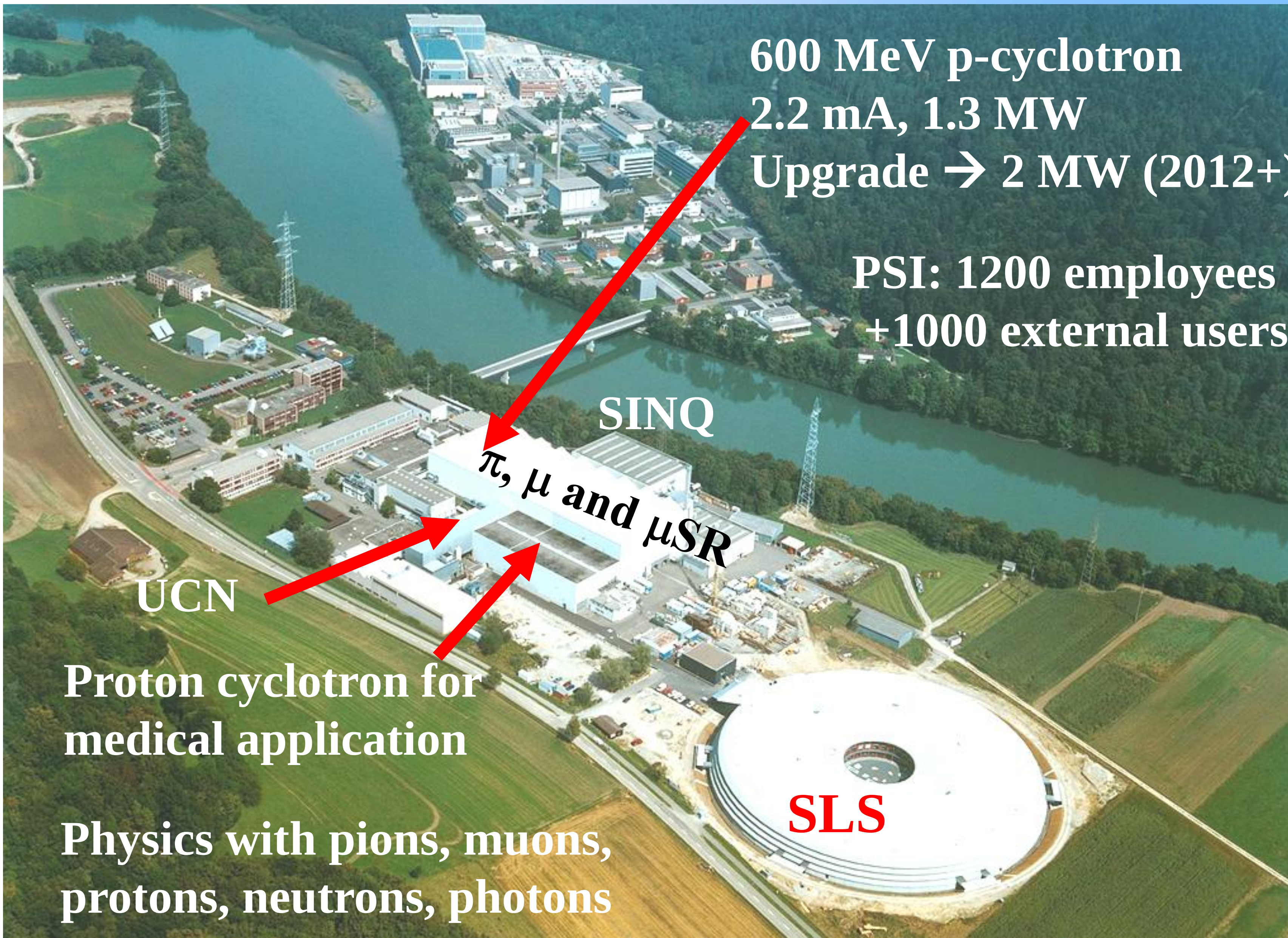
presented at ISINN20, Alushta, Ukraine, May 21, 2012

Outline

- PSI, Paul-Scherrer-Institut
- Ultracold Neutrons
- The facility and the essential components
- First performance results
- Summary and Outlook

Switzerland - Ukraine

Paul-Scherrer-Institut, PSI



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Ultracold Neutrons and nEDM

Ultra Cold Neutron Source

Permanent electric dipole moments (EDM) can contribute to resolve some physical observations which are not understood in the frame of the Standard Model of Particle Physics, e.g. the baryon asymmetry in the universe.

At PSI we started in 1997 to think about the possible improvement of sensitivity of the nEDM.

The ansatz is
1) to build a new UCN source with highest UCN density, a factor ~50 higher than the current best facility at the ILL, the Institue Laue-Langevin in Grenoble, France.
2) to perform an improved nEDM search in vacuum and at room temperature

Boltzmann and De Broglie

$$E_{\text{kin}} = \frac{mv^2}{2} = \frac{3}{2}kT \qquad \lambda = \frac{h}{m \cdot v}$$

e.g. air at 20 °C: ~400 m/s

neutrons	v	T	λ
thermal (25 meV)	2200 m/s	300 K	0.18 nm
cold (5 meV)	1000 m/s	60 K	0.4 nm
UCN (< 300 neV)	< 7 m/s	0.003 K	> 50 nm
		hence the name	

Neutrons with E_{kin} < 300 neV are storeable (E. Fermi, 1946)

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The new PSI UCN source

UCN Ultra Cold Neutron Source

Main components:

1) Proton beam: 600 MeV, 2.2 mA = 1.3 MW beam power

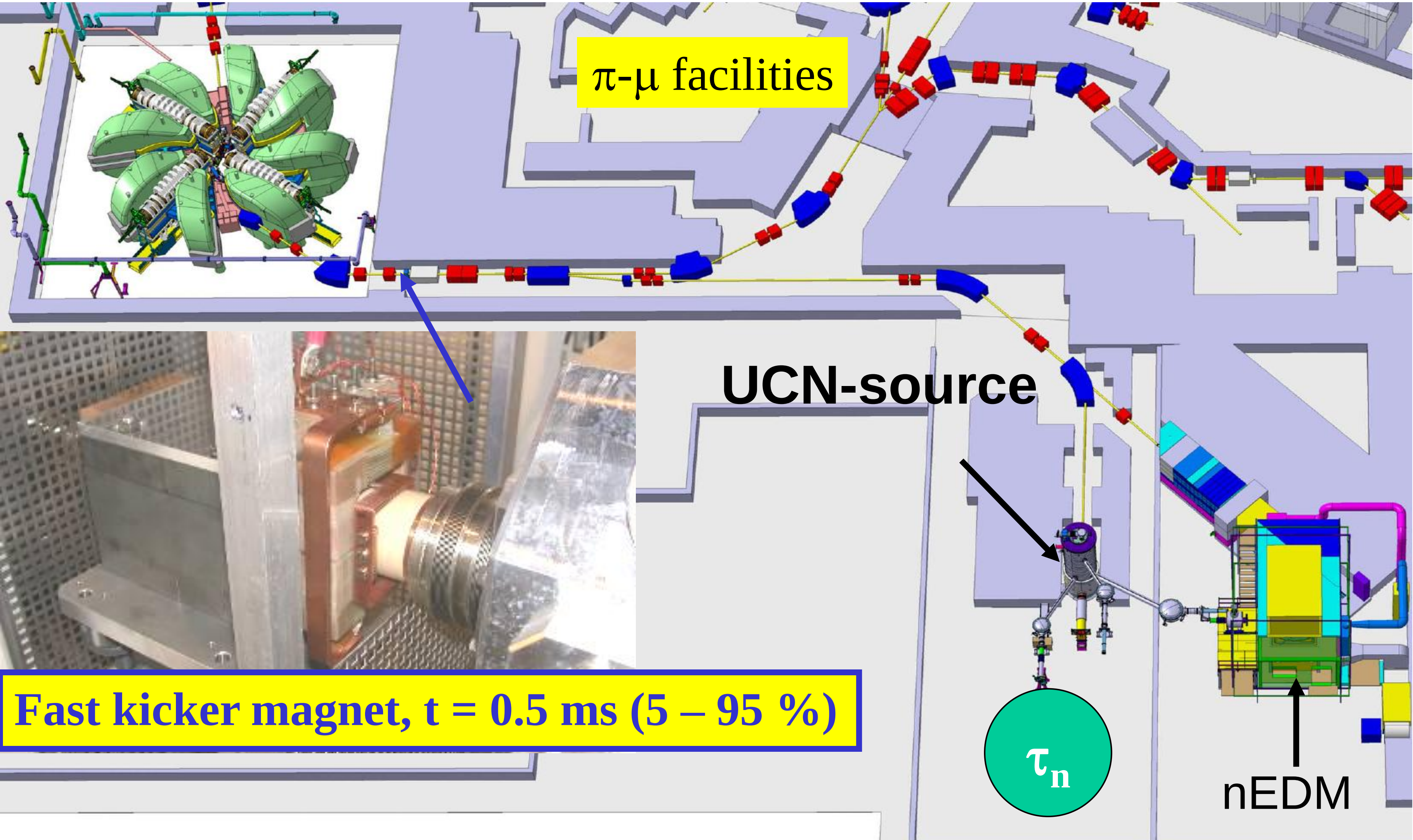
2) Neutron spallation target: Lead in circalloy tubes

3) Heavy water system for thermalisation of spallation neutrons

4) Solid deuterium for downscattering and neutron cooling

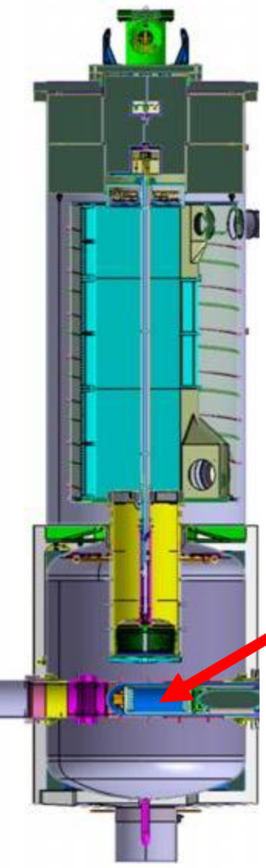
5) UCN storage volume and neutron guides.

Proton accelerator & UCN Source



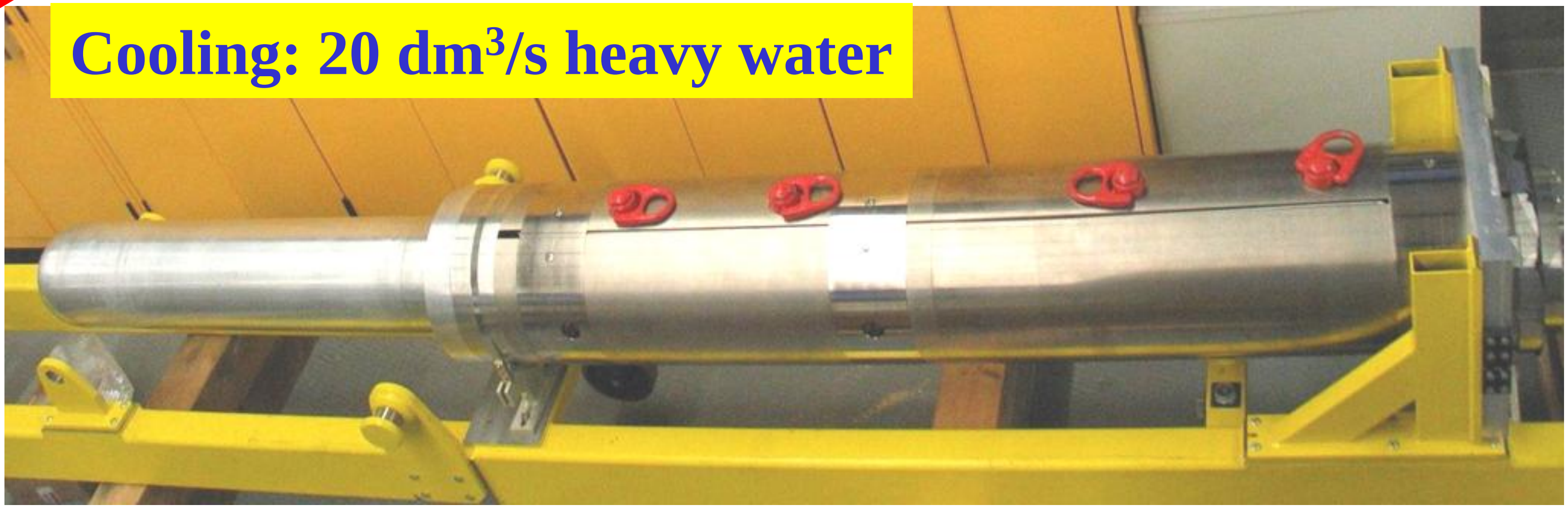
PSI proton cyclotron: 600 MeV, 2.2 mA → 1.3 MW (UNIQUE!)

The lead spallation target



Zr/Pb
~800 tubes

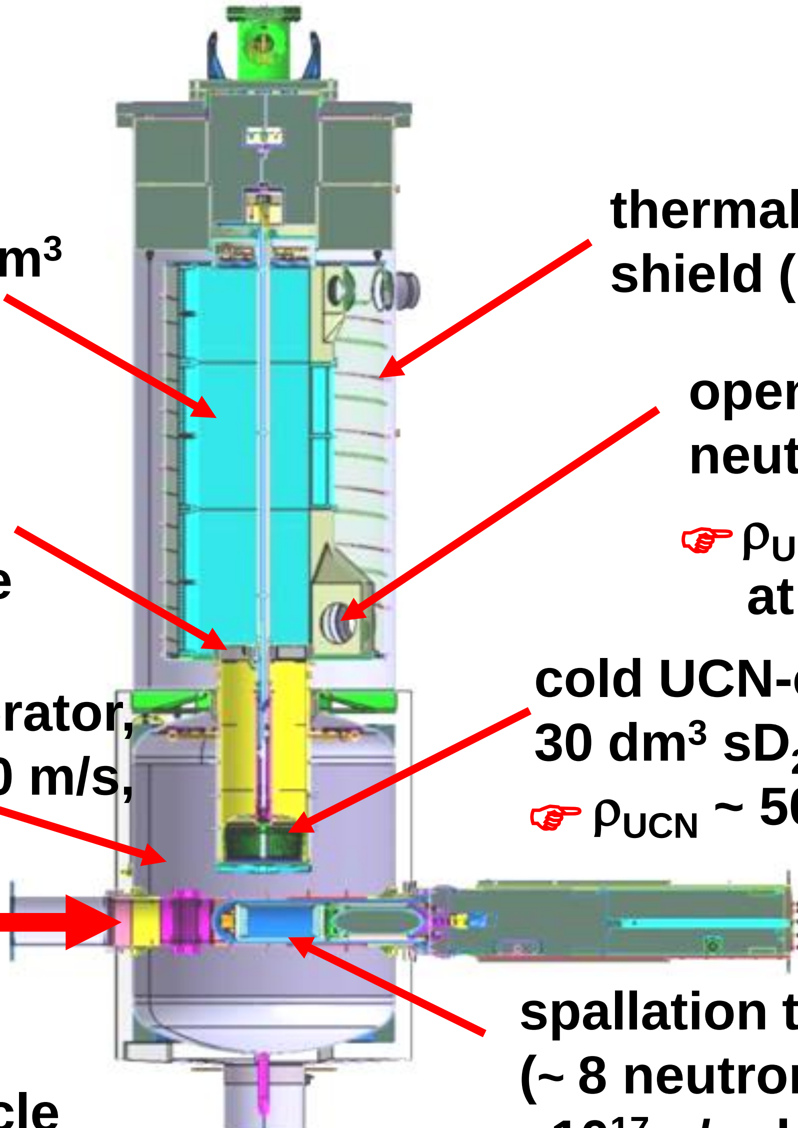
Cooling: 20 dm^3/s heavy water



Spallation process

UCN-Source

Ultra Cold Neutron Source



UCN storage volume,
height 2.5 m, volume 2 m^3
☞ ρ_{UCN} ~ 2000 cm^{-3}

thermal
shield (70K)

opening for
neutron guide
☞ ρ_{UCN} ~ 1000 cm^{-3}
at experiments

7 m

UCN shutter
verticle guide

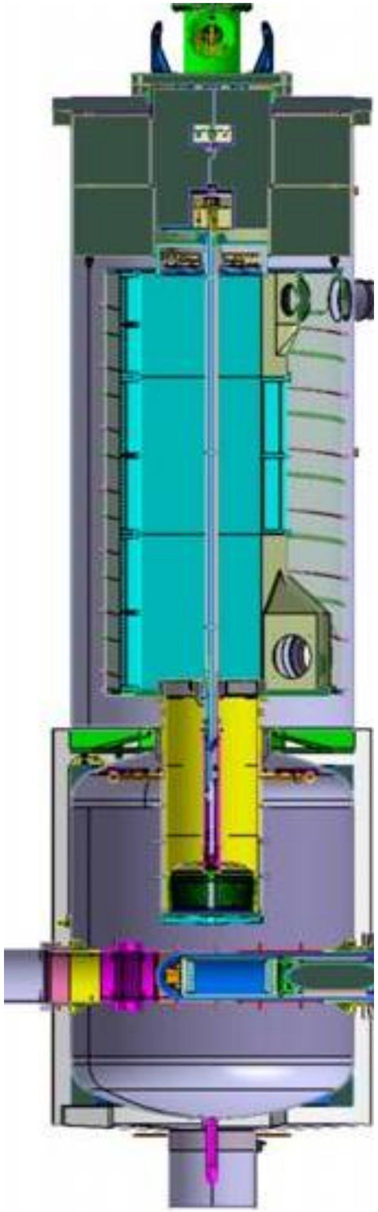
cold UCN-converter
30 dm^3 sD_2 at 5 K
☞ ρ_{UCN} ~ 5000 cm^{-3}

3.5 m^3 heavy water moderator,
thermal neutrons, v=2200 m/s,
neutrons travel ~10 m.

pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% macro duty cycle
(8 s every ~800 s)

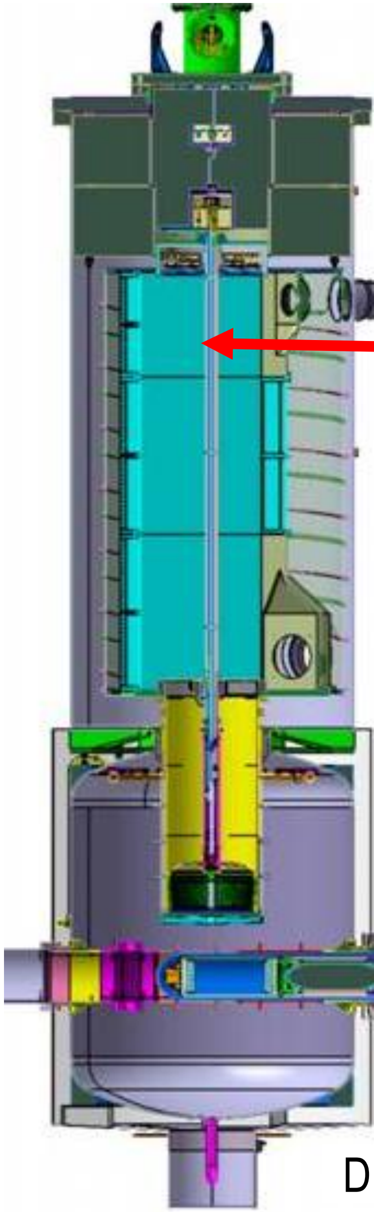
spallation target (Pb/Zr)
(~ 8 neutrons per proton,
~10^{17} n/pulse)

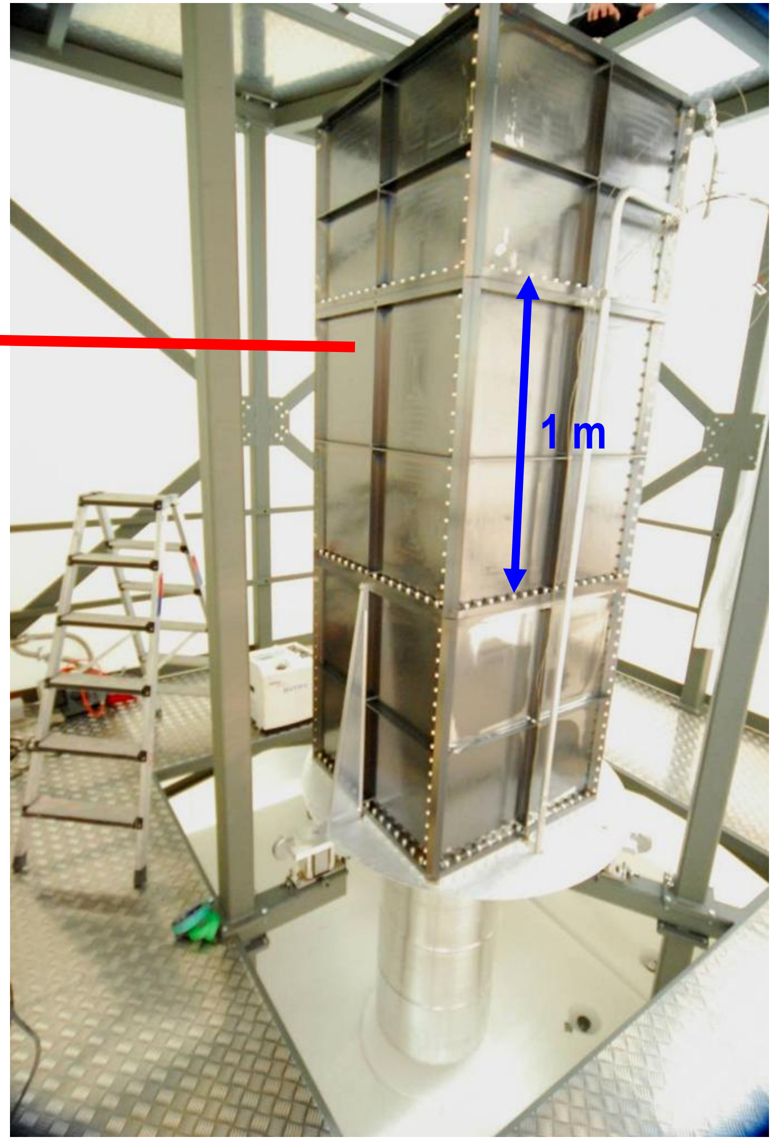
UCN Tank



Delivery of tank
Sept. 04, 2008

UCN storage volume





DLC coating storage volume in mounting rack storage volume & thermal shield

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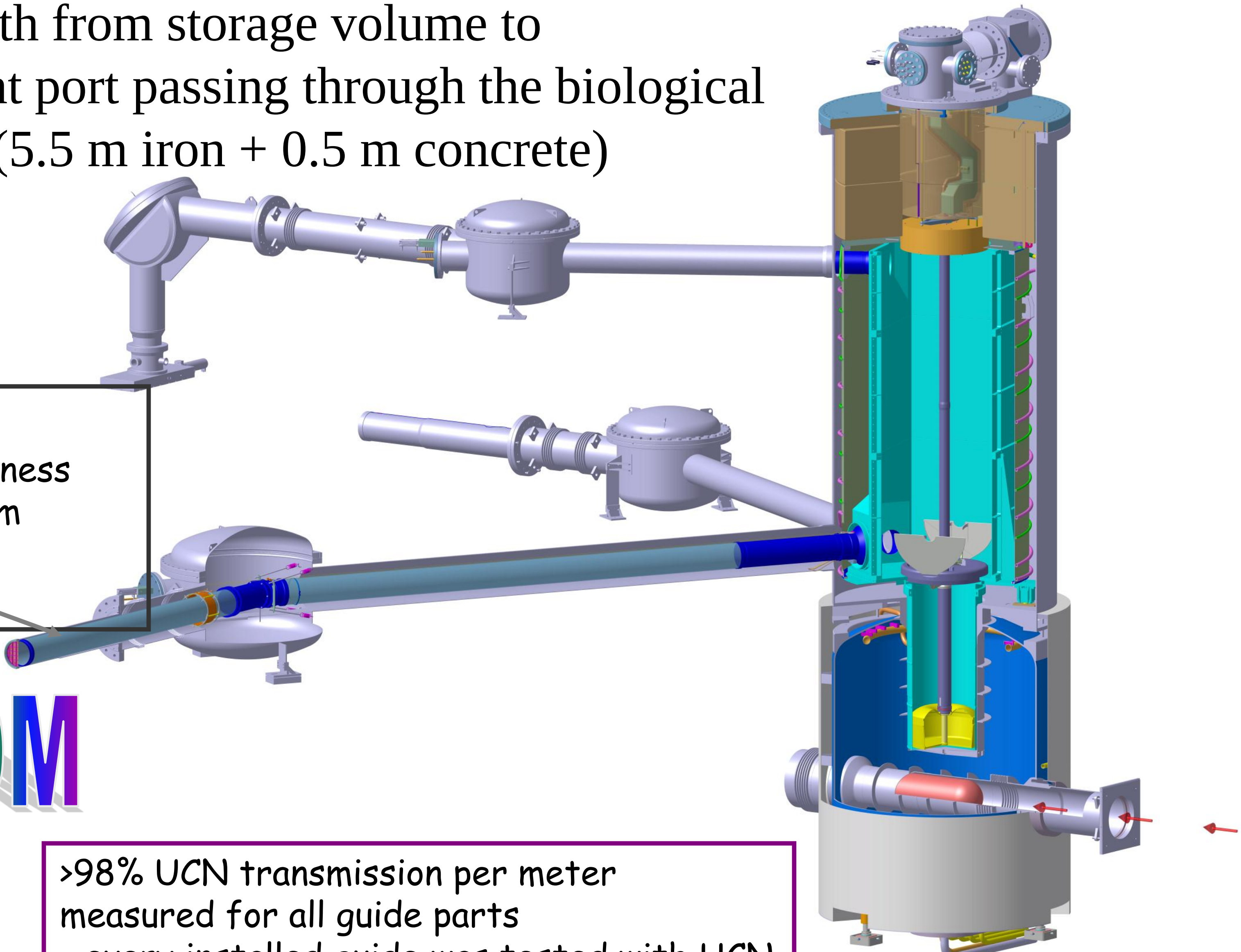
UCN guides

Ultra Cold Neutron Source

~8 m length from storage volume to experiment port passing through the biological shielding (5.5 m iron + 0.5 m concrete)



glass parts
- -surface roughness better than 1nm
- -coated with NiMo85/15

nEDM

>98% UCN transmission per meter measured for all guide parts
- every installed guide was tested with UCN

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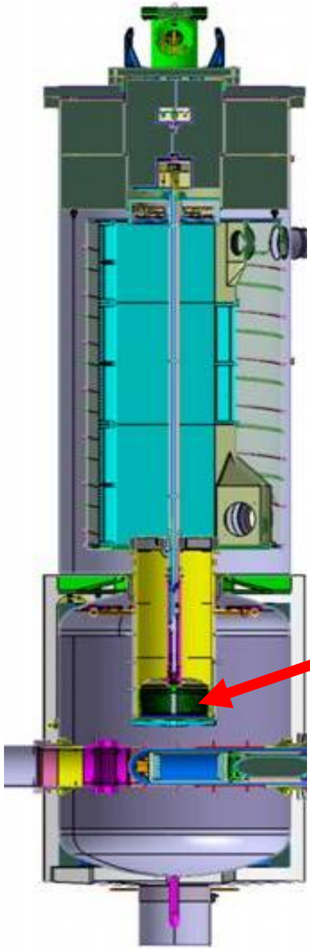
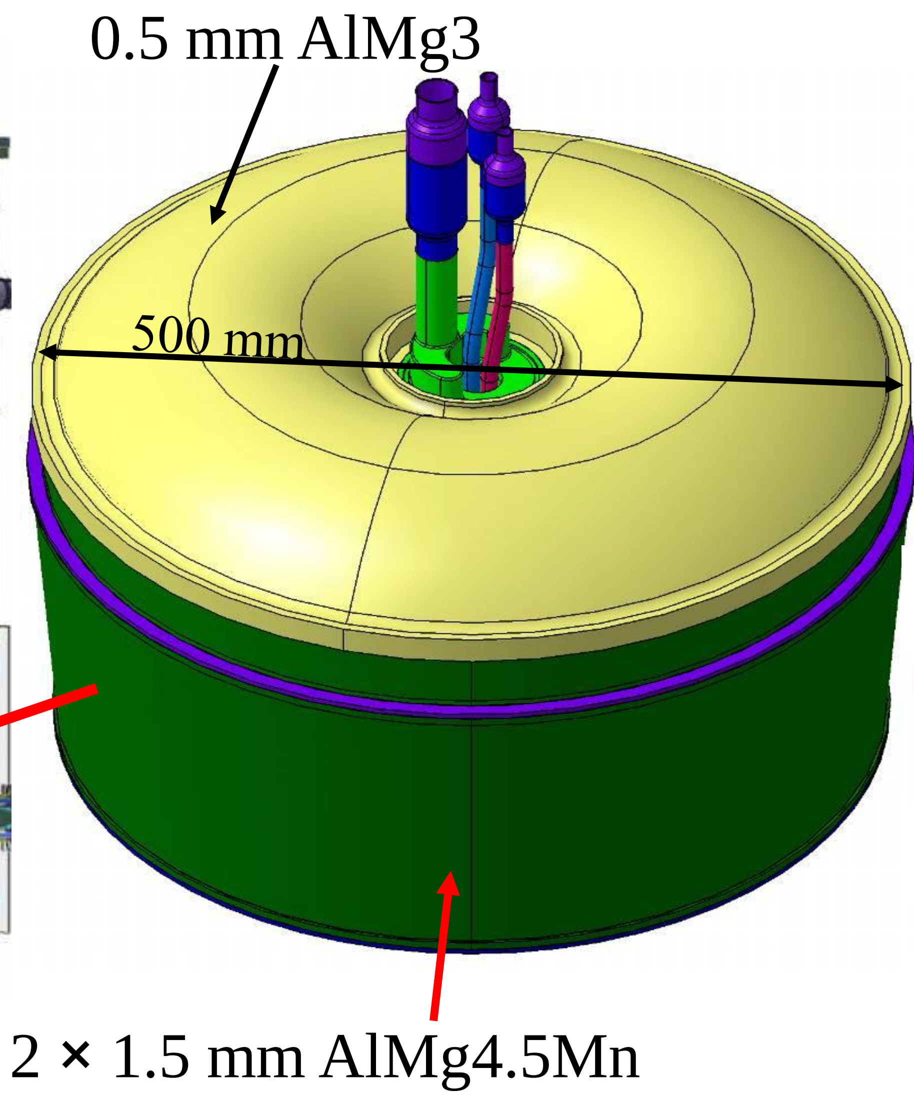
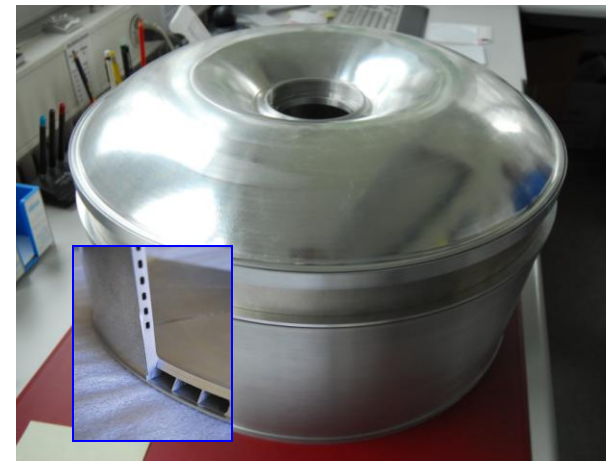
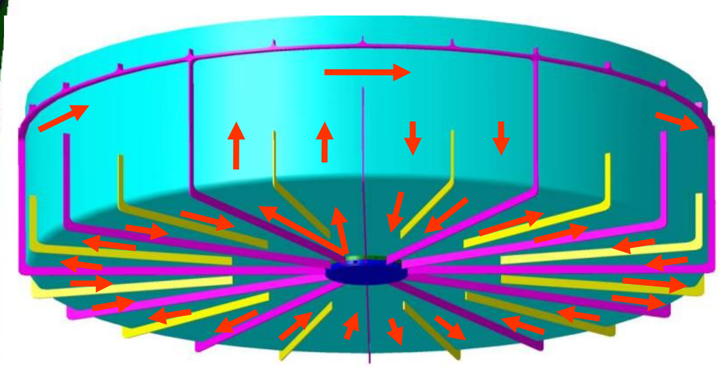
Solid Deuterium Vessel

Ultra Cold Neutron Source



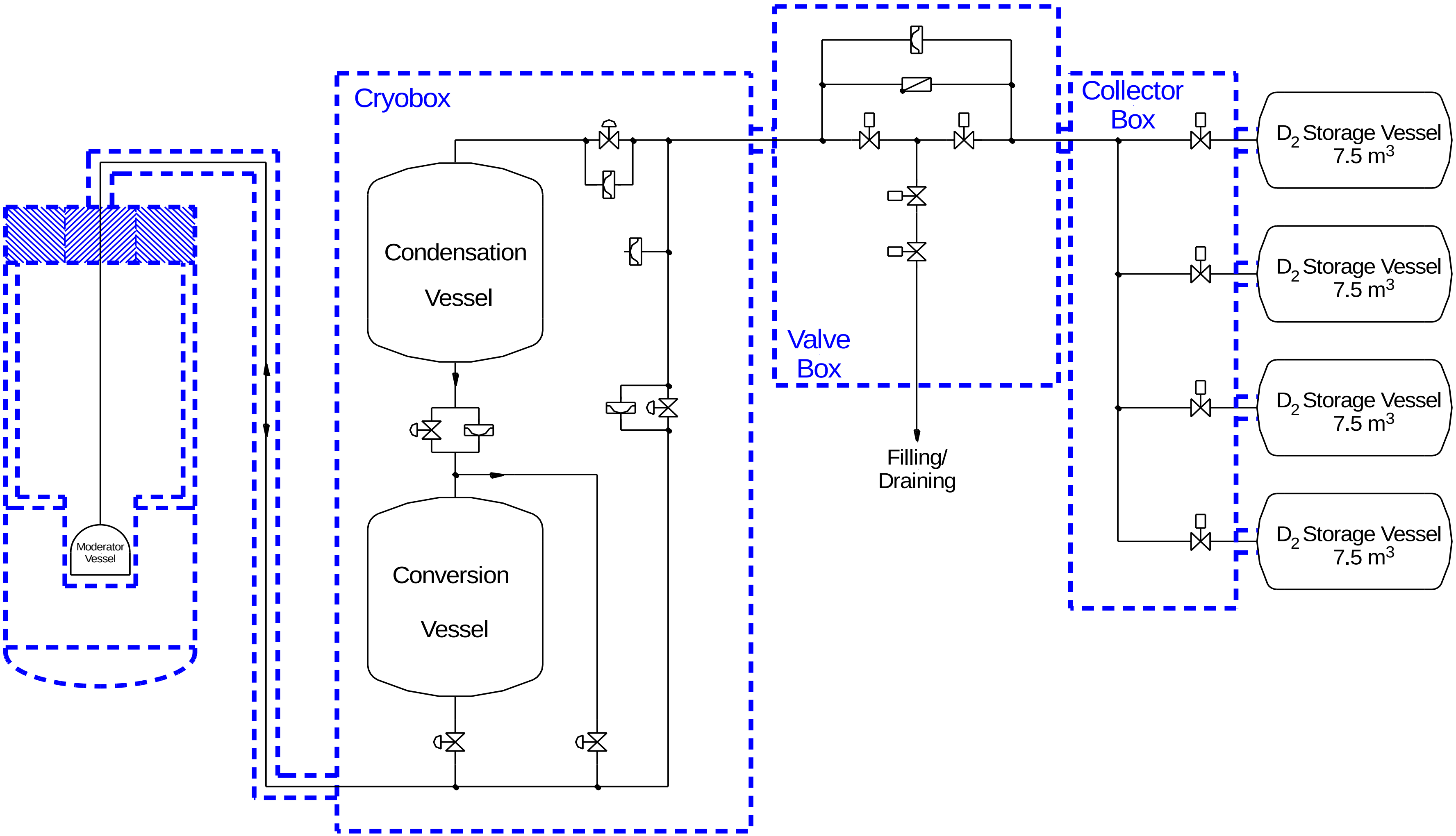






Cooling Agent:
Supercritical Helium

Deuterium System



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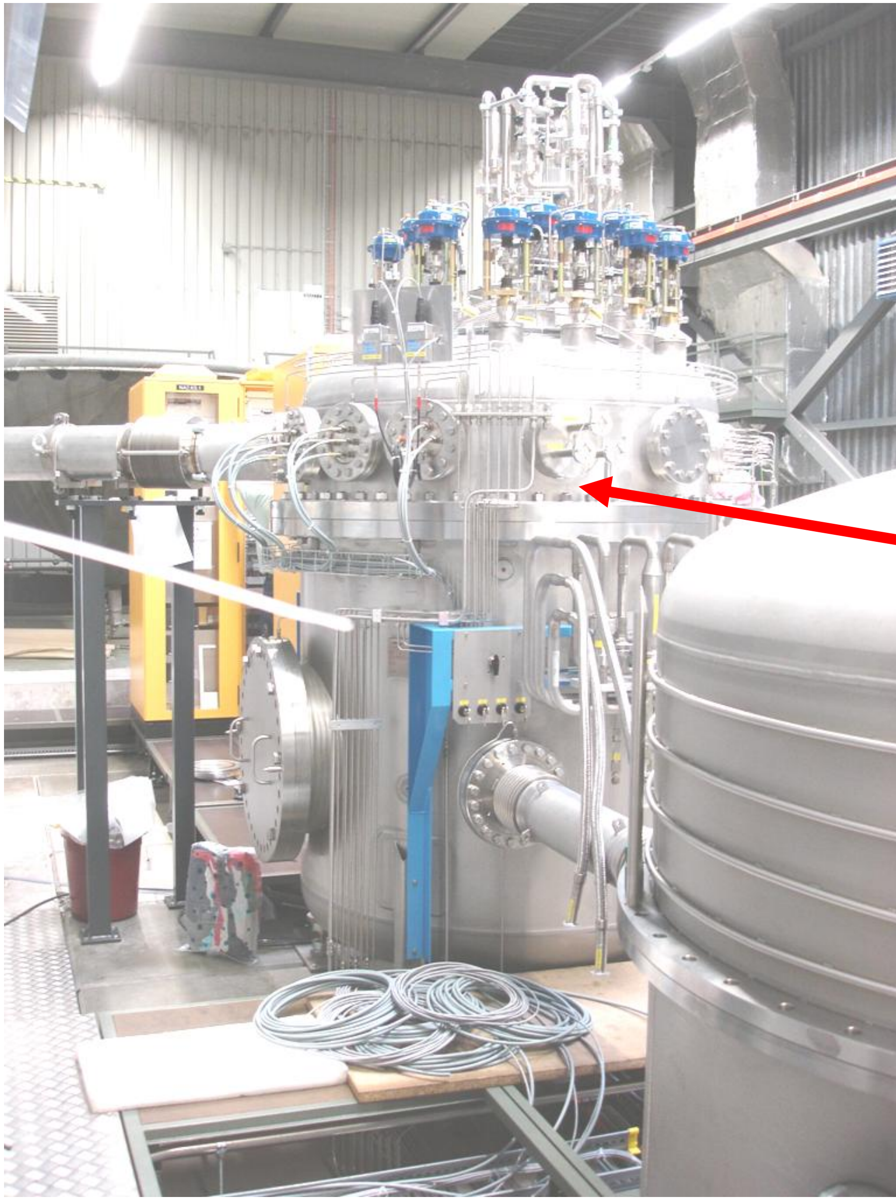
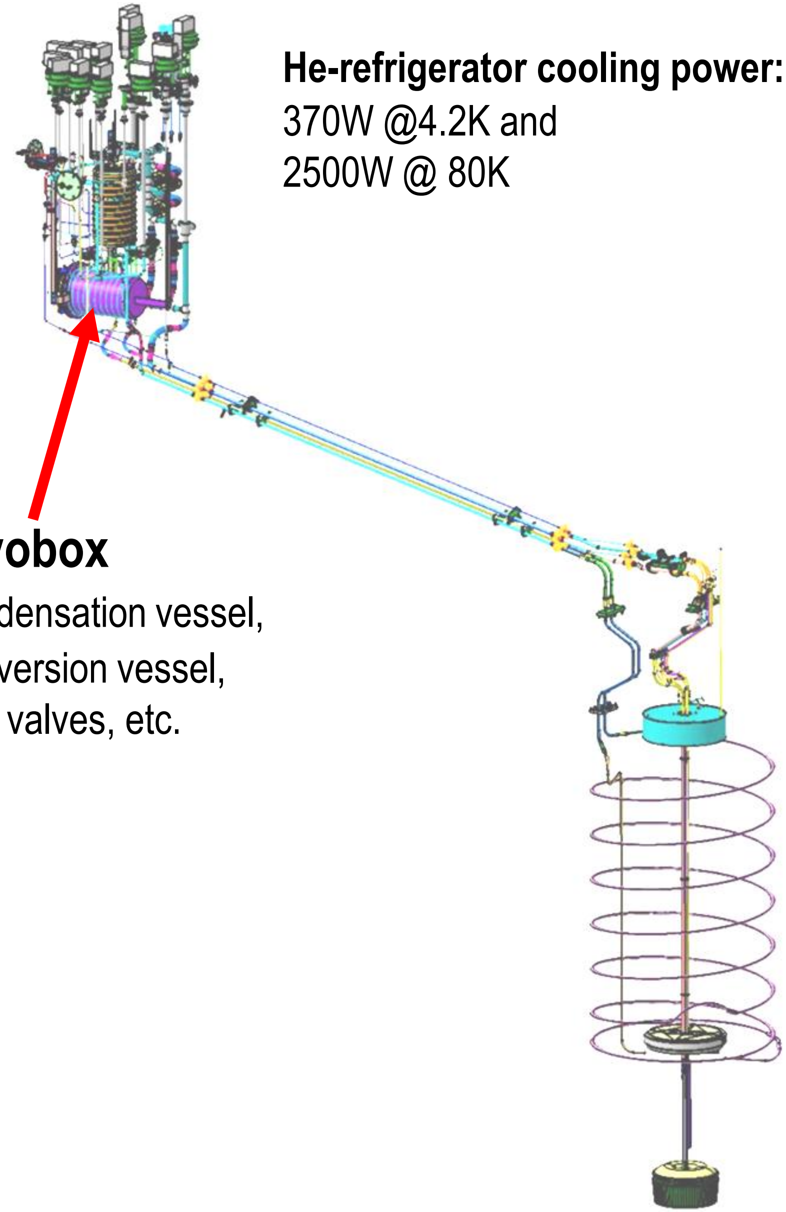
He and D_2 Cryogenic System

UCN Ultra Cold Neutron Source





He-refrigerator cooling power:
370W @4.2K and
2500W @ 80K

Cryobox
Condensation vessel,
Conversion vessel,
cryo valves, etc.

UCN production

F. Atchison et al., PHYSICAL REVIEW C **71**, 054601 (2005)

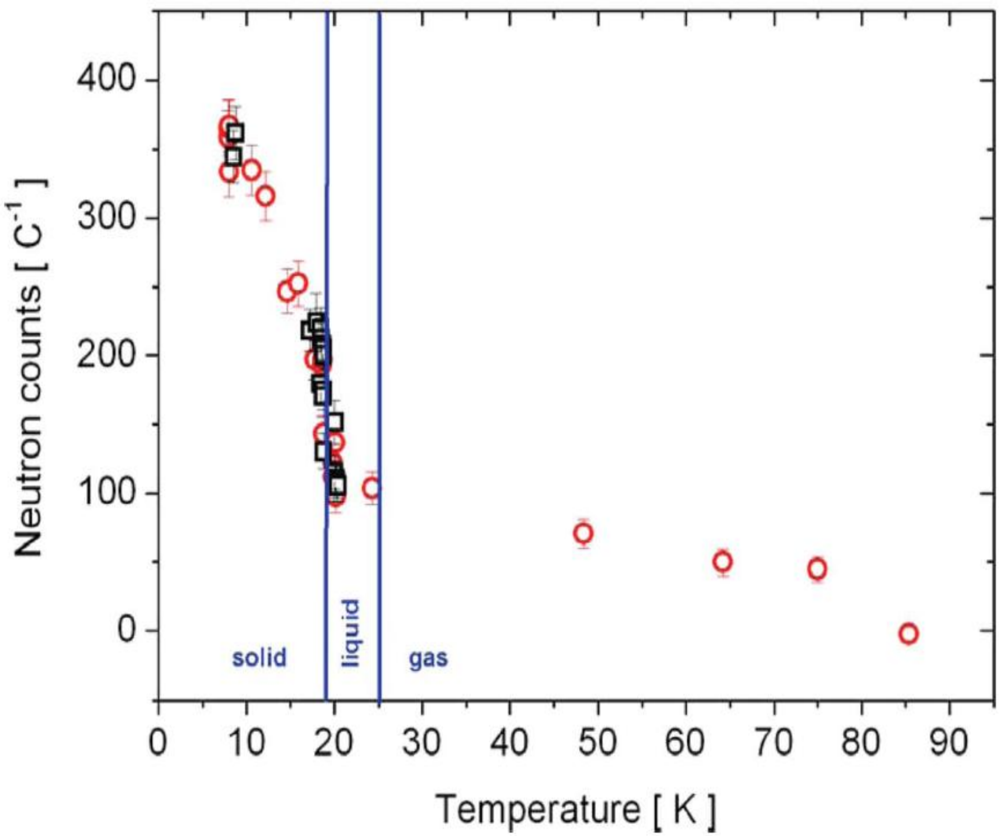
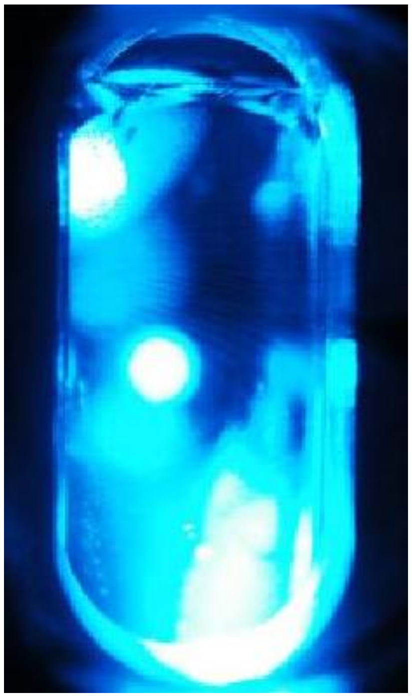
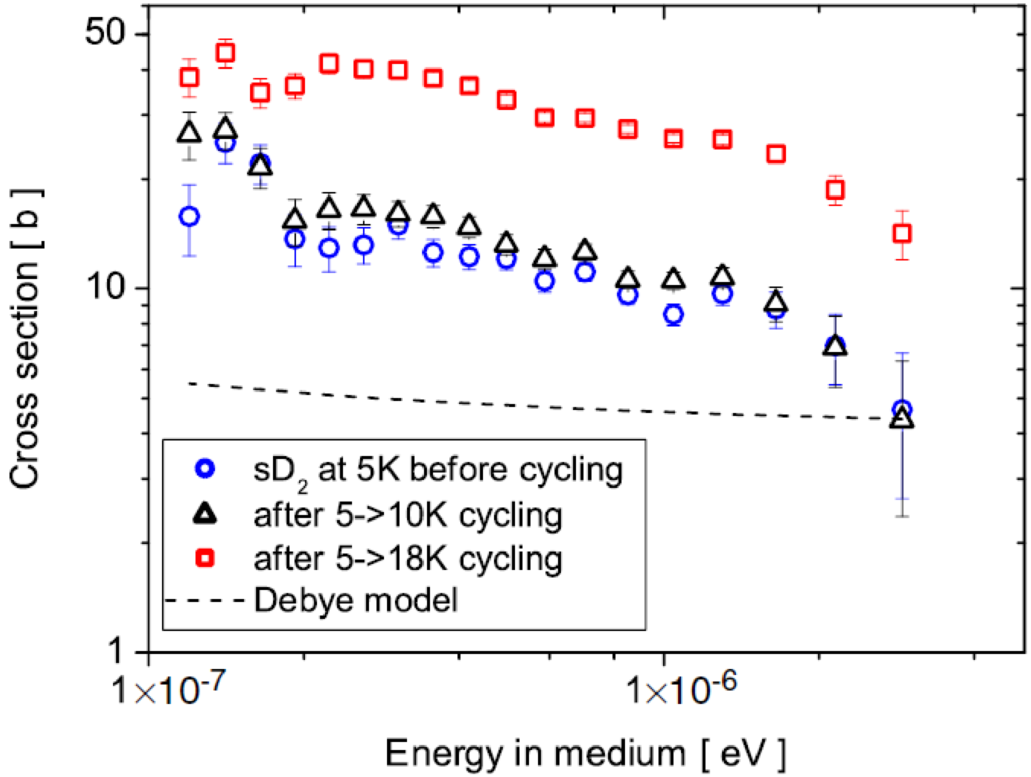
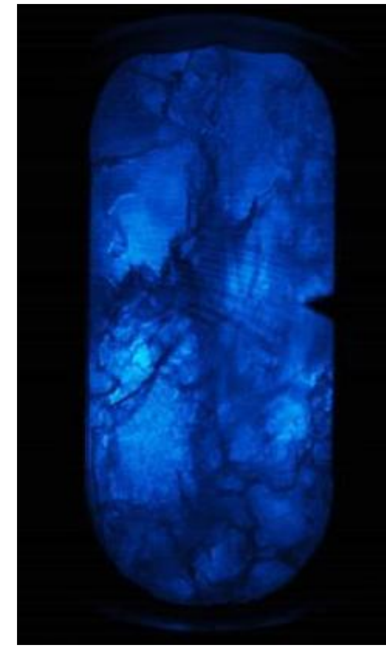


Figure 2. *Experimentally determined temperature dependence of UCN production in deuterium [22]. The sharp increase with solidification is obvious.*

UCN production



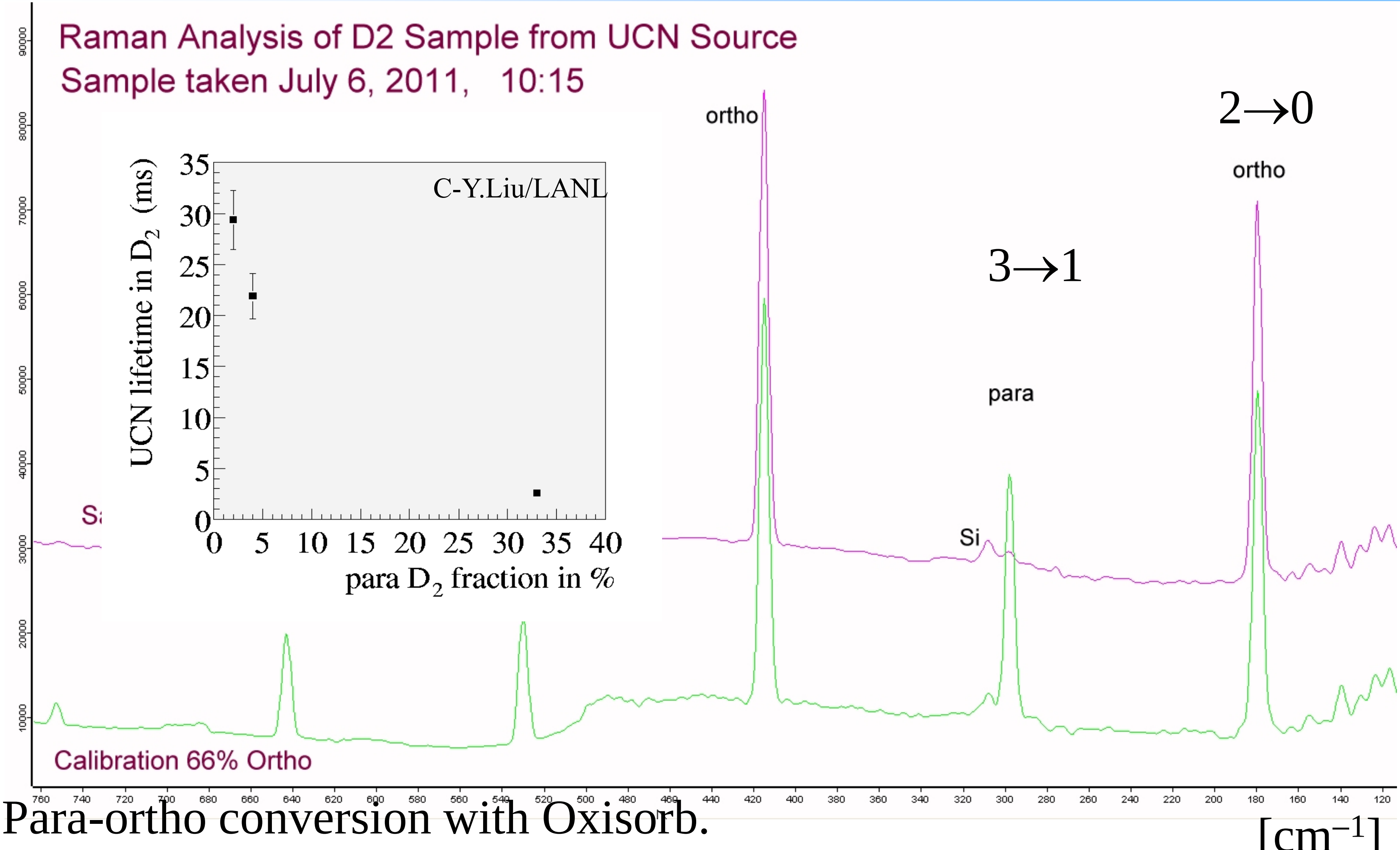




sD_2 crystal
after slow freezing

sD2 crystal after fast freezing
and/or after thermal cycling

Para-ortho conversion in D_2



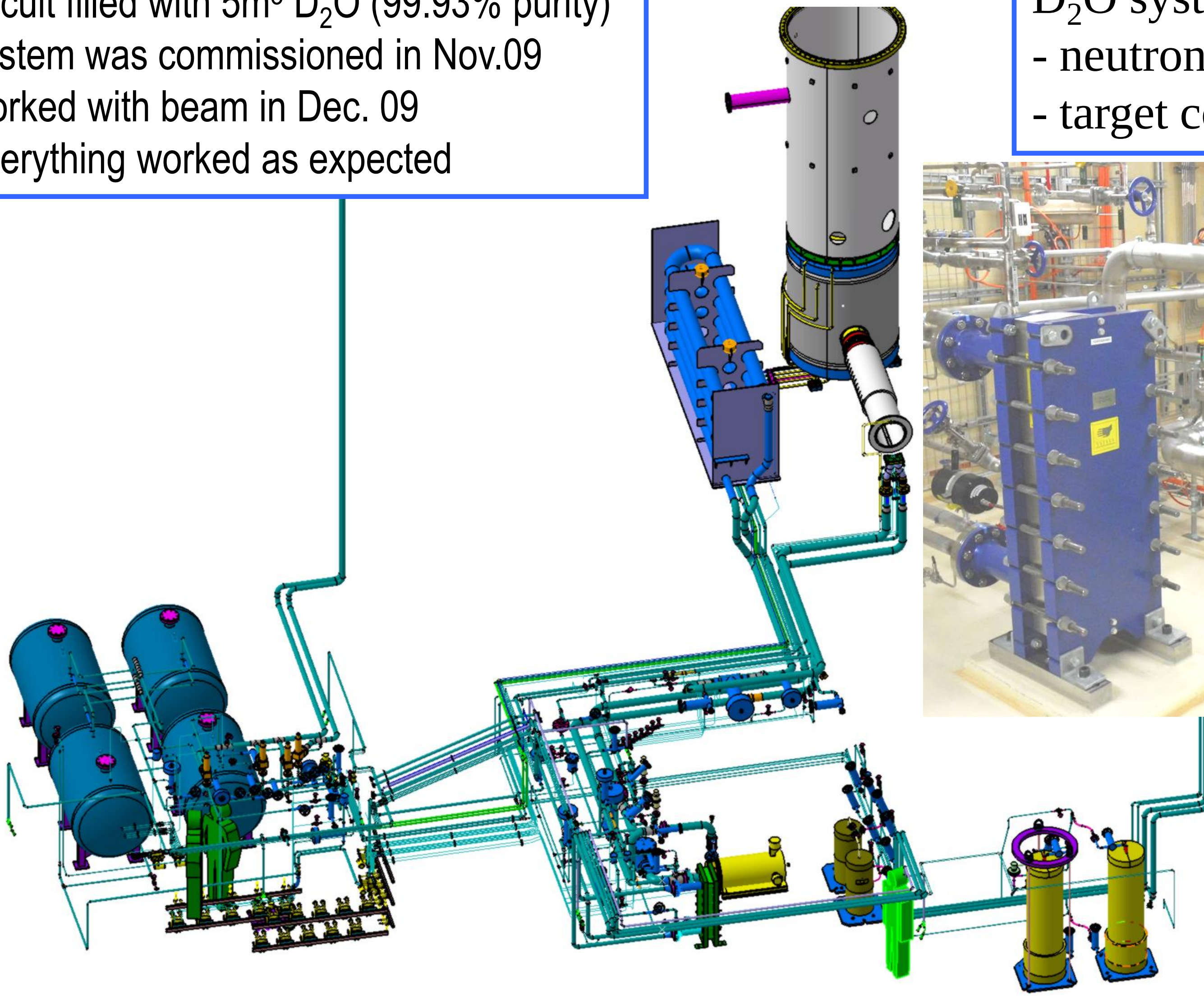
Para-ortho conversion with Oxisorb.

After conversion (97 2) % ortho-deuterium → improve spectrometer!

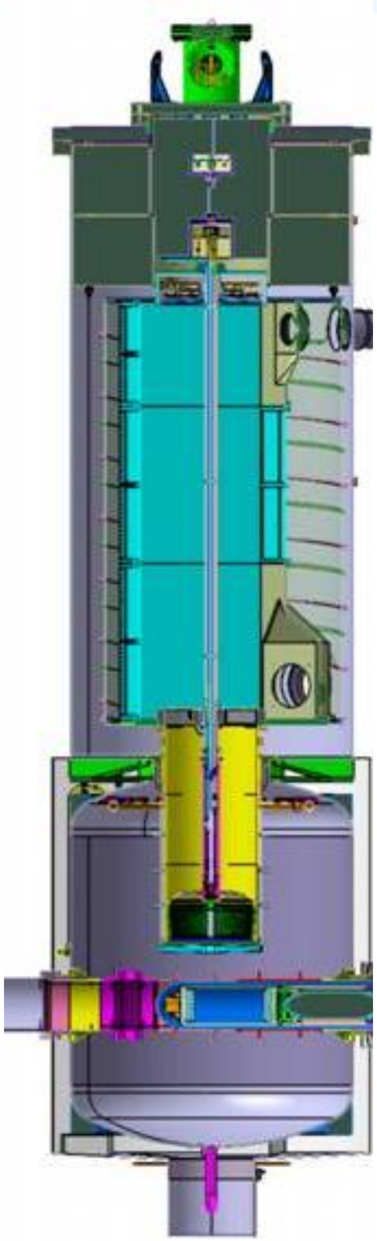
Heavy Water System

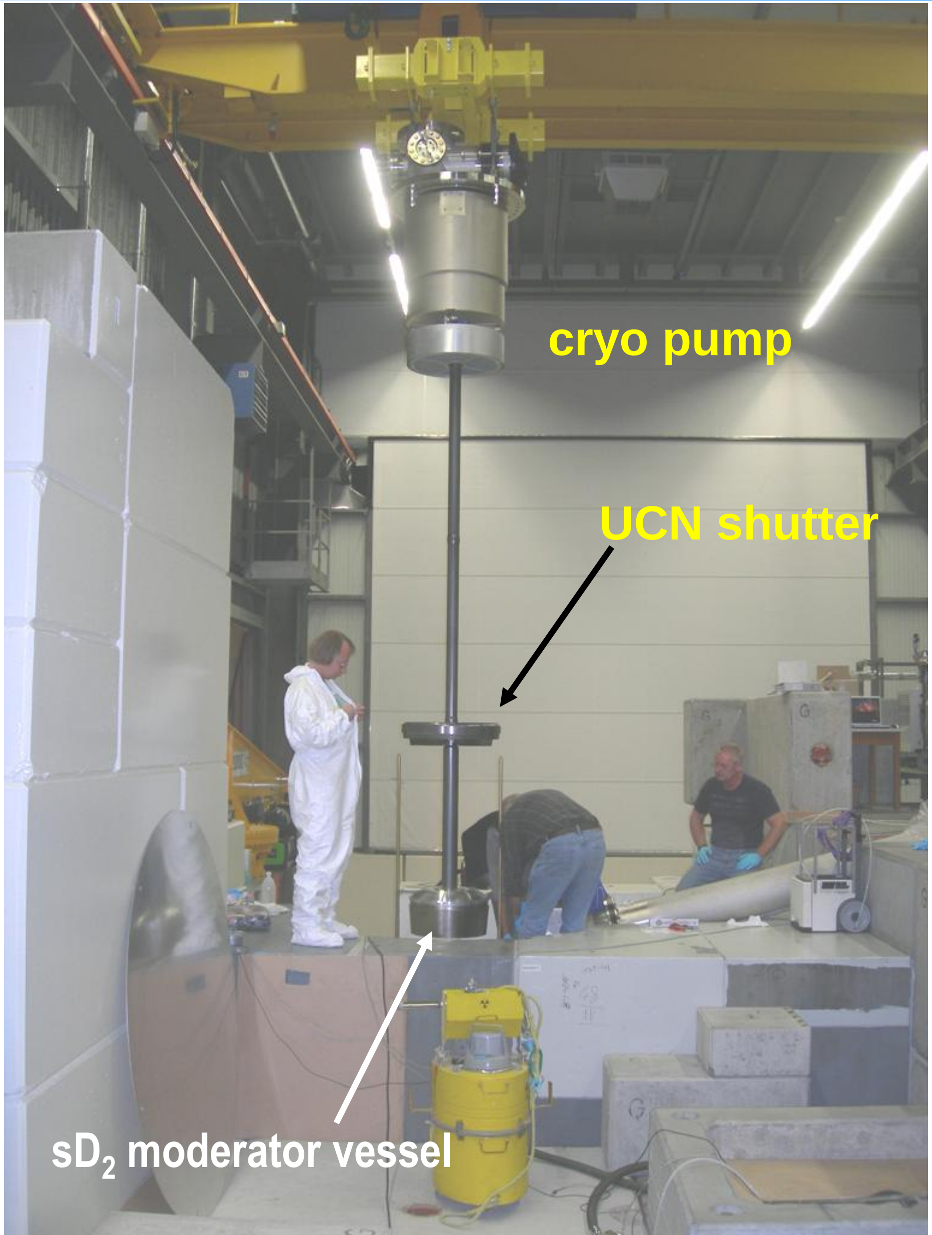
- circuit filled with 5m^3 D_2O (99.93% purity)
- system was commissioned in Nov.09
- worked with beam in Dec. 09
- everything worked as expected

D_2O system is used for:
- neutron moderation
- target cooling



Mounting of SD_2 moderator unit





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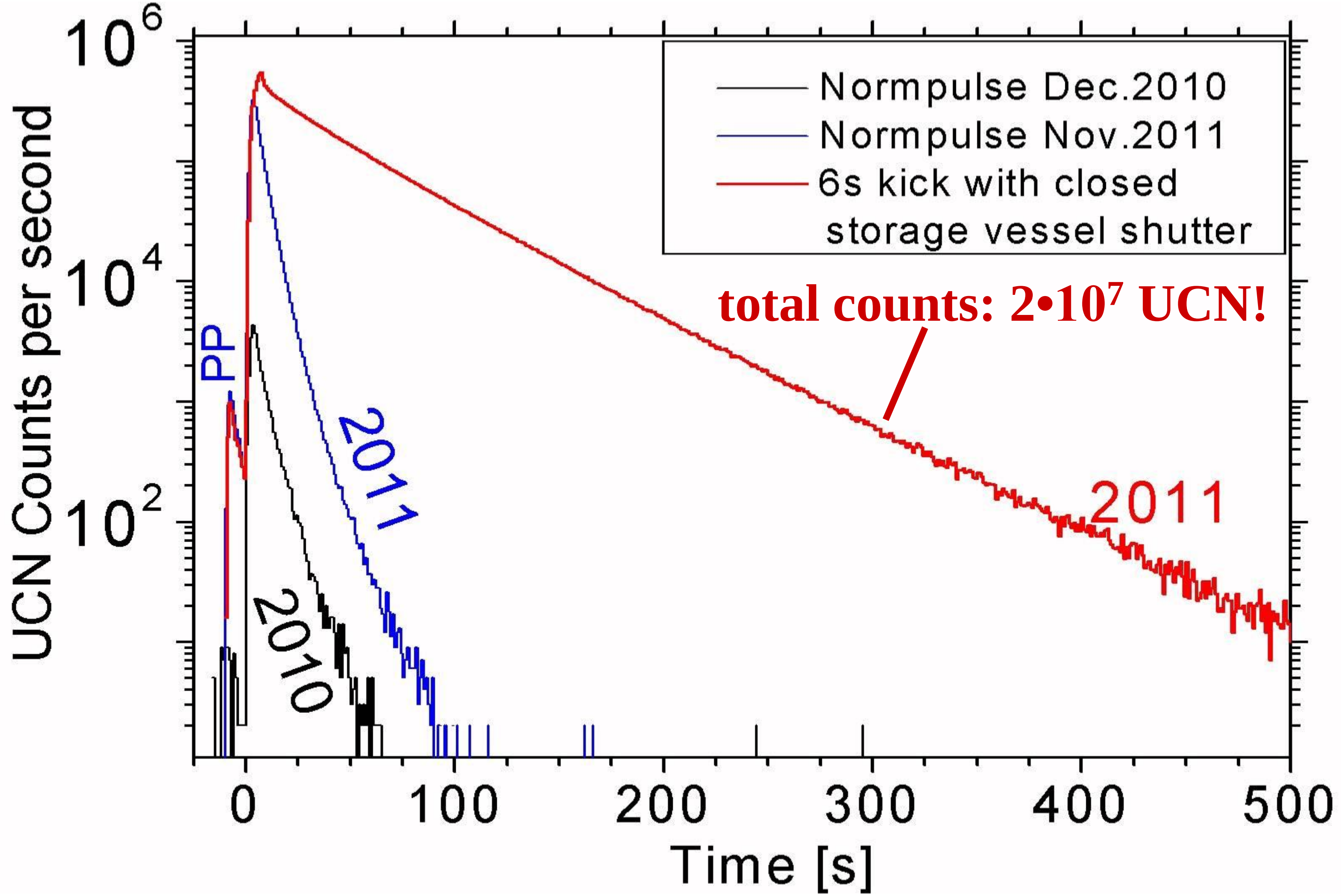
Proton Beam Line Commissioned

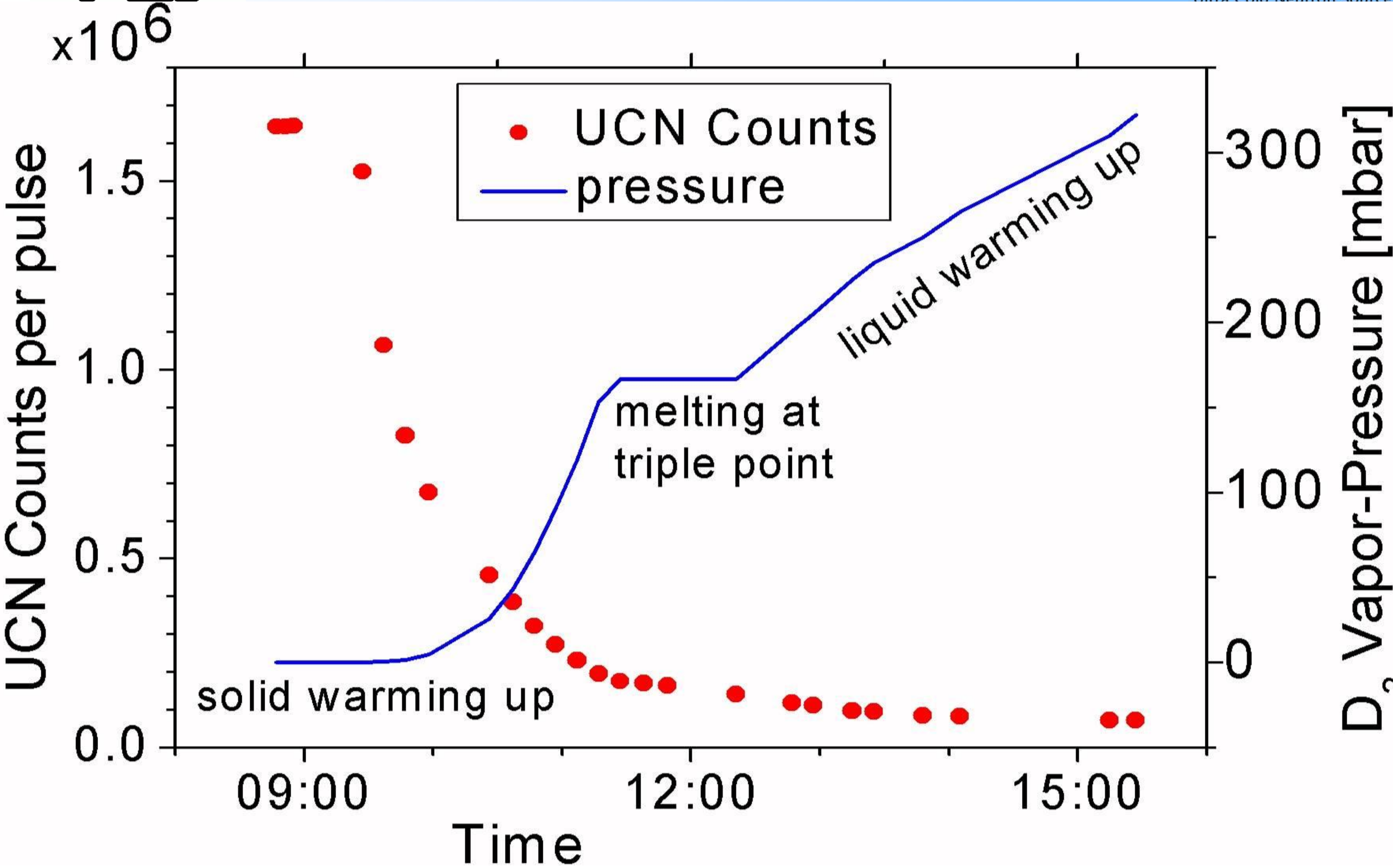
Ultra Cold Neutron Source

UCN counting

Improvement Dec. 2010 → Nov. 2011: x 70



UCN production during warm-up



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Summary

Ultra Cold Neutron Source

- PSI UCN source was successfully commissioned **with full beam** in December 2010
- all sub-systems are working reliably
- since October 2011 fully-automated UCN production, i.e. regular UCN user operation in two user areas (~18 UCN/cm^3)
- successful commissioning of nEDM apparatus (~1-2 UCN/cm^3)
- in 2011 UCN intensity could be increased by a factor of 67 (ortho-para); an additional factor of 30 - 50 to reach design value
- due to valve restrictions, suffiently slow crystallization not possible in 2011, but now! **This is the most suspicious candidate for gain factor >> 10!**
- UCN source optimization procedure in progress: e.g. by optimization of shutter timing

The top is near!

UCN since December 2010!
Improvement 2011 factor ~70!
2012: hunting a factor of ~50!
We know, where the bear is sitting!

Remember: First proton beam 5 nA
Today 2.2 mA tendency increasing

Hunting the bear!

UCN source status,May 16 2012

Since the repair-works on the He plant groundwater circuit have been finished the UCN source has been cooled again without any problems.

We have now frozen the D2 inside the condensor vessel. In there we startet to liquefy the D2 which, once liquid is then transferred to the para-ortho converter for conversion, where it will stay at least 2 days boiling.

During this process we will also test further cryo-valves which have been replaced in the last shutdown. We also await a program module-update for part of the cryo-circuit control software of the UCN source by next Tuesday. Then we plan to transfer the ortho-D2 to the moderator vessel freeze it there, and then test the new cooling valves of this circuit during D2 liquefaction inside the moderator vessel. After successful completion we will have the first D2 crystal in 2012.

At the same time now all safety procedures which are necessary for beam operation are being performed. As the person who did this in the past has left PSI the new responsible needs some time to re-establish the procedure. For next week a full beam-switch-off test with a responsible from the Swiss Ministry for health (BAG) is scheduled. After this we will be able to operate the proton beam and the UCN source again.

The nEDM collaboration @ PSI

Ultra Cold Neutron Source

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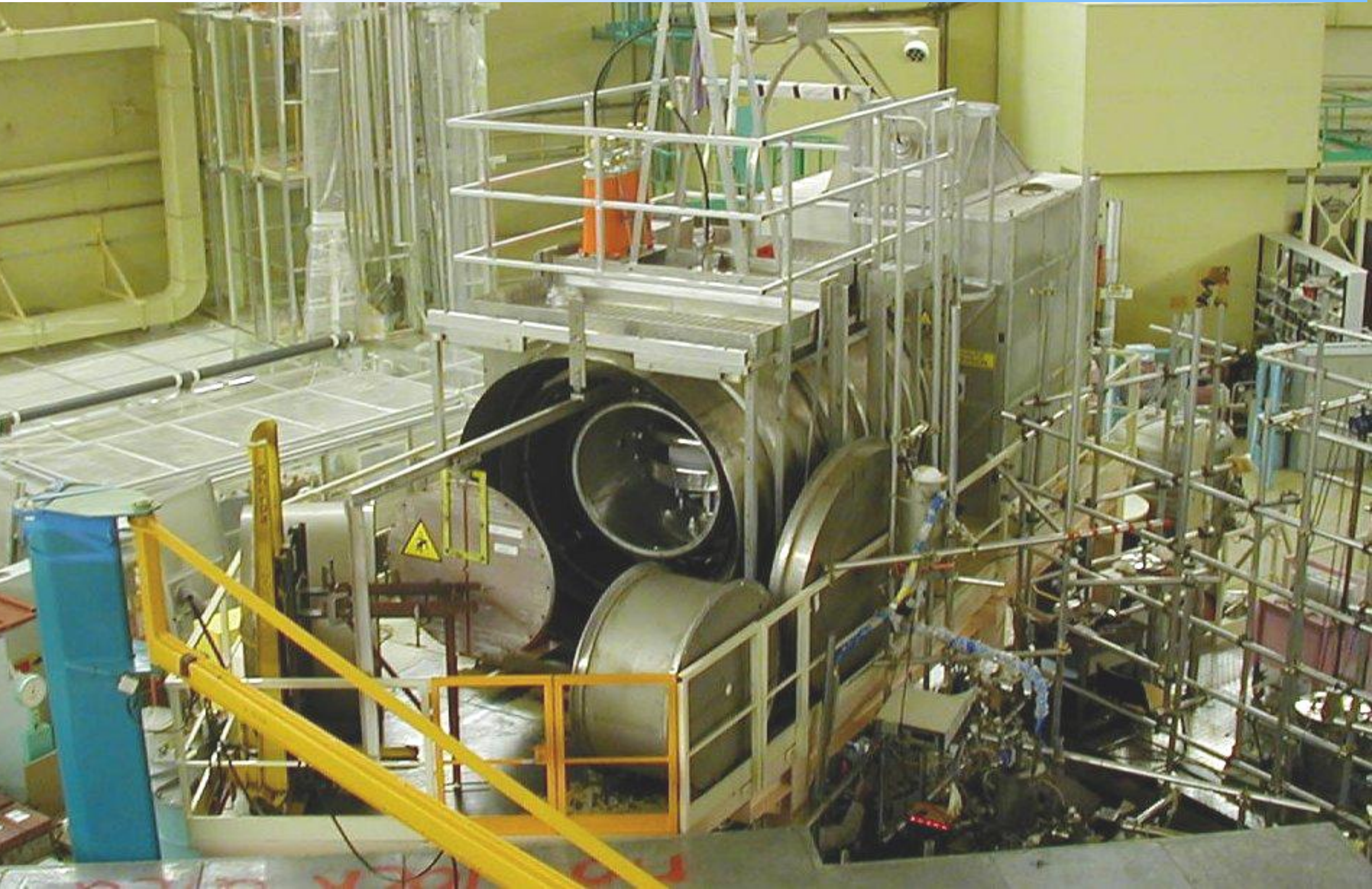
Our strategy

- Phase I:
  - Operated nEDM@ILL (-2008)
  - Moved nEDM to PSI in March 2009
  - Design of n2EDM, related R&D
- Phase II:
  - Operate nEDM@PSI (2009-2012)
  - Sensitivity goal: 5×10^{-27}ecm
  - Setup of n2EDM, continued R&D
- Phase III:
  - Operate n2EDM (2012-2015)
  - Sensitivity goal: 5×10^{-28}ecm

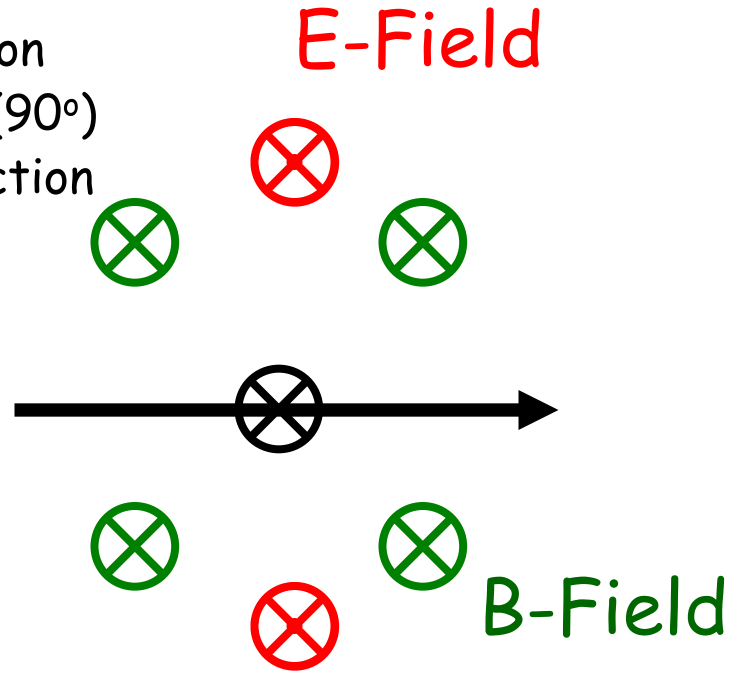
Optimize in-vacuum, room-temperature technique

Phase I: Sussex-RAL-ILL Apparatus at ILL



Measurement principle

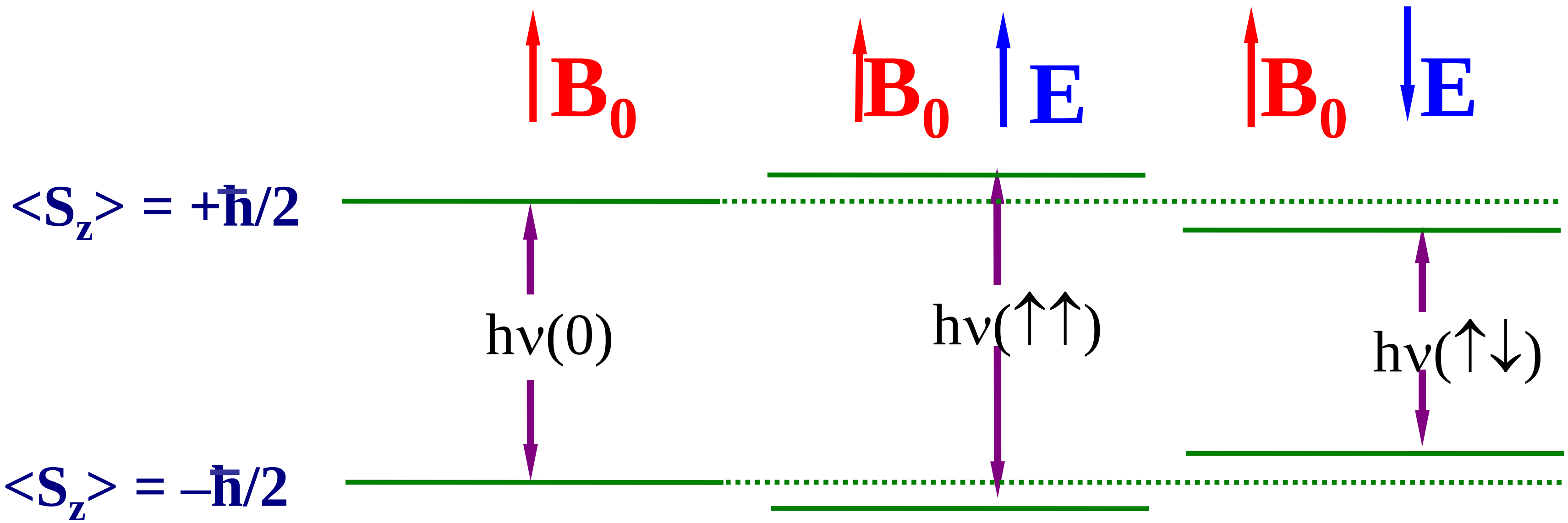
1. Inject a polarised neutron
2. Rotate the spin by π/2 (90°)
3. Change the E field direction
4. Measure the frequency difference



$$\nu = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

nEDM measurement principle

Neutron energy levels in magnetic and electric fields



$$h\nu(\uparrow\uparrow) - h\nu(\uparrow\downarrow) = -4\,E\,d/\,h$$

assuming **B** unchanged when **E** is reversed.

nEDM measurement principle

Spin precession frequency (+E): $h\nu^{+} = 2(\mu_n B + d_n E)$

(–E): $h\nu^{-} = 2(\mu_n B - d_n E)$

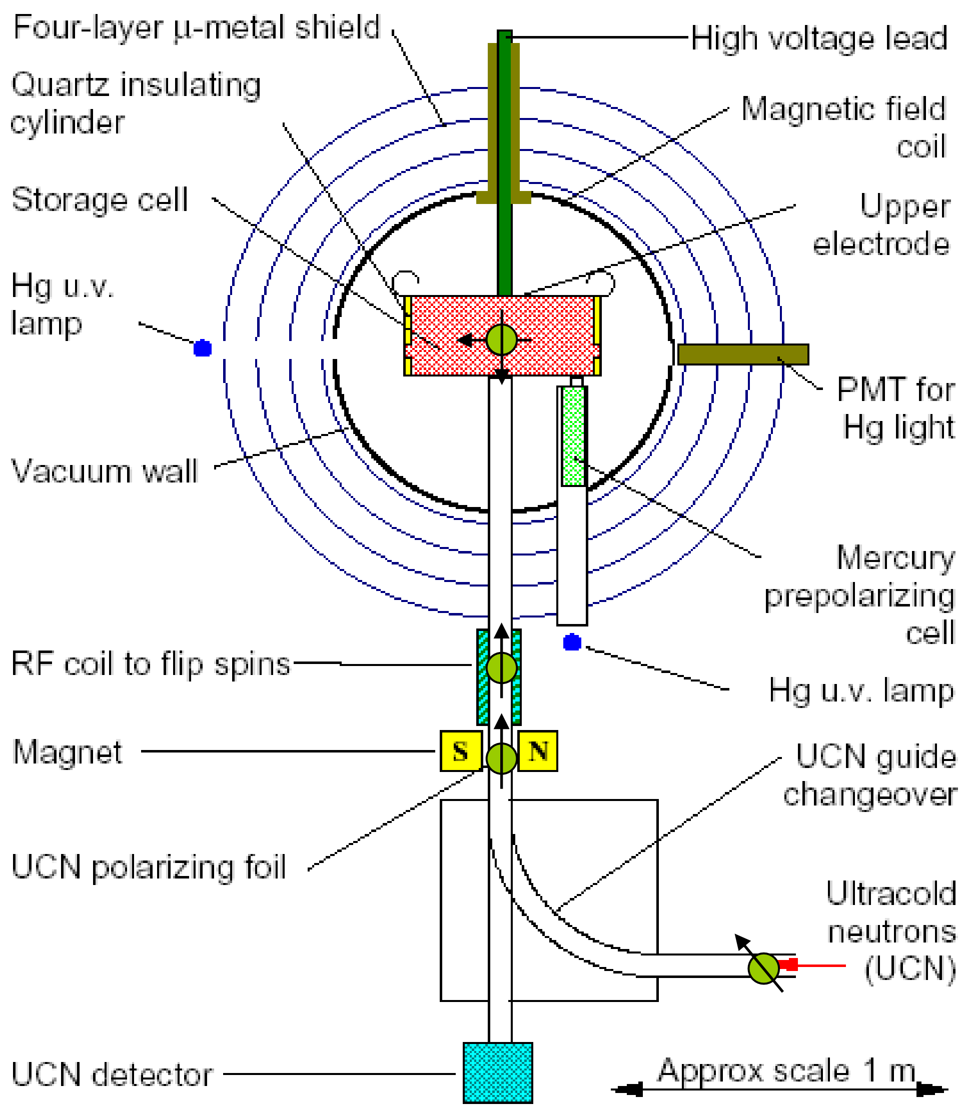
Differenz: $h\Delta\nu = 4 d_n E$

$$d_n = h\Delta\nu / 4E$$

$$d_n \pm \delta d_n = h/4E(\Delta\nu \pm \delta\Delta\nu)$$

$$\delta d_n = \frac{h}{4\pi\alpha} \cdot \frac{1}{T \cdot E \cdot \sqrt{N_0}}$$

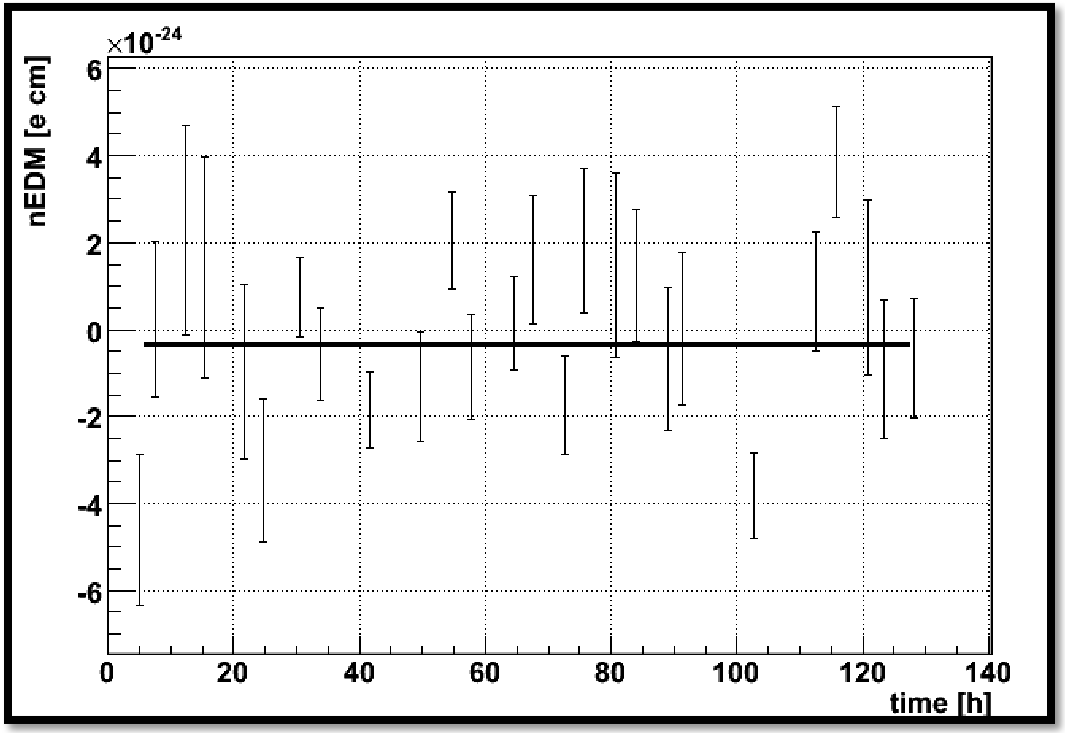
nEDM measurement principle



Last cycle at ILL (Grenoble)

Neutron polarization:
$\alpha(t=0) = 0.92$
T2 = 400 s

Mercury polarization:
$\alpha(t=0) = 0.3$
T2 = 90 s



$d_n = (-3.4 \pm 2.7)\ 10^{-25}$ e cm
[$d_n = (+0.2 \pm 1.5 \pm 0.7)\ 10^{-26}$ e cm RAL-Sussex-ILL]
Just for demonstration that we are able to run the thing!

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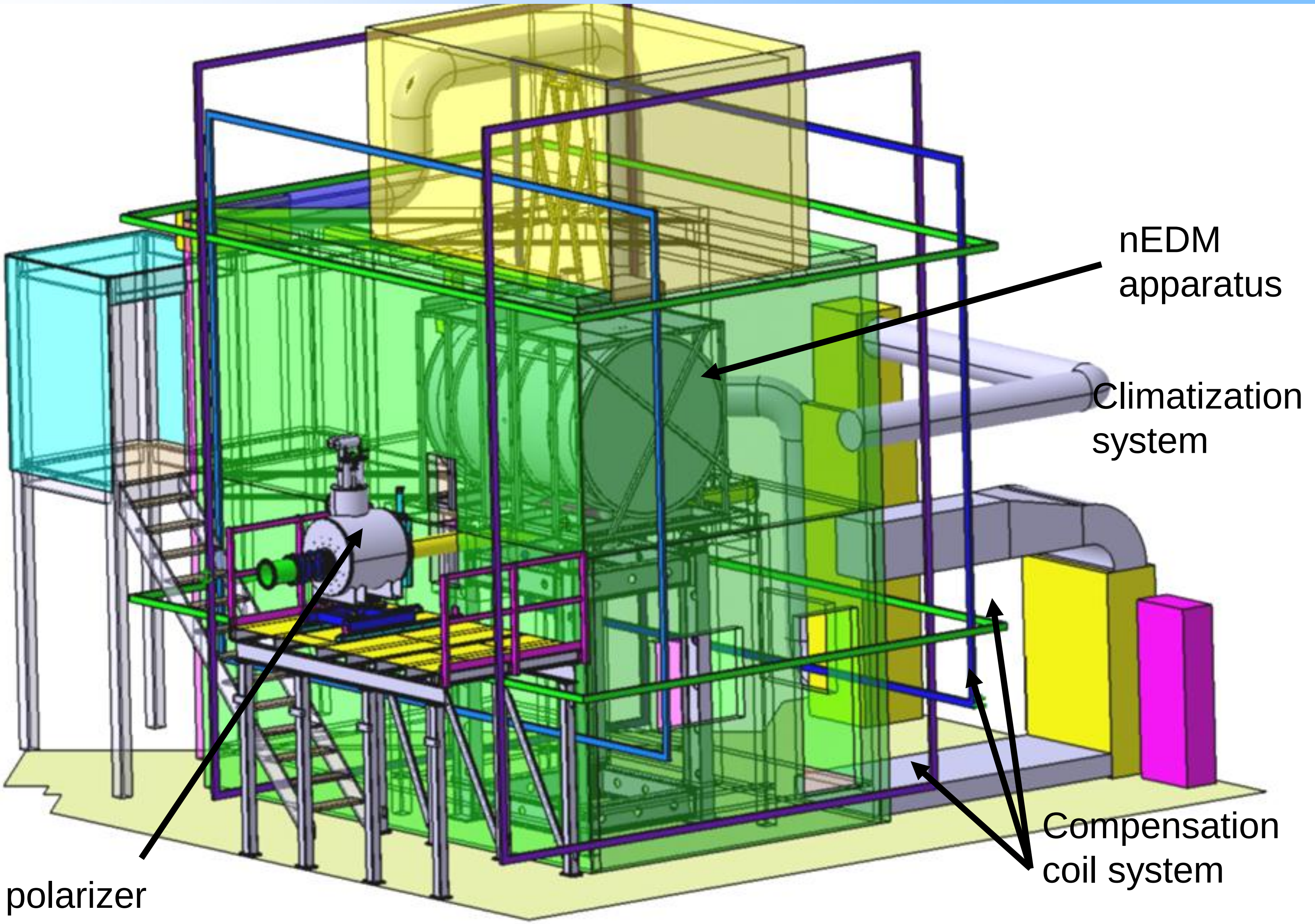
Dismantling @ ILL

Ultra Cold Neutron Source

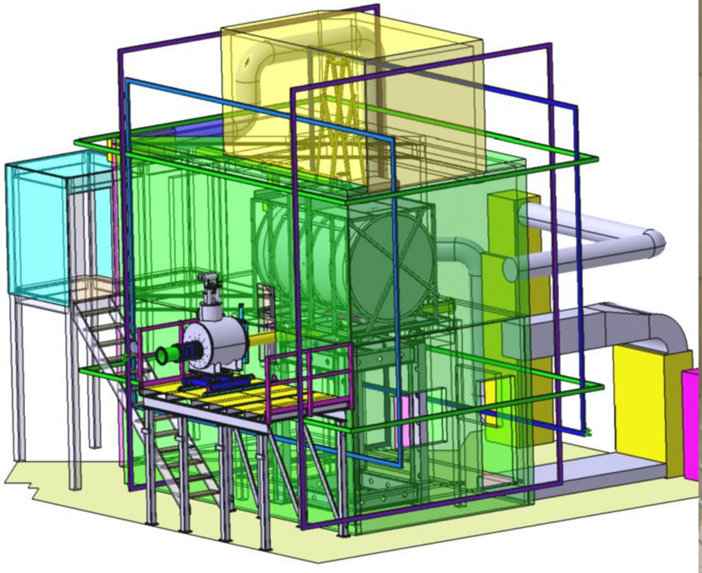
Feb. 17th, 2009

Phase II: Set up @ PSI

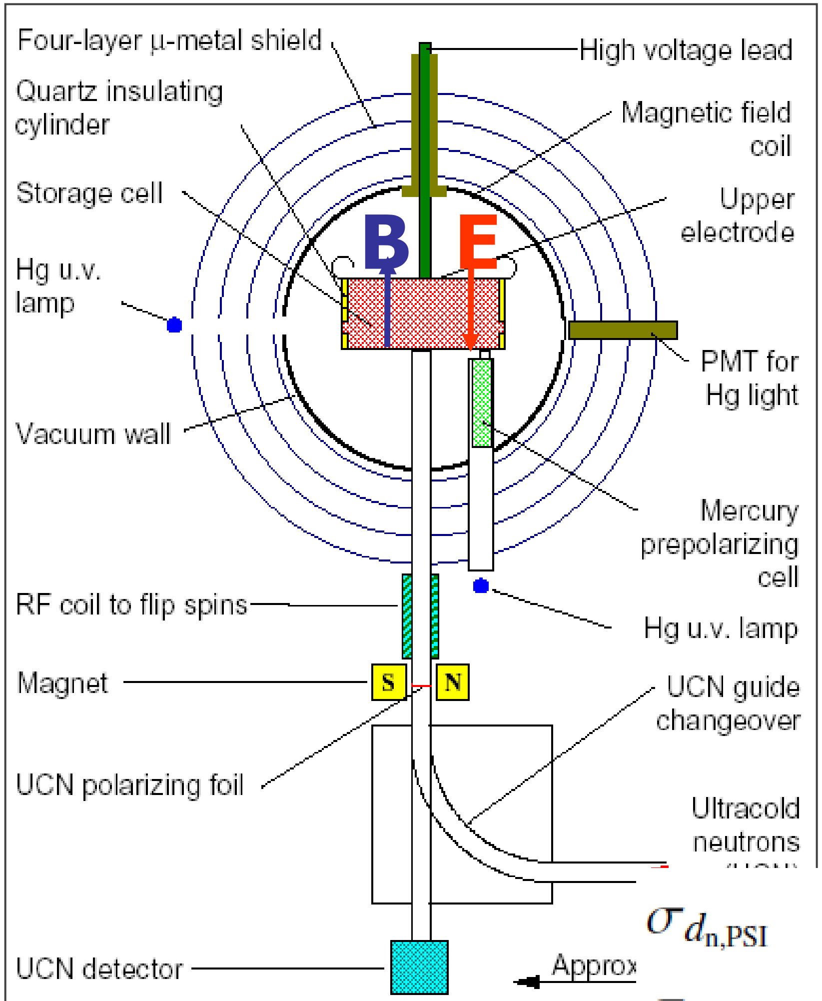
Ultra Cold Neutron Source



Phase II: Set up @ PSI

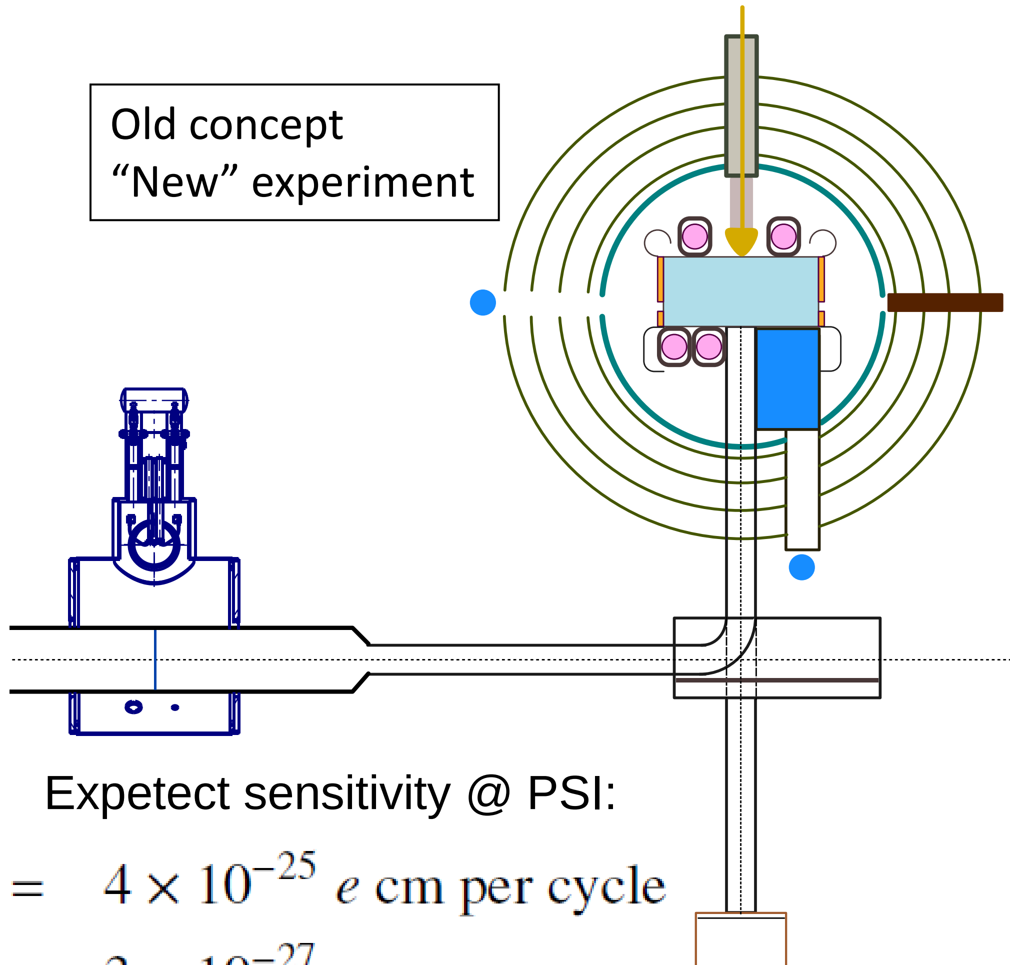


Spin precession



Courtesy RAL/Susse

Old concept
“New” experiment



Expetect sensitivity @ PSI:

$$\sigma_{d_{n,\mathrm{PSI}}} = 4 \times 10^{-25}\ e\ \mathrm{cm\ per\ cycle}$$

$$\sigma_{d_{n,\mathrm{PSI}}} = 3 \times 10^{-27}\ e\ \mathrm{cm\ per\ year}$$

(1.6×10^{-26} e cm, RAL-Sussex-ILL)

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Error Budget: Systematics

Ultra Cold Neutron Source

Effect	Shift (see Ref.) $[10^{-27}$ *e*cm]	σ (see Ref.) $[10^{-27}$ *e*cm]	σ (at PSI) $[10^{-27}$ *e*cm]
Door cavity dipole	-5.6	2.00	**0.10**
Other dipole fields	0.0	6.00	**0.40**
Quadrupole difference	-1.3	2.00	**0.60**
v×E translational	0.0	0.03	**0.03**
v×E rotational	0.0	1.00	**0.10**
Second-order **v×E**	0.0	0.02	**0.02**
ν_{Hg} light shift (geo phase)	3.5	0.80	**0.40**
ν_{Hg} light shift (direct)	0.0	0.20	**0.20**
Uncompensated *B* drift	0.0	2.40	**0.90**
Hg atom EDM	-0.4	0.30	***0.06***
Elastic forces	0.0	0.40	**0.40**
Leakage currents	0.0	0.10	**0.10**
ac fields			**0.01**
Total			**1.37**

Ref: PRL **97,** 131801 (2006)

After 2 years, statistics & systematics
$d_n = 0$: $|d_n| < 5 \times 10^{-27}$ ecm (95% C.L.)
or, e.g., $d_n = 1.3 \times 10^{-26}$ ecm (5σ)

n2EDM concept

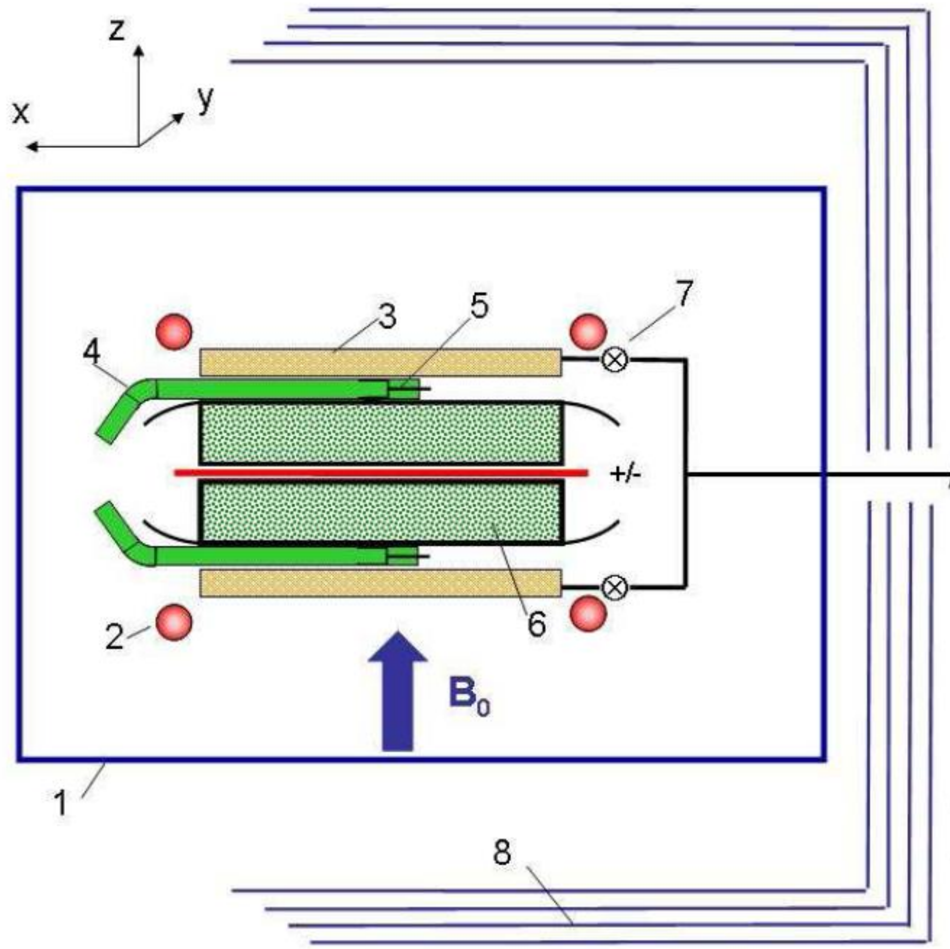
- double chamber system,
  vertical stack of cylindrical chambers

- co-magnetometer (Hg, Xe?, He?)
- Cs magnetometer array (64, 128, ?)
  also inbetween UCN and He-3
- 2 large He-3 magnetometers with
  He-3 read-out by CsM
- B-field and gradient stabilization by CsM

- 5-6-layer mu-metal shield,
  conceptual design ongoing
- external stabilization as needed

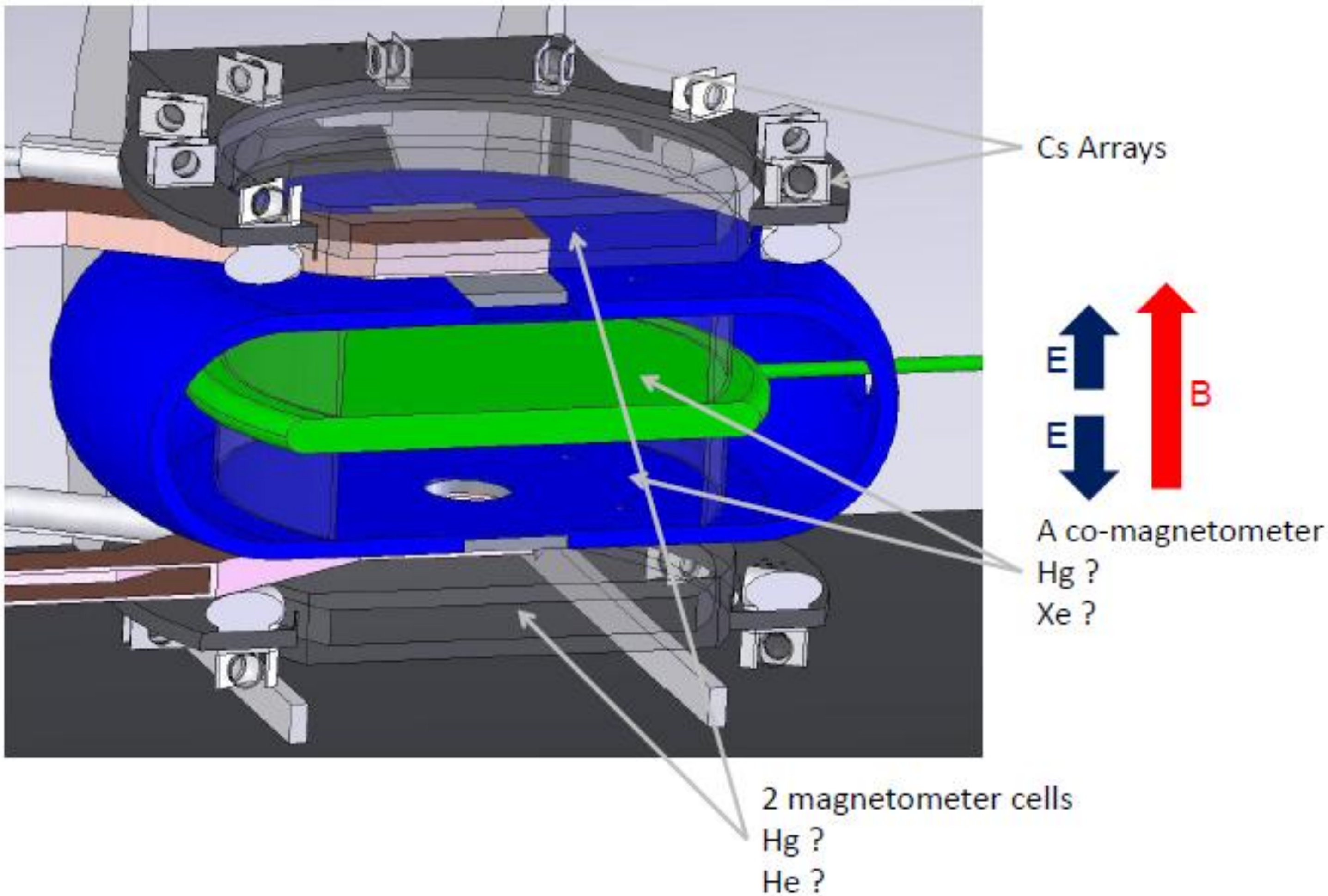
- UCN polarized by SC polarizer
- UCN spin analysis detector,
  eventually simultaneous analysis

- Flexible DAQ



n2EDM concept

A double chambers concept
With redundant and complementary magnetometers system



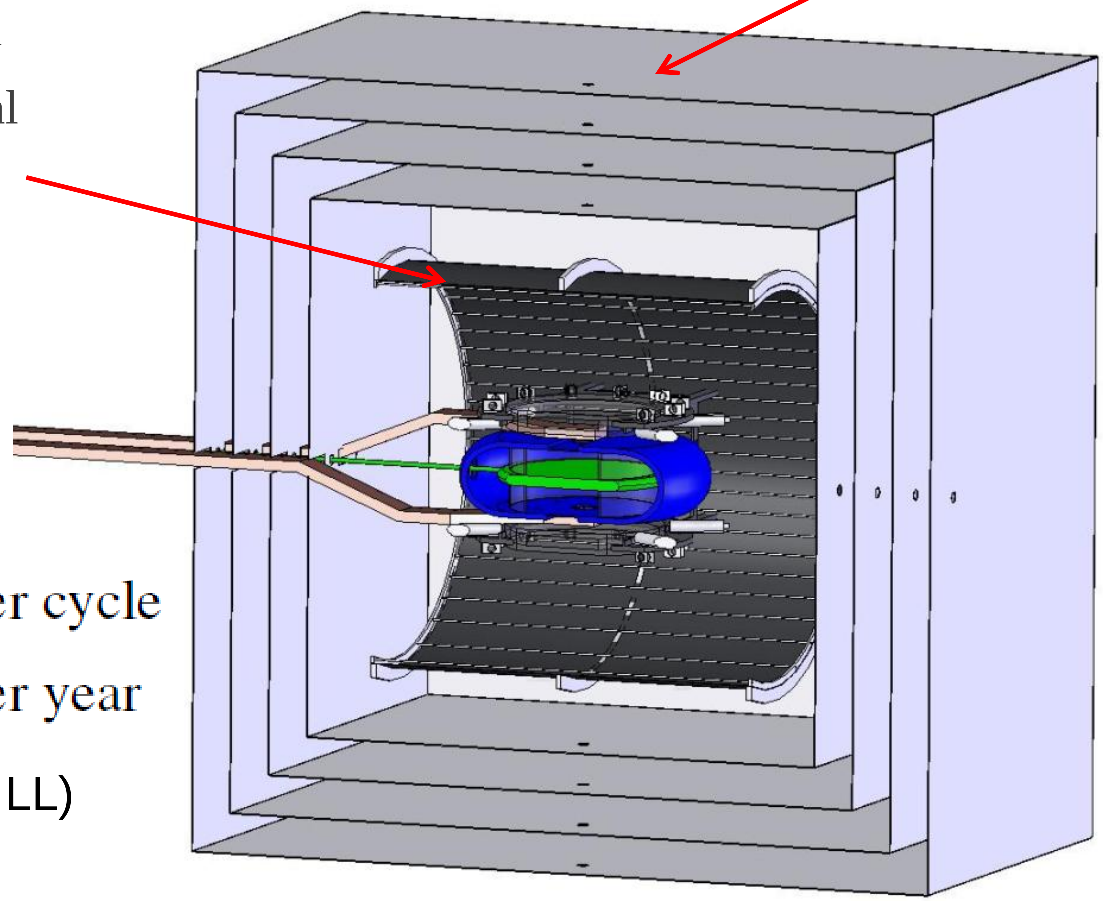
n2EDM concept

Shield characterization in 2010

Cubic shield: large shielding factor
Cylindrical shield: better field homogeneity

Multi-layer shield

Cylinder from highly magnetizable material



Expetect sensitivity @ PSI:

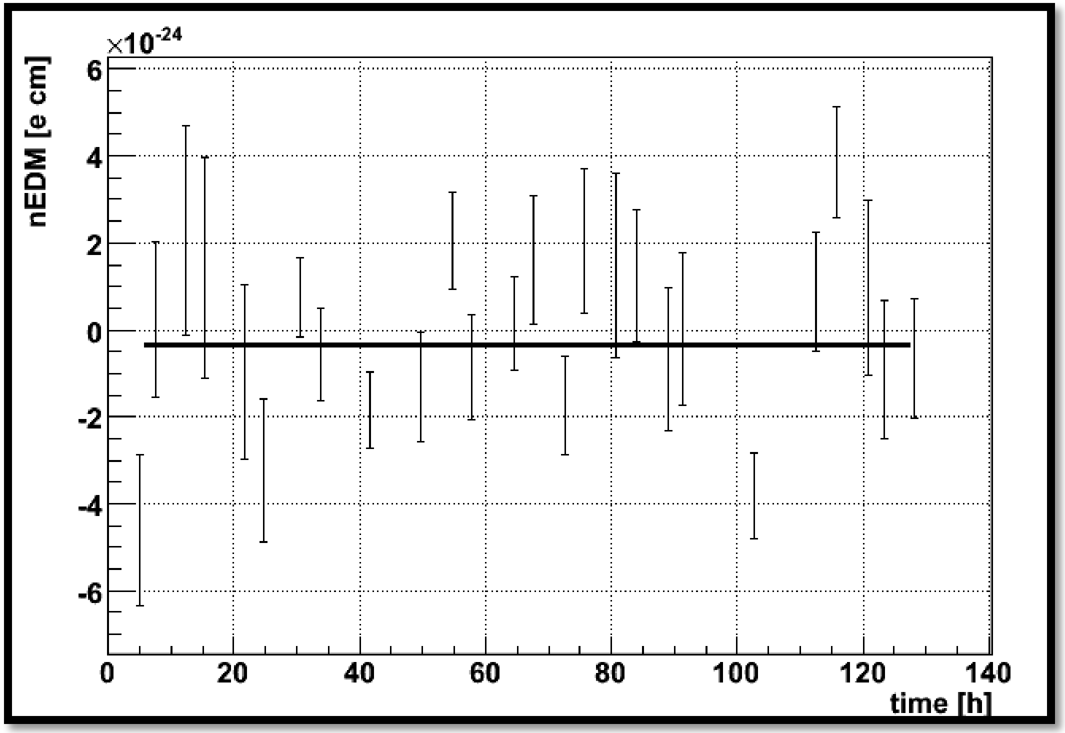
$$\sigma_{d_{\mathrm{n,PSI}}} = 4 \times 10^{-25}\ e\ \mathrm{cm\ per\ cycle}$$
$$\sigma_{d_{\mathrm{n,PSI}}} = 3 \times 10^{-27}\ e\ \mathrm{cm\ per\ year}$$

(1.6×10^{-26} e cm, RAL-Sussex-ILL)

Last cycle at ILL (Grenoble)

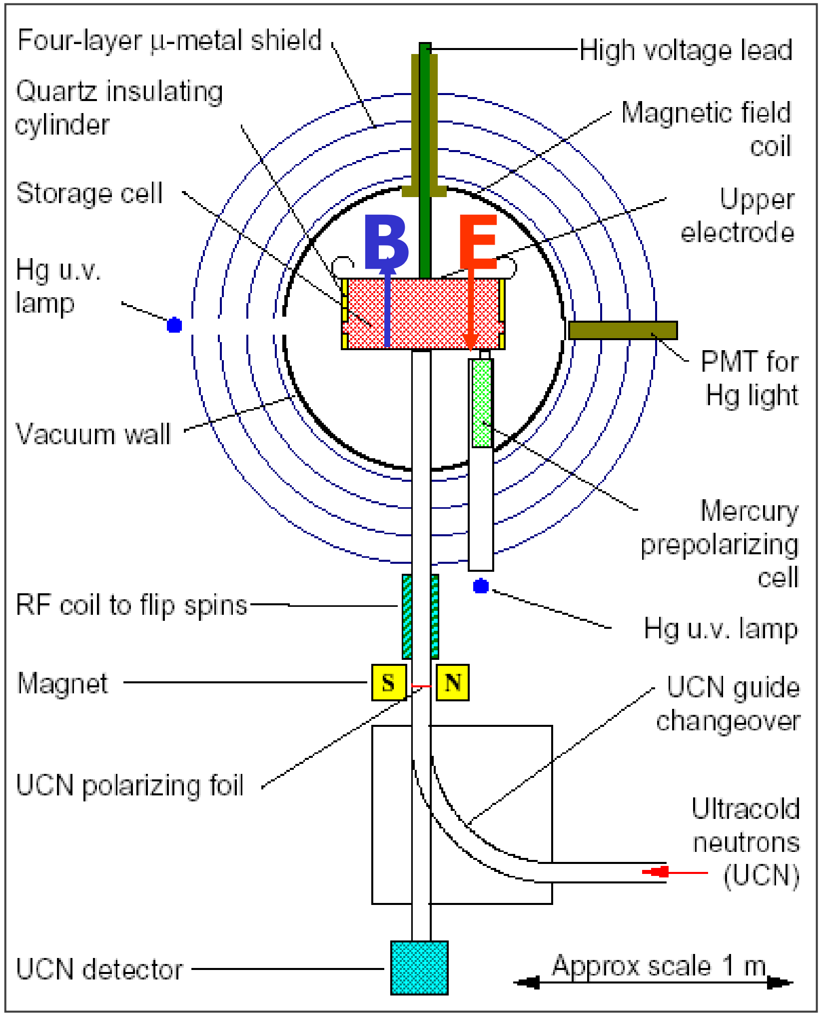
Neutron polarization:
α(t=0) = 0.92
T2 = 400 s

Mercury polarization:
α(t=0) = 0.3
T2 = 90 s



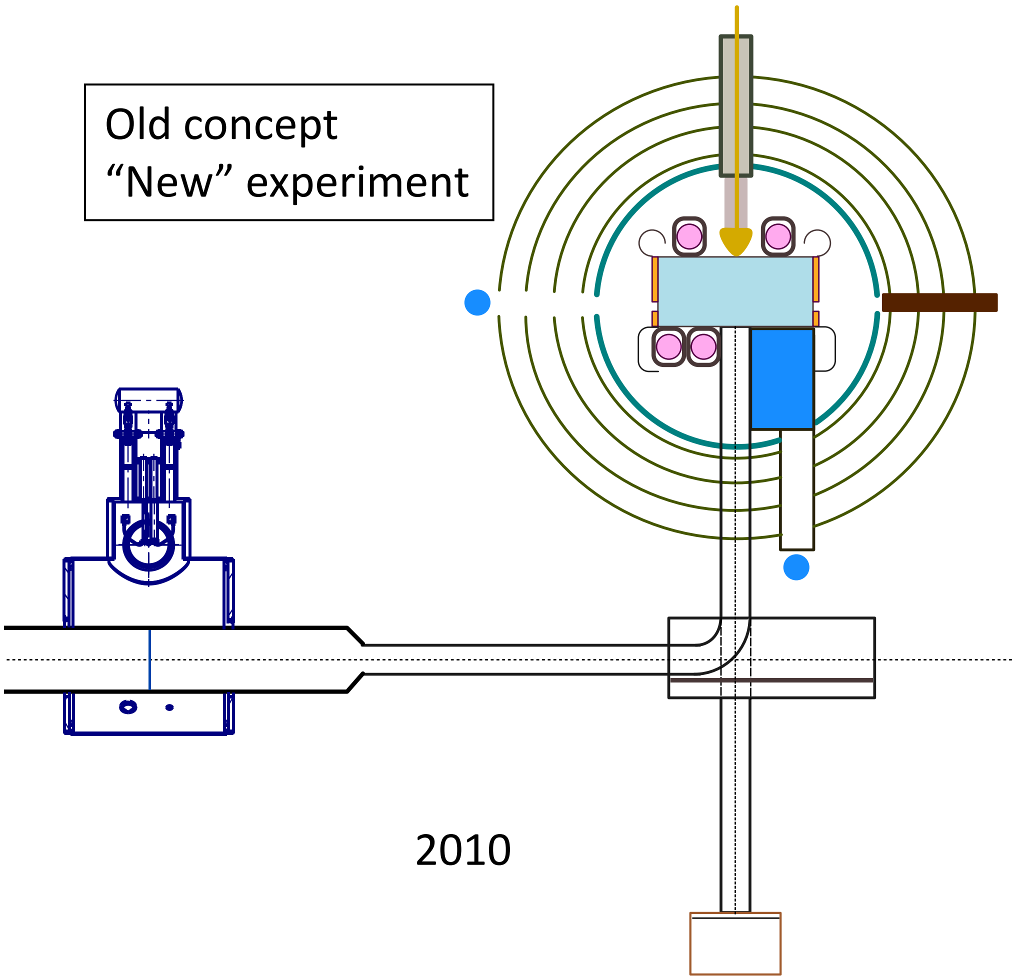
$d_n = (-3.4 \pm 2.7)\ 10^{-25}$ e cm

Spin precession



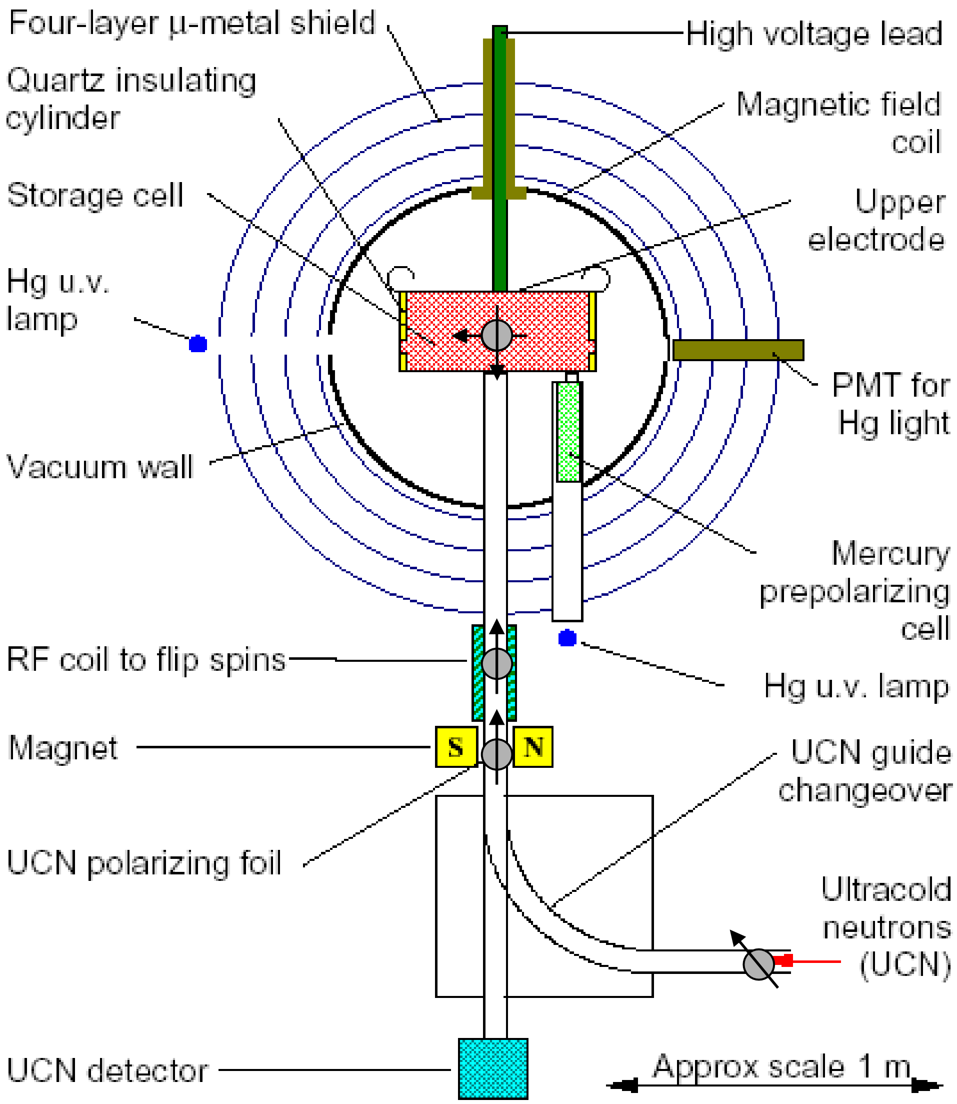
Courtesy RAL/Sussex/Ill collab.

Old concept
“New” experiment



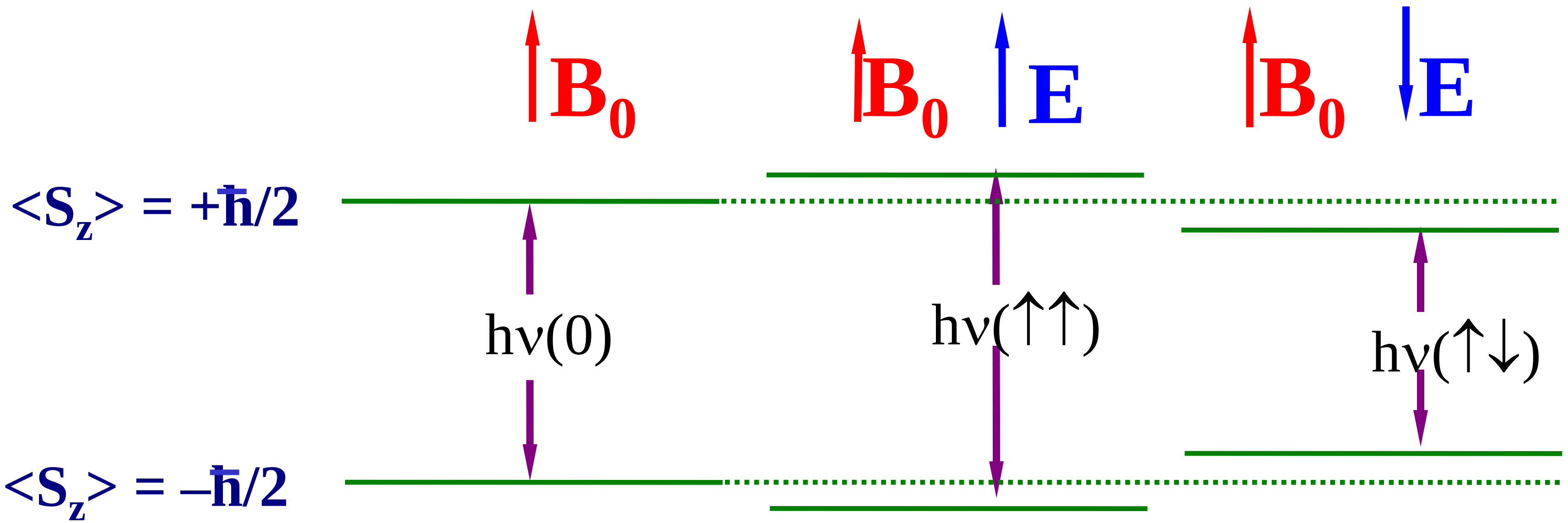
2010

Wie misst man nEDM?



nEDM measurement principle

Neutron energy levels in magnetic and electric fields



$$h\nu(\uparrow\uparrow) - h\nu(\uparrow\downarrow) = -4\,E\,d/h$$

assuming **B** unchanged when **E** is reversed.

nEDM measurement principle

Spin precession frequency (+E): $h\nu^{+} = 2(\mu_n B + d_n E)$

(–E): $h\nu^{-} = 2(\mu_n B - d_n E)$

Differenz: $h\Delta\nu = 4 d_n E$

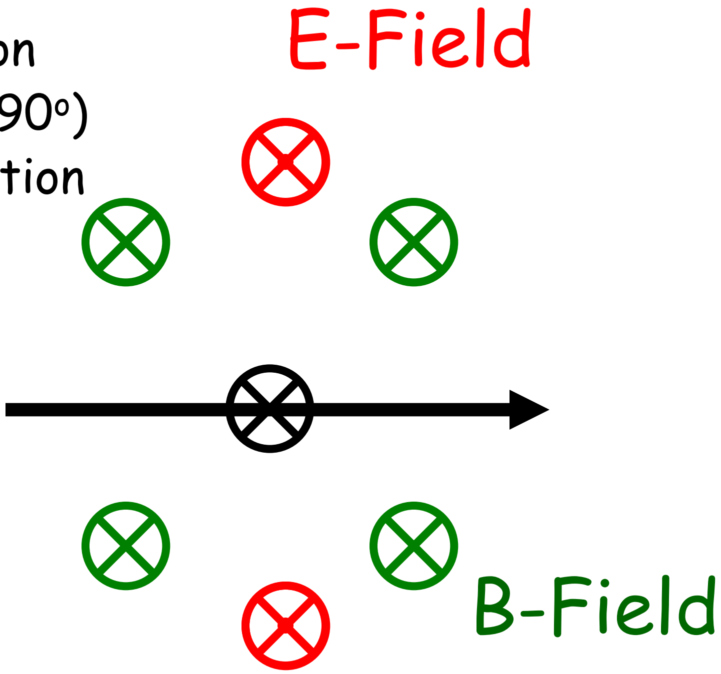
$$d_n = h\Delta\nu / 4E$$

$$d_n \pm \delta d_n = h/4E(\Delta\nu \pm \delta\Delta\nu)$$

$$\delta d_n = \frac{h}{4\pi\alpha} \cdot \frac{1}{T \cdot E \cdot \sqrt{N_0}}$$

Measurement principle

1. Inject a polarised neutron
2. Rotate the spin by $\pi/2$ (90°)
3. Change the E field direction
4. Measure the frequency difference



$$\nu = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

Measurement principle

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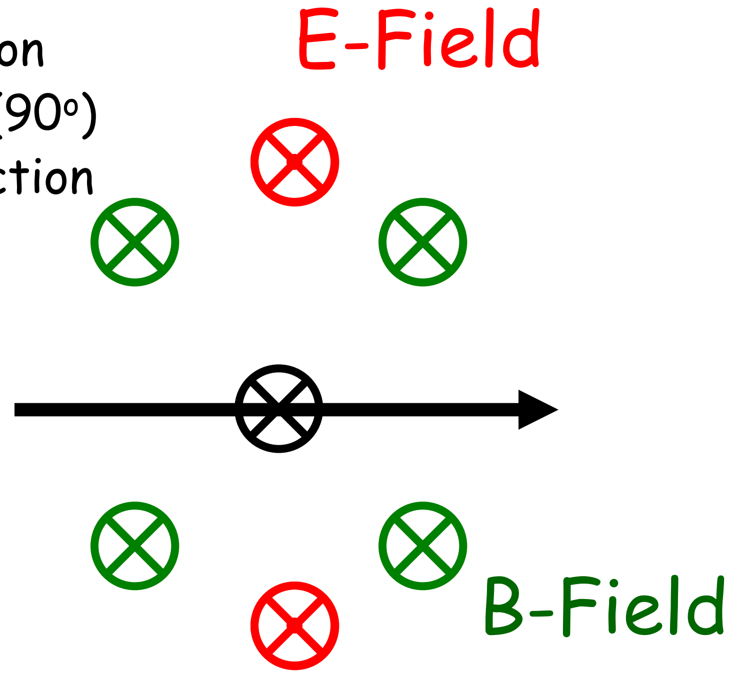
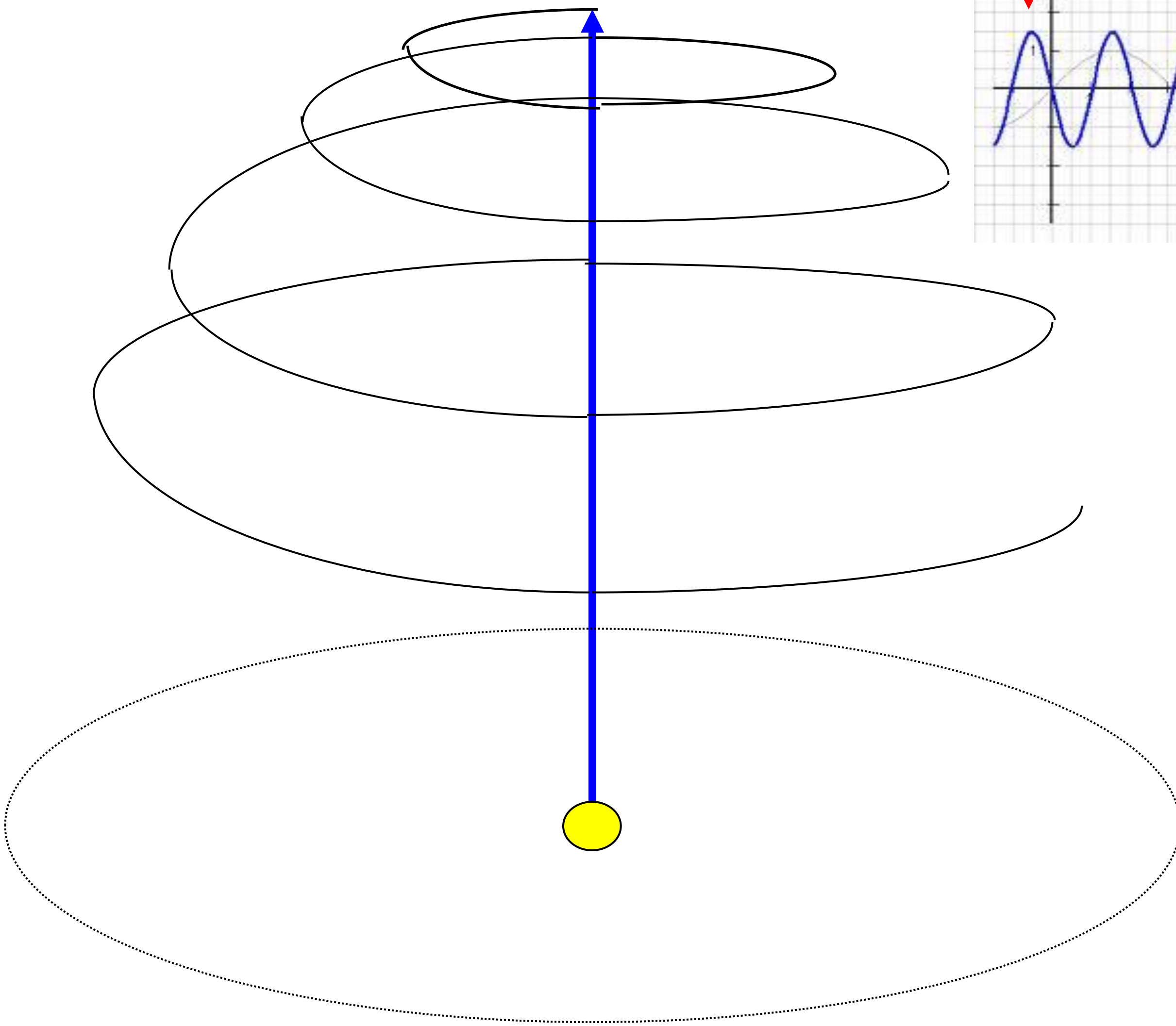
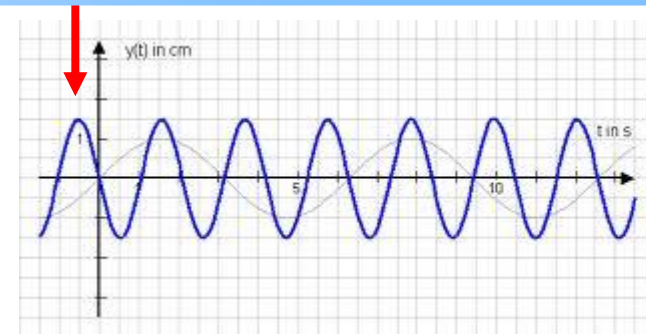


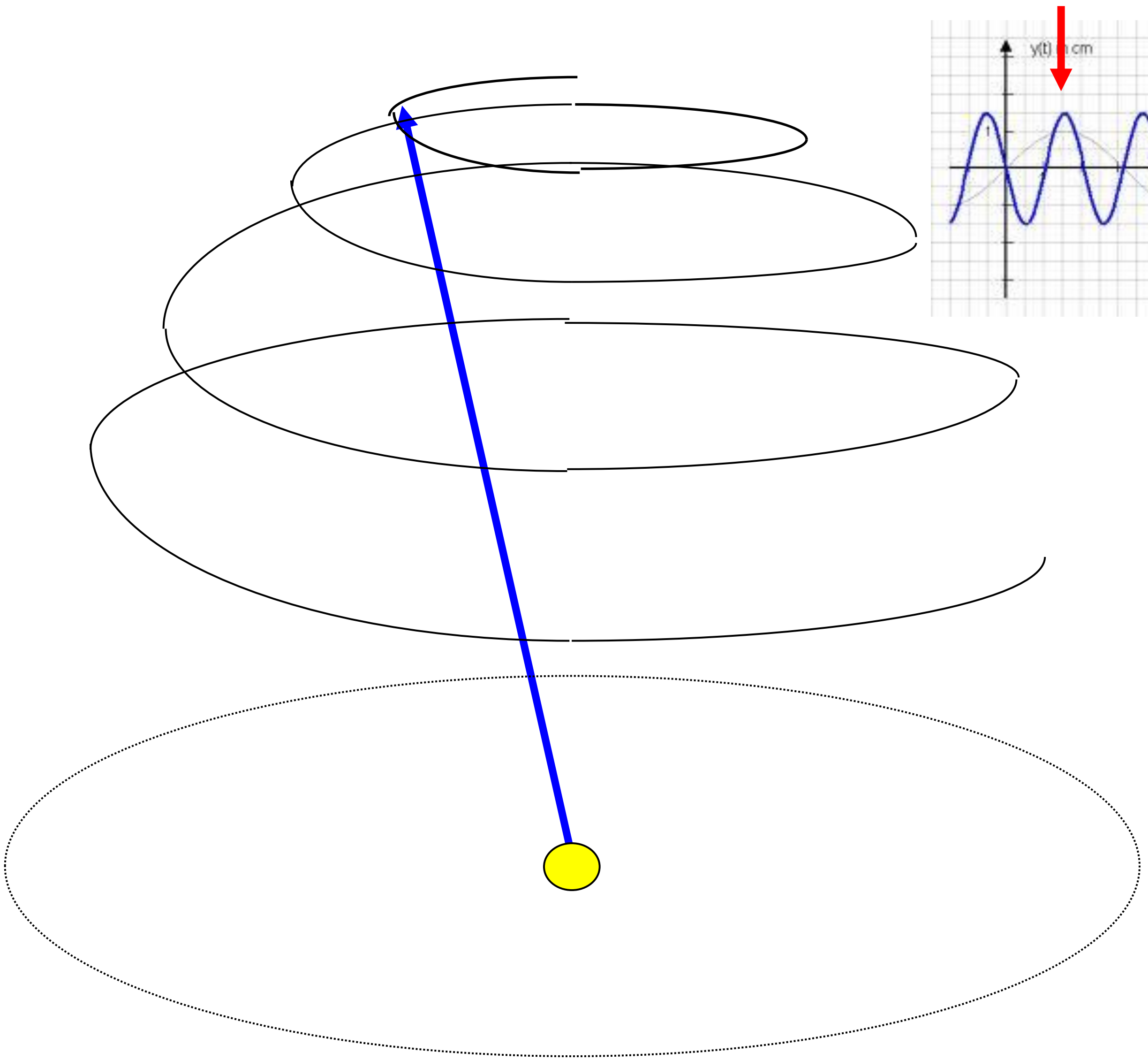
$$\nu = \frac{2\vec{\mu} \cdot \vec{B} \pm 2\vec{d} \cdot \vec{E}}{h}$$

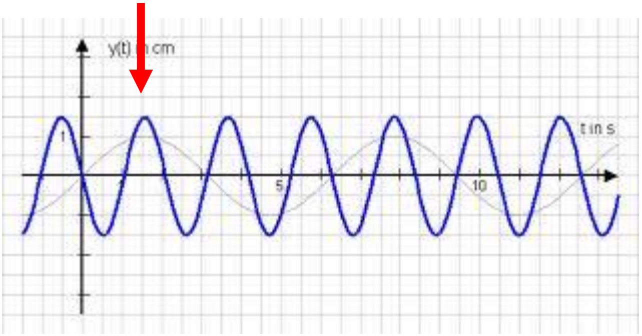
Oscillatory fields



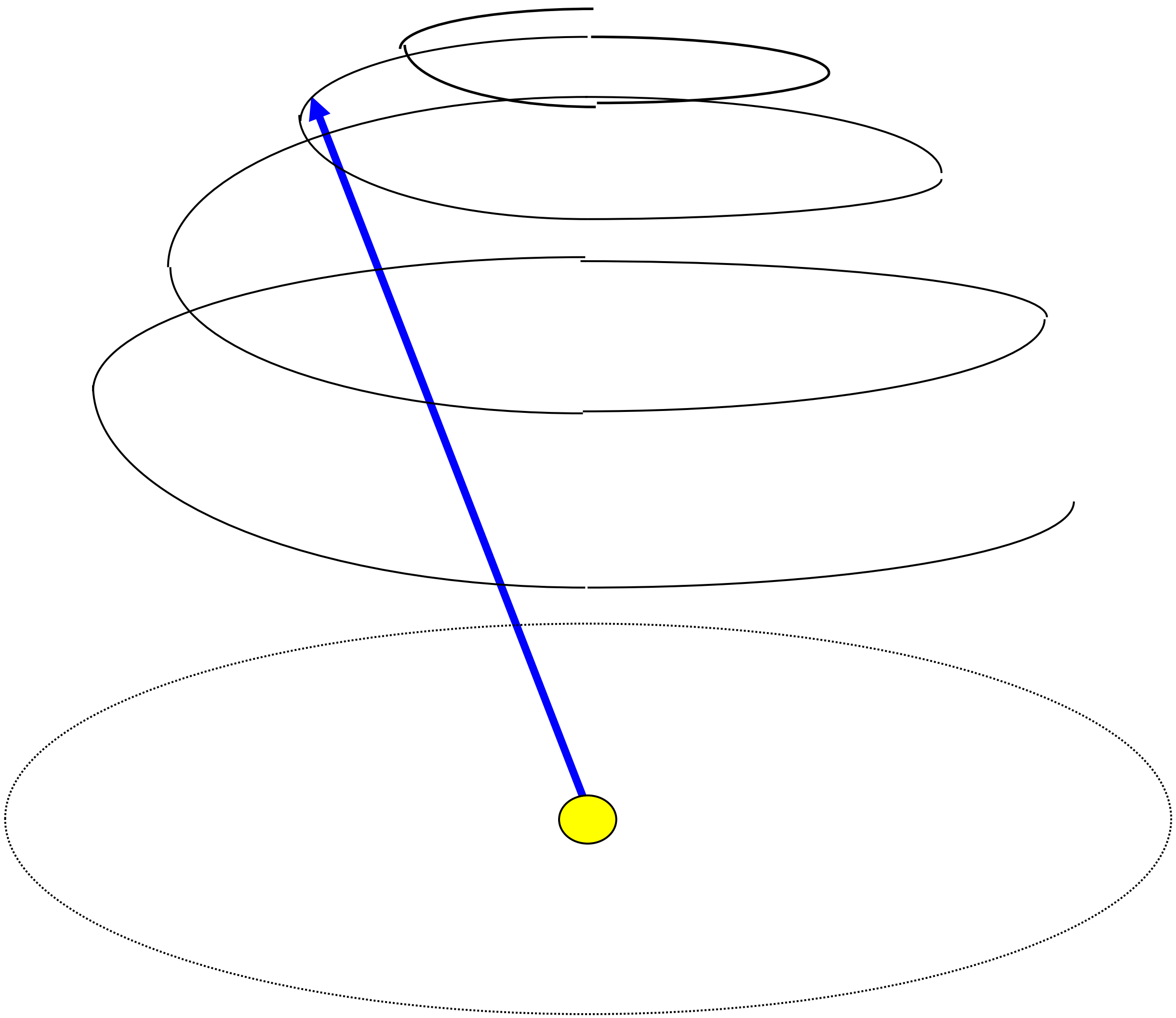


Oscillatory fields

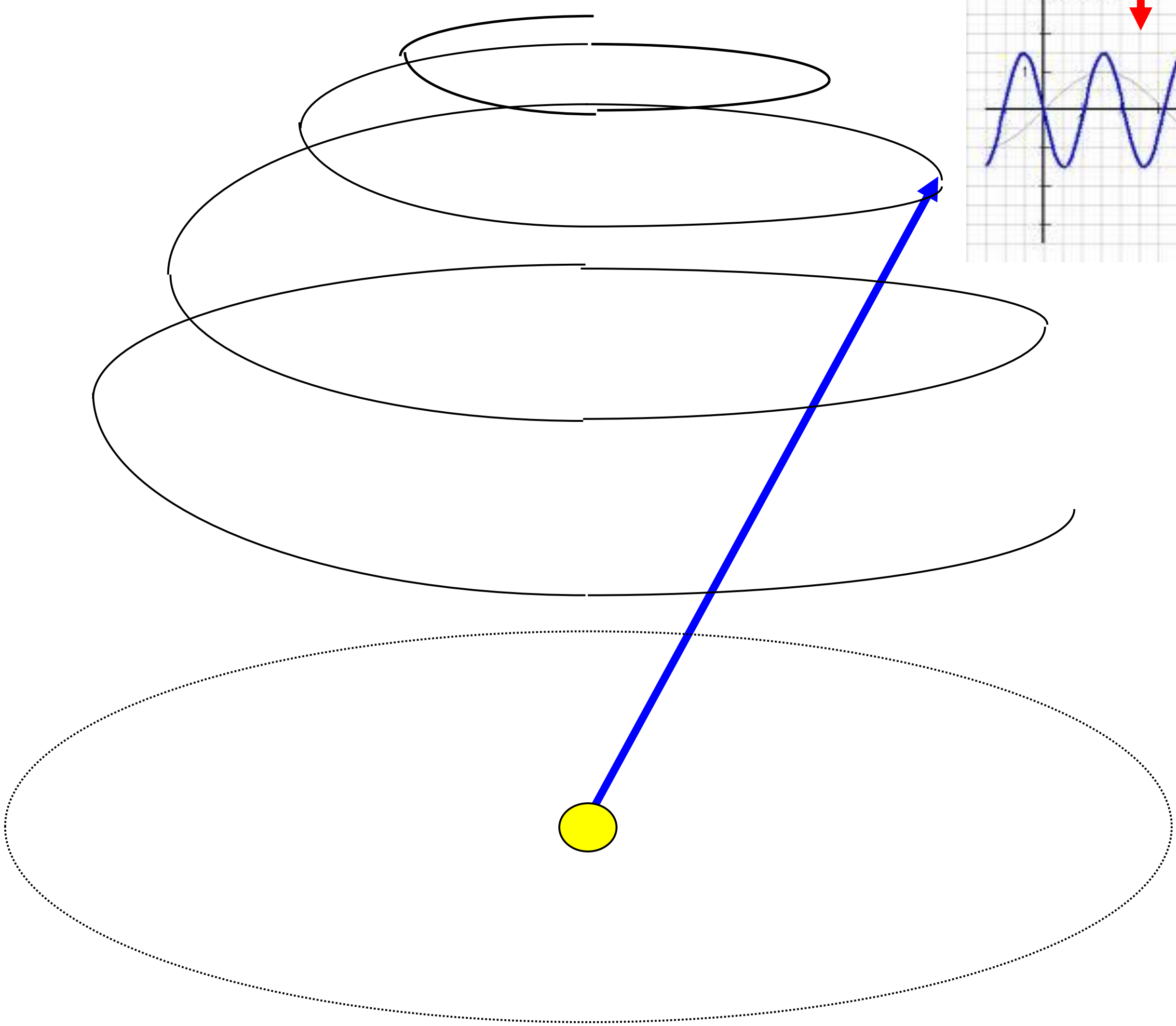


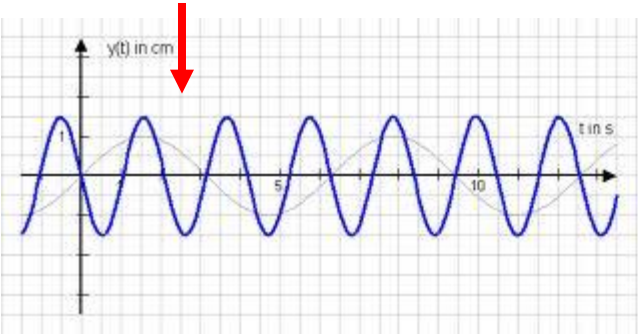


Oscillatory fields

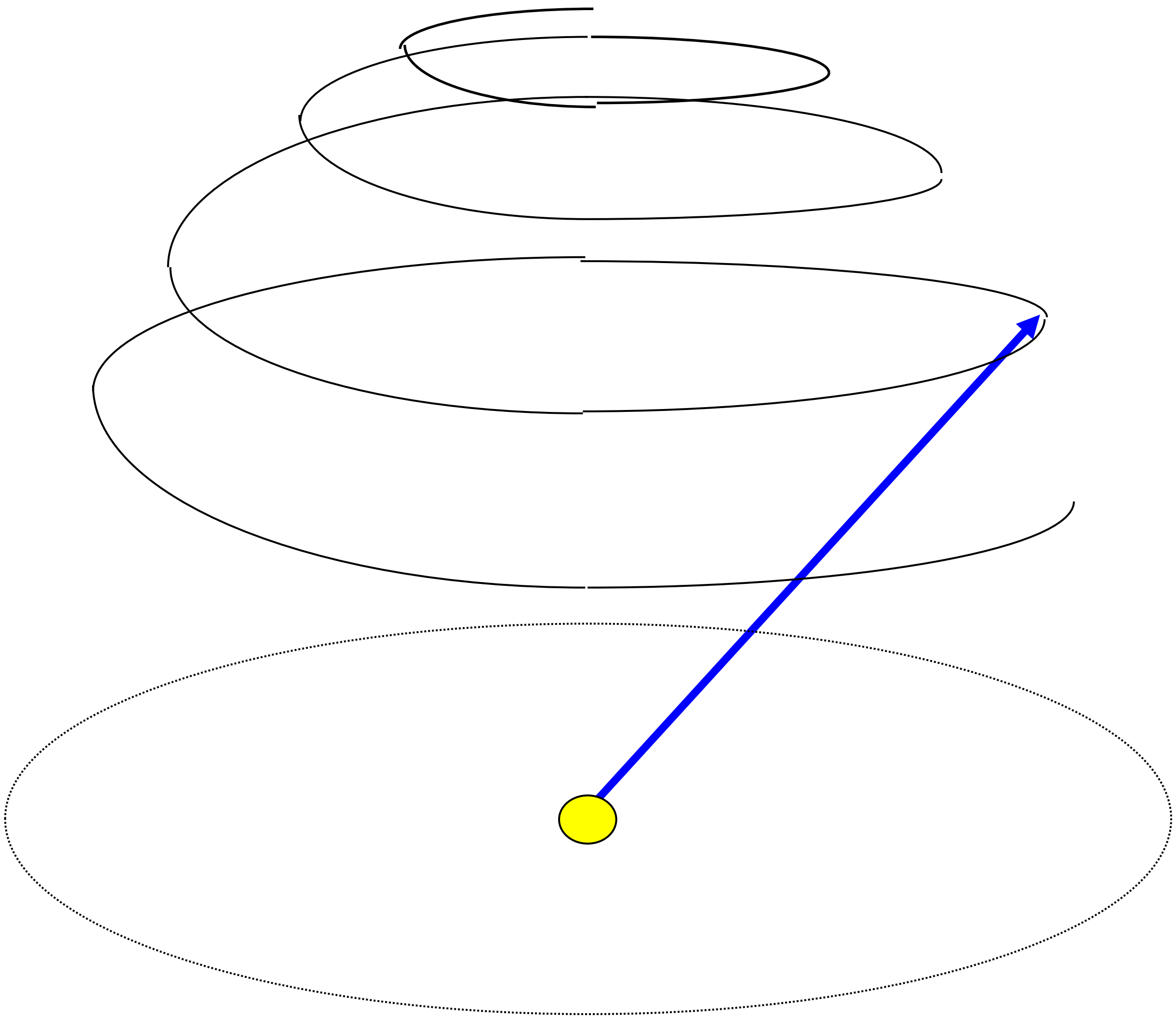


Oscillatory fields

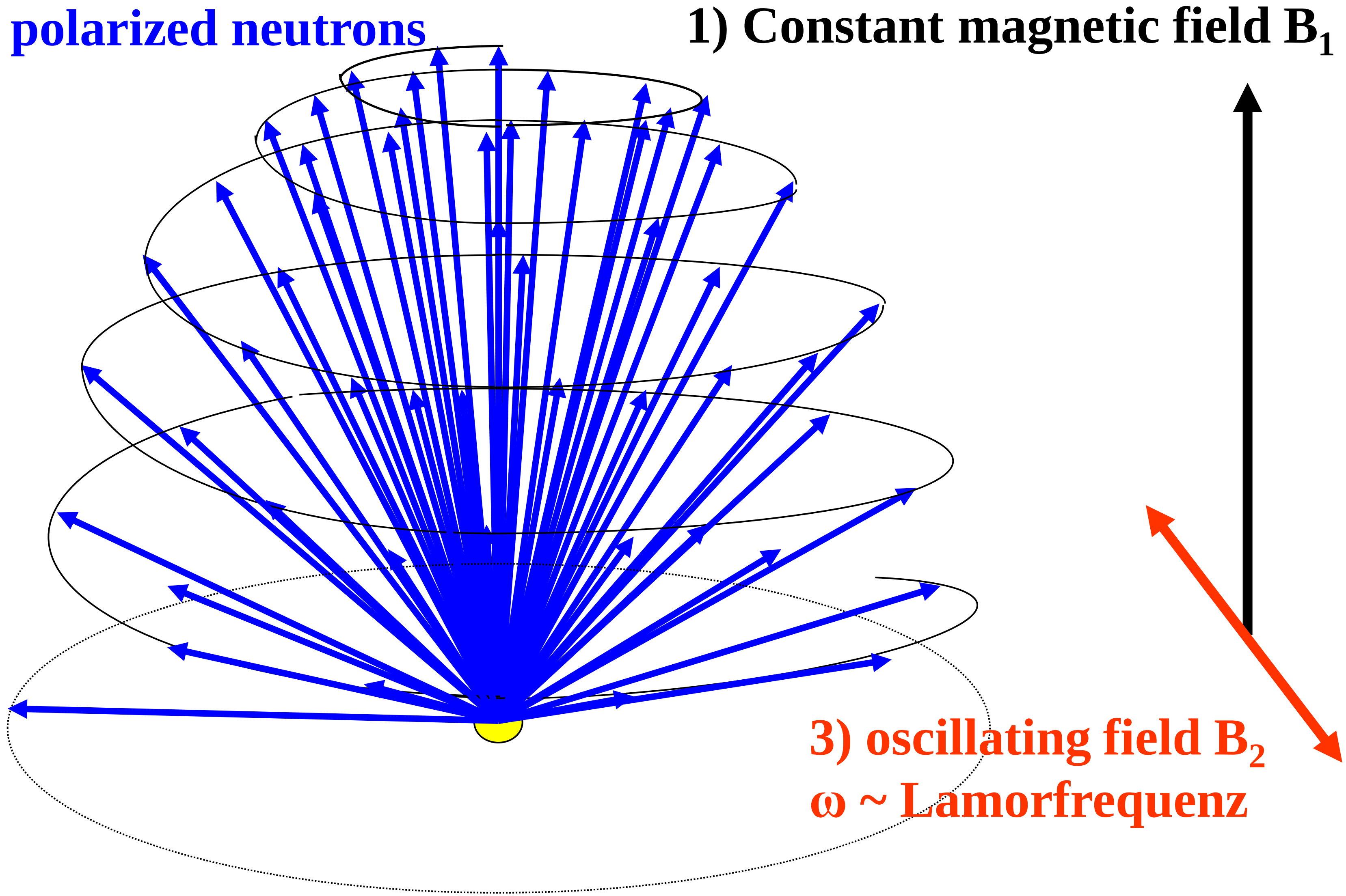




Oscillatory fields

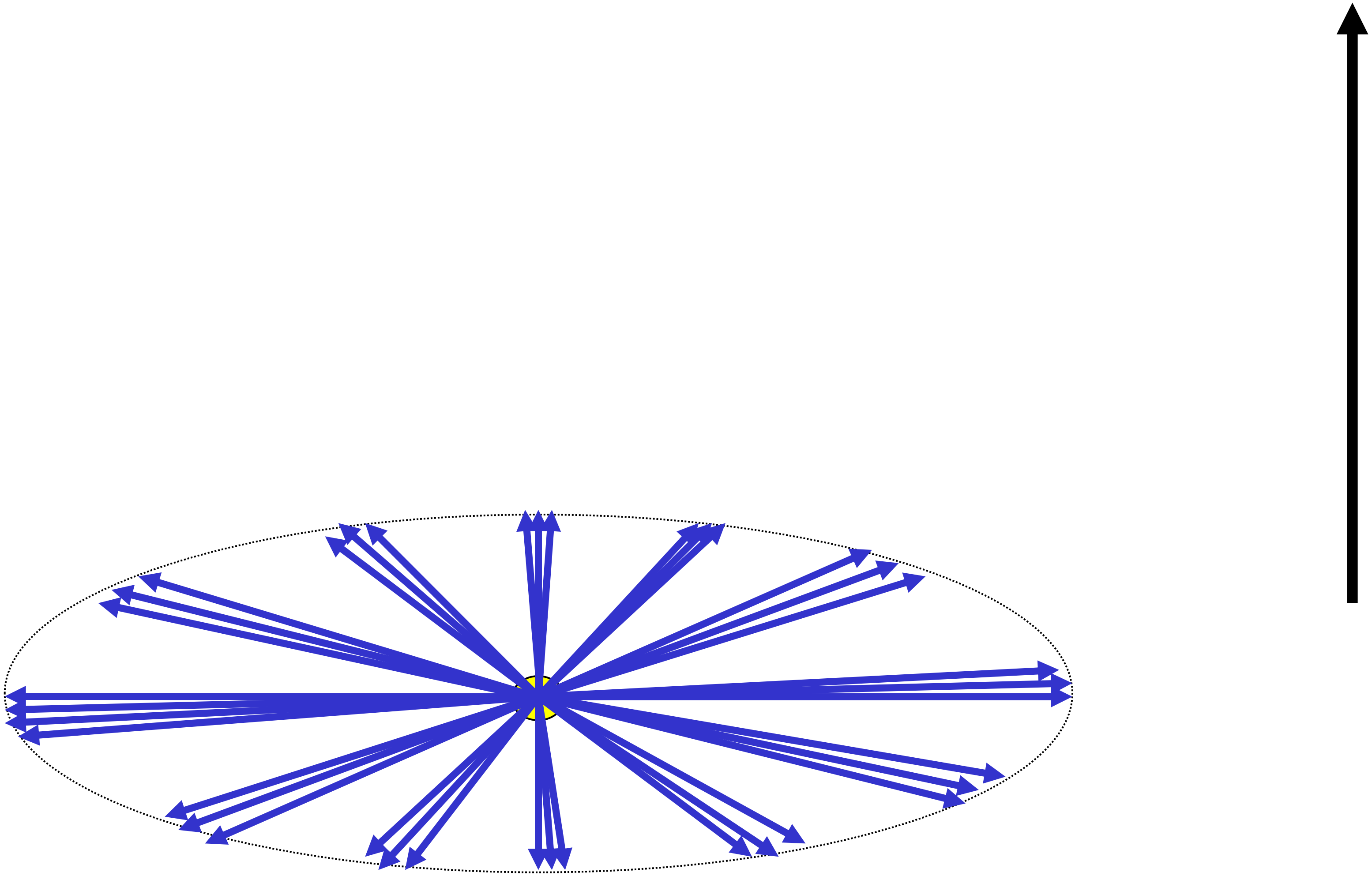


Oscillatory fields

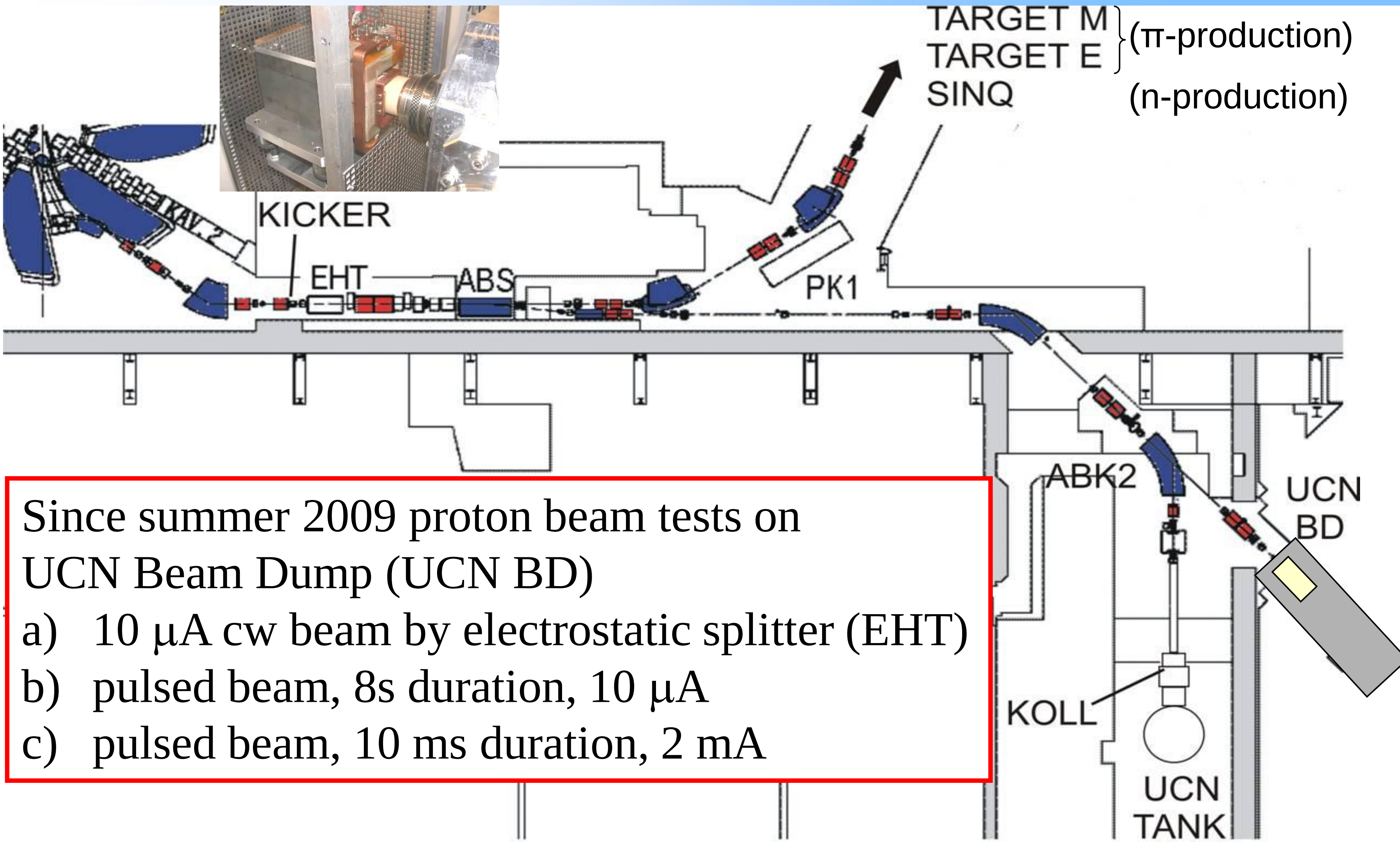


Oscillatory fields

Constant magnetic field B_1



Proton Beam Line Commissioned



Since summer 2009 proton beam tests on UCN Beam Dump (UCN BD)

a) 10 µA cw beam by electrostatic splitter (EHT)

b) pulsed beam, 8s duration, 10 µA

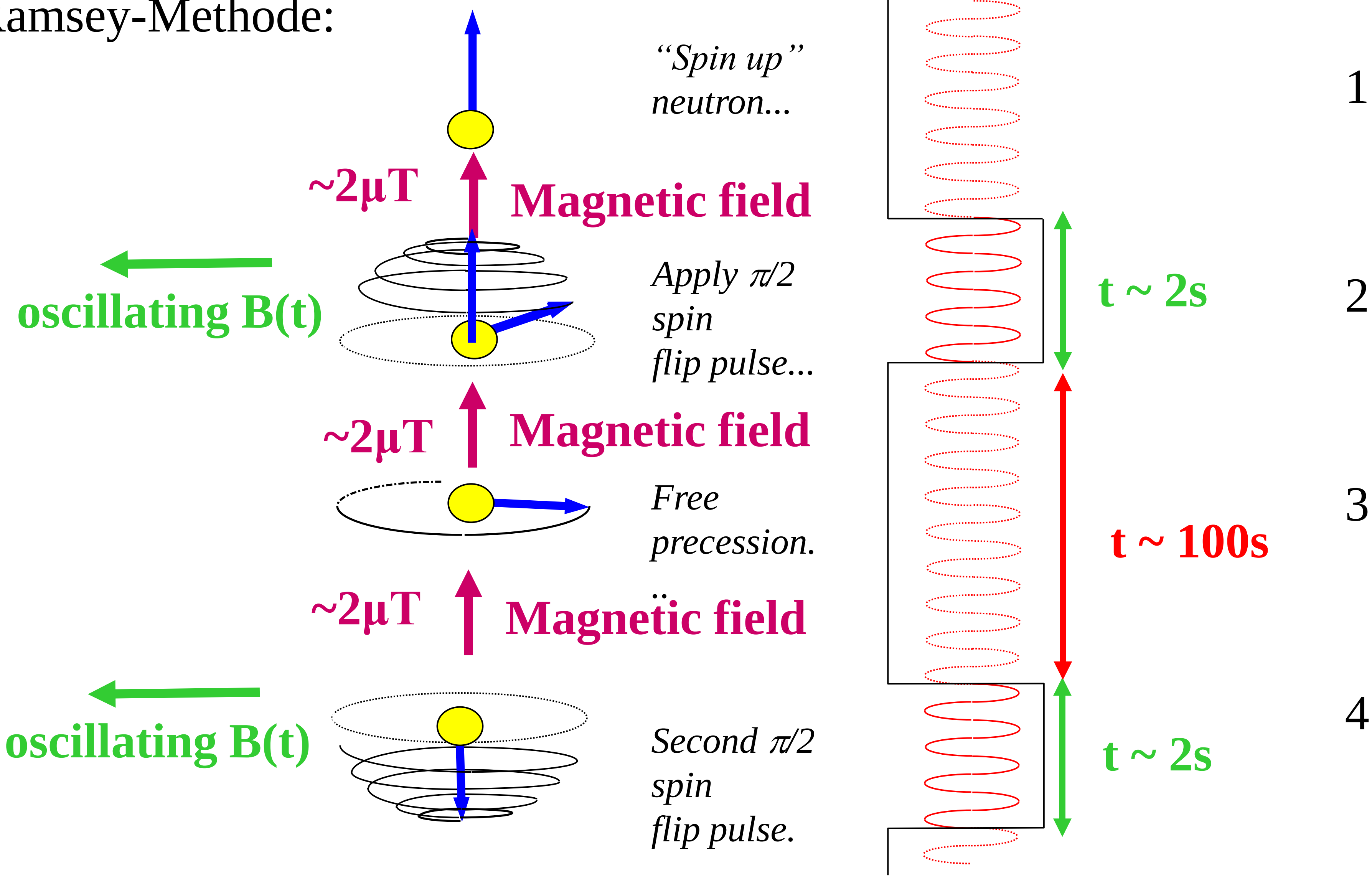
c) pulsed beam, 10 ms duration, 2 mA

PAUL SCHERRER INSTITUT

nEDM experiment

Ultra Cold Neutron Source

Ramsey-Methode:



The nEDM collaboration @ PSI