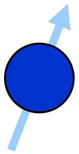
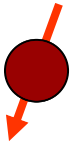


What a particle physicist does without an accelerator

The Neutron Electric Dipole Moment

James Karamath, University of Sussex



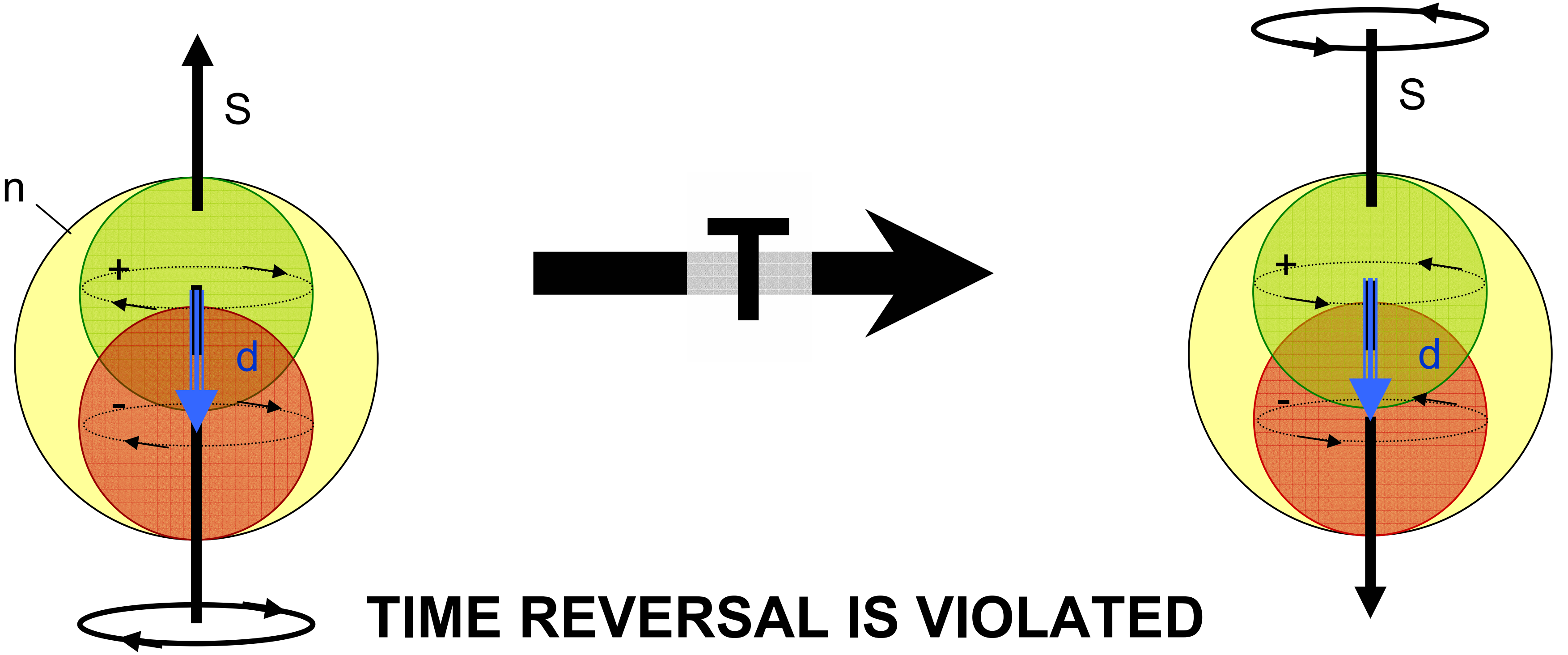
IOP-HEP Conference 2006

Overview of talk

- What is the neutron electric dipole moment (nEDM) and why measure it?
- How to measure it! - the physics
- How to measure it! - the experiment
- Summary

EDMs and time reversal

- If there is a charge distribution asymmetry there are implications for time reversal…



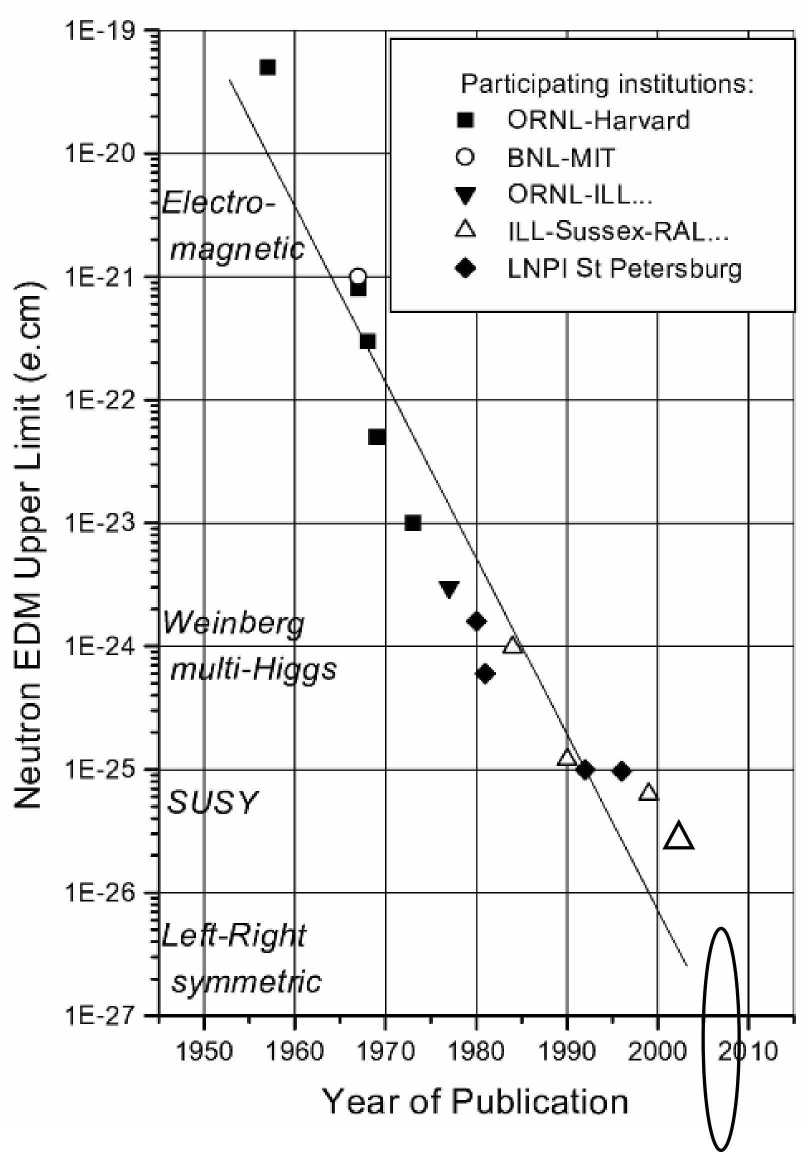
TIME REVERSAL IS VIOLATED

(In a similar way so is parity)

So…?

- nEDM ➔ **(C)P** and **T** violation at some level. Currently not enough **CP**V to explain matter-antimatter asymmetry.
- SM: no 1st order nEDM effects

  ➔ $d_n^{SM} \sim 10^{-31}$ecm
- Other theories…



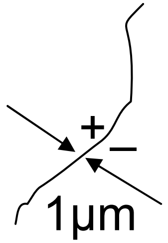
Results to date

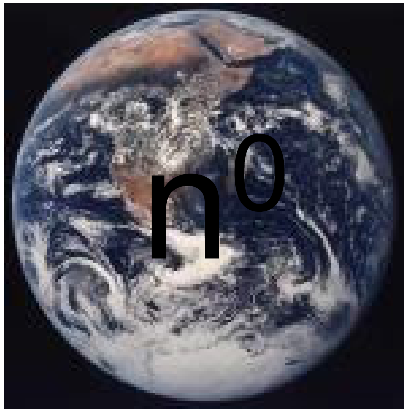
- Room temperature experiment complete!
- Soon to be published result:

$d_n = (+0.4 \pm 1.6(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-26}$) ecm

i.e. $d_n < 3.0 \times 10^{-26}$ ecm

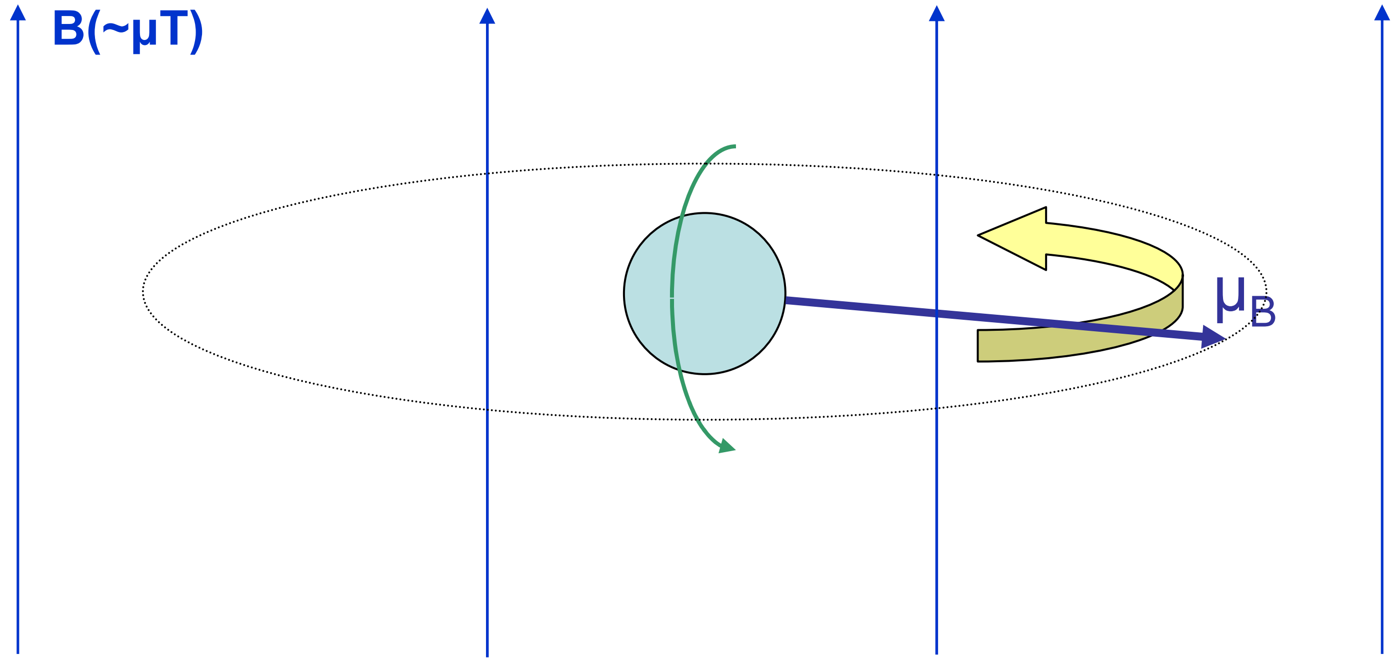
- New cryogenic experiment will be x100 more sensitive…





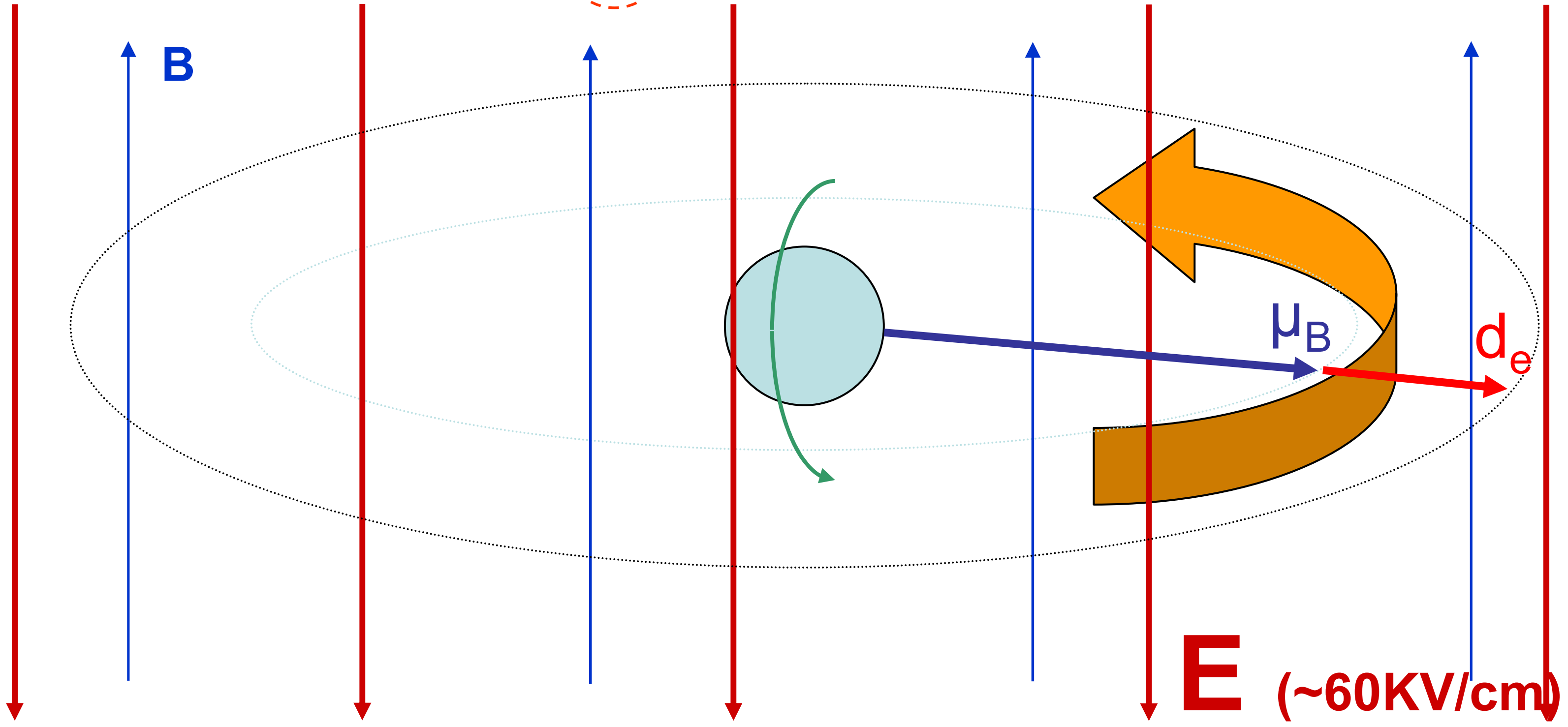
How to measure a nEDM

- B-field causes dipoles to Larmor precess, frequency determined by field magnitude.
- $E = h\nu_L = 2\mu_n.\mathbf{B}$



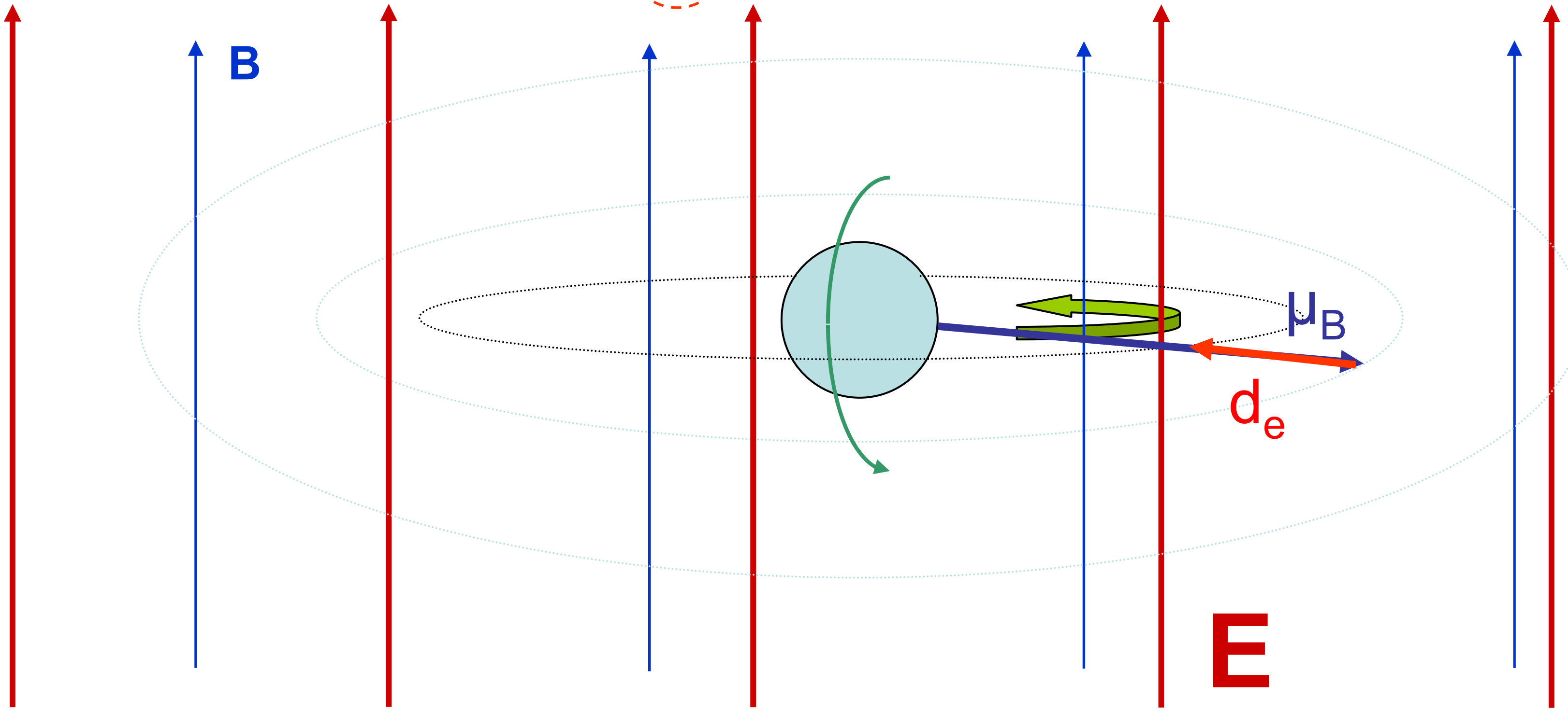
How to measure a nEDM

- B-field causes dipoles to Larmor precess, frequency determined by field magnitude.
- $E = h\nu_L = 2\mu_n.\mathbf{B} - 2d_n.\mathbf{E}$ frequency increase



How to measure a nEDM

- B-field causes dipoles to Larmor precess, frequency determined by field magnitude.
- $E = h\nu_L = 2\mu_n.\mathbf{B} + 2d_n.\mathbf{E}$ frequency decrease



How to measure a nEDM

- Thus measuring the difference in frequency of these two states gives the nEDM d_n…

$$\boxed{\Delta \nu = 4 d_n . \overline{E} / h}$$

- If $d_n = 10^{-26}$ecm and E = 10KV/cm ➔ $\Delta\nu$ = 0.1μHz, measured by NMR techniques.

Limiting uncertainty (statistics)

- Error from counting stats alone

$$\boxed{\delta\left(d_n\right)=\frac{\hbar}{2\alpha ET\sqrt{N}}}$$

α = detect/polarise efficiency
E = **E**-field strength
T = neutron storage time
N = total # counted

→ 10^{-28}ecm

Systematics

- Biggest concern: keeping B-field extremely uniform

$$h(\nu_{\uparrow\uparrow}-\nu_{\uparrow\downarrow}) = 2|\mu_B|(B_{\uparrow\uparrow}-B_{\uparrow\downarrow}) - 4d_nE$$

False signal due to varying B ☹

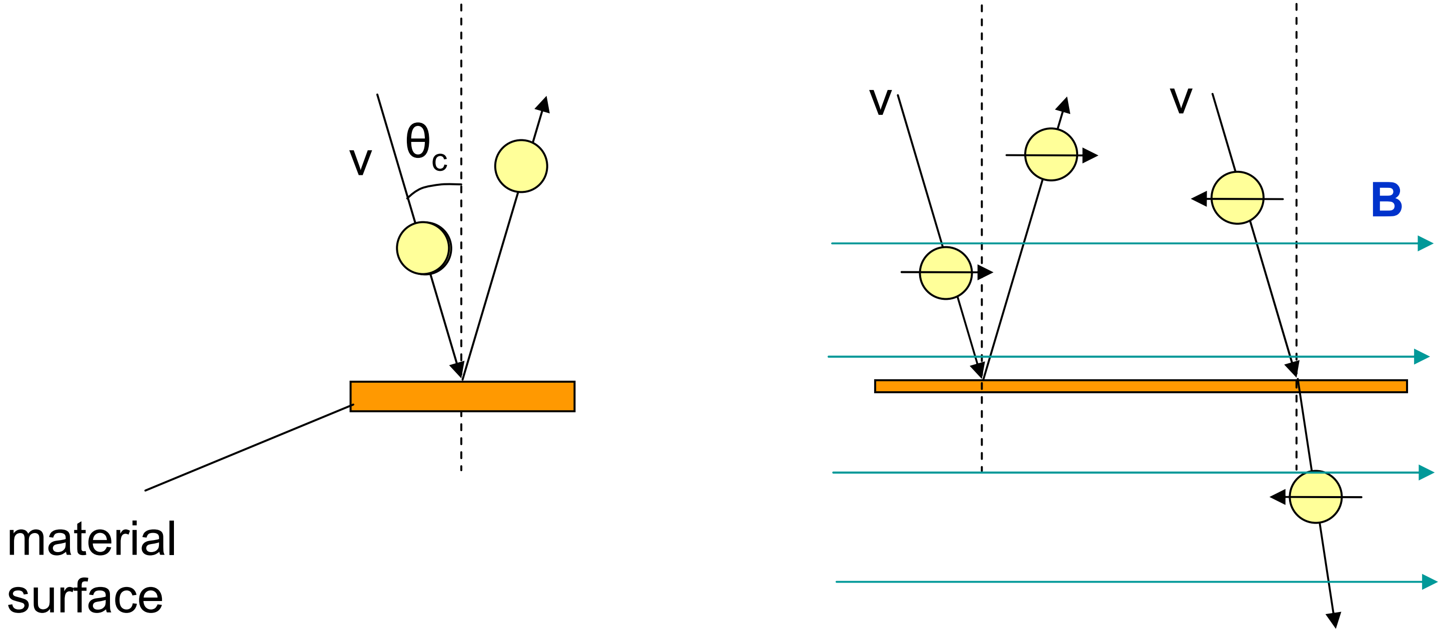
True nEDM signal ☺

- Mu-metal & superconducting shields and active correction coils reduce external perturbations.
- SQUIDS & magnetometer cells measure variation and gradients in B-field.
- Flip directions of E (should reverse $\Delta\nu$) relative to B every so often.

Ultra Cold Neutrons

$$\delta(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

UCN: E~neV, v~ms^{-1}



Can trap (and guide) neutrons below a critical speed.

Can polarise and spin analyse these neutrons α~1.

Can store neutrons for a long time T~400s.

$$\delta(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

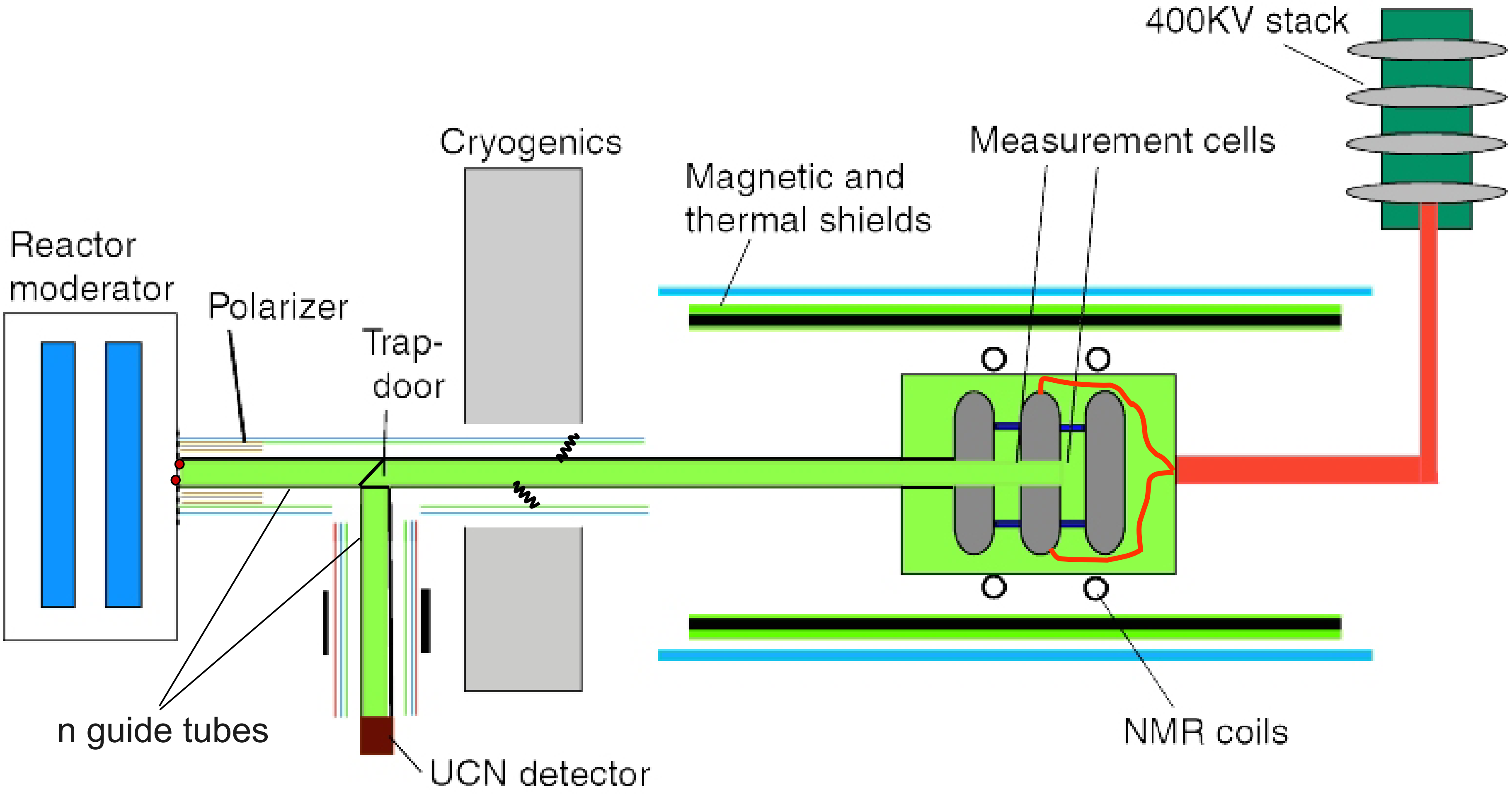
Superfluid Helium-4

1) Cold neutrons (0.89nm) lose all energy by phonon emission in superfluid He ➔ UCN.
2) Cold surrounding reduce neutron scattering to higher (non-storable) energies
3) High dielectric strength, will accept the extreme electric field necessary across it without breakdown.

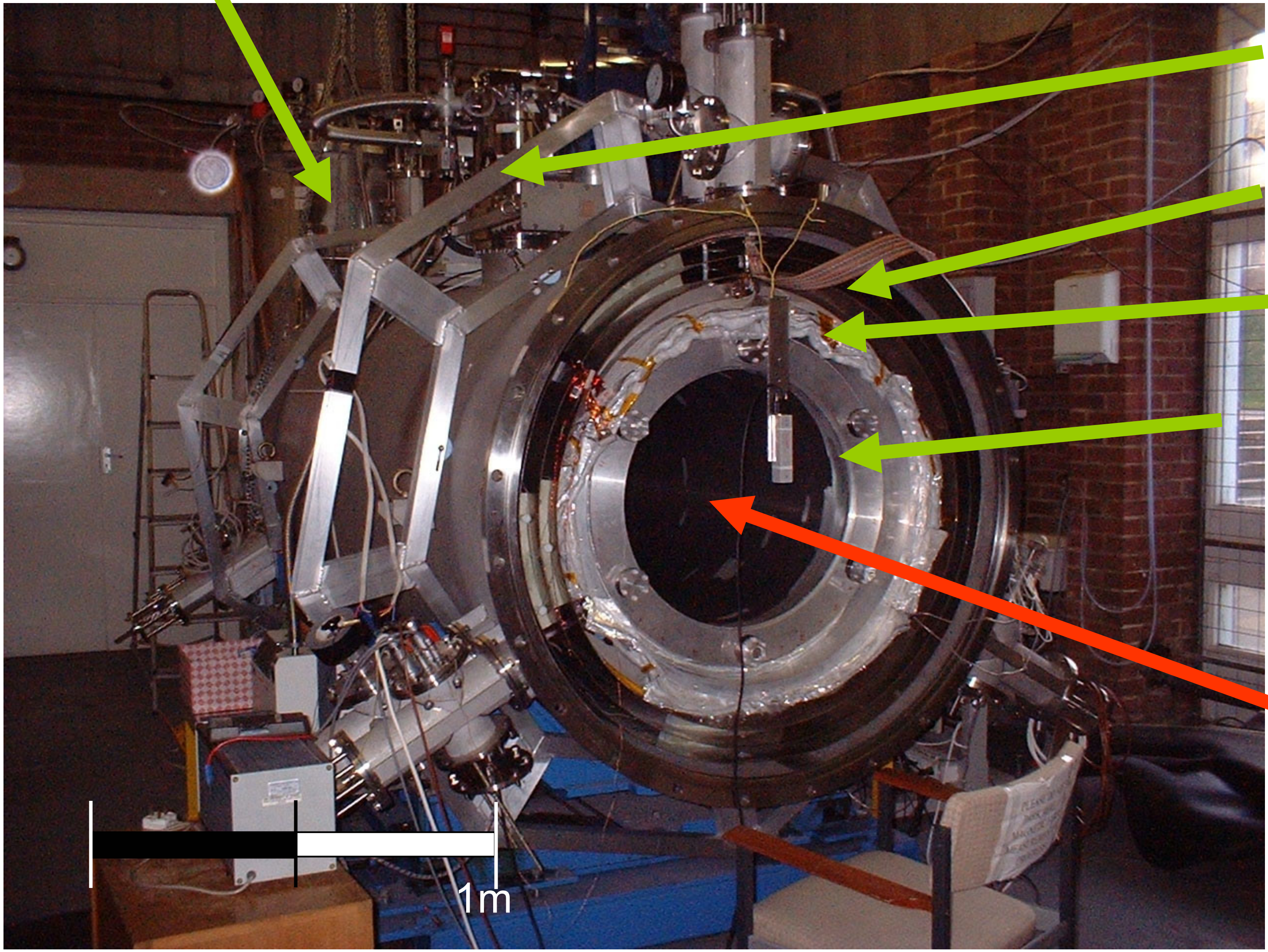
Can produce a large number N of UCN

Can sustain E~100KV/cm.

Core experimental setup



Checklist



Cryogenics

Field correction coils

Magnetic (mu-metal) shields

Thermal shielding

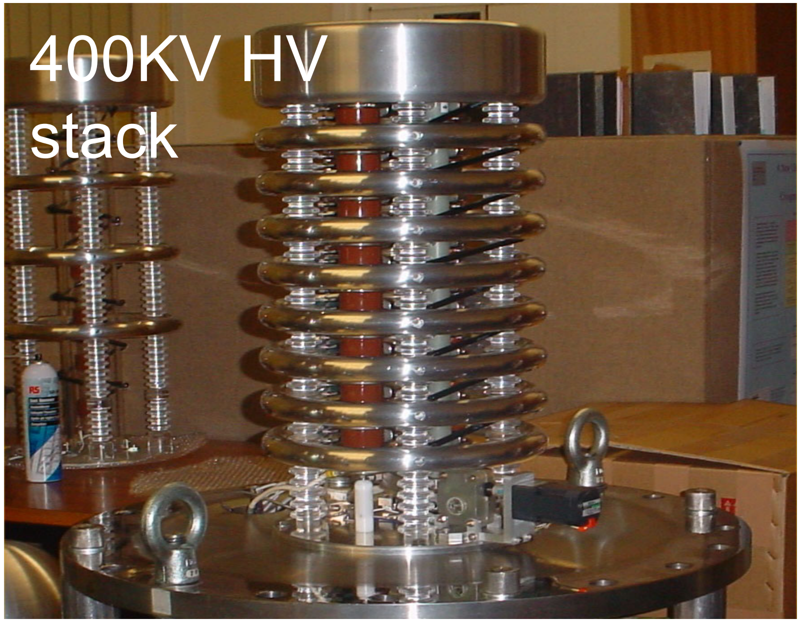
Superconducting shield ✓

Ramsey (NMR) chamber

HV feed line & electrodes

Checklist

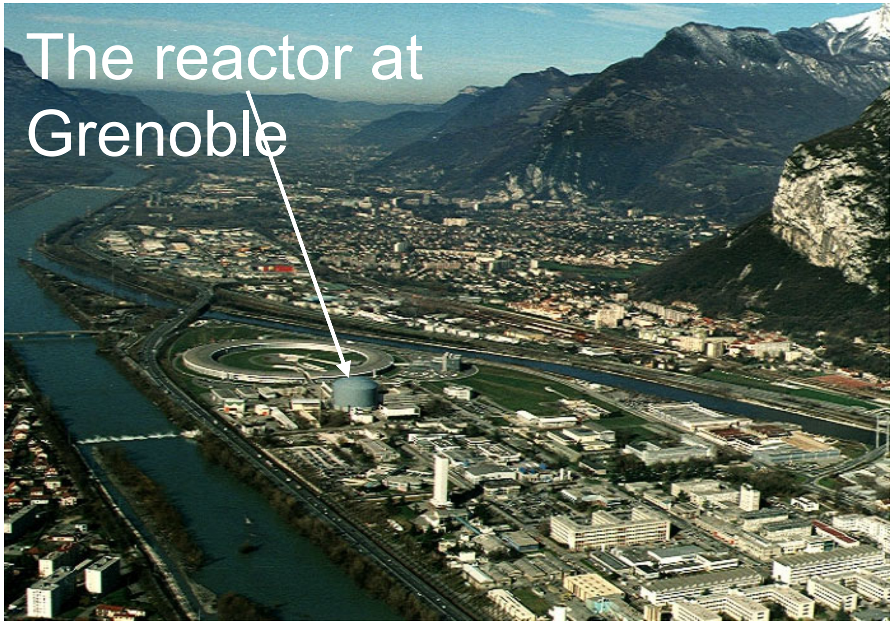
- Not shown was the high voltage supply. Essentially just a voltage multiplier to 400KV. ✓


400KV HV stack


Be coated Cu n guide tubes

- Guide tubes – Be coated Cu polished to ~5nm finish, from reactor to start of experiment ✓

Checklist

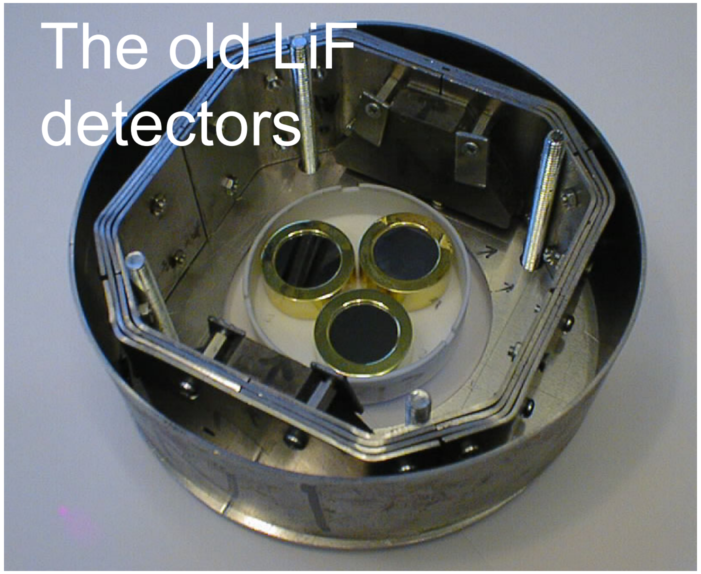


Also need the nuclear reactor at ILL for an intense source of cold neutrons at 89nm!

✓

Finally the neutrons are spin analysed and detected on silicon SS detectors coated in ^{6}LiF to utilise the ^{6}Li(n,α)t reaction (works in sfHe)

✓



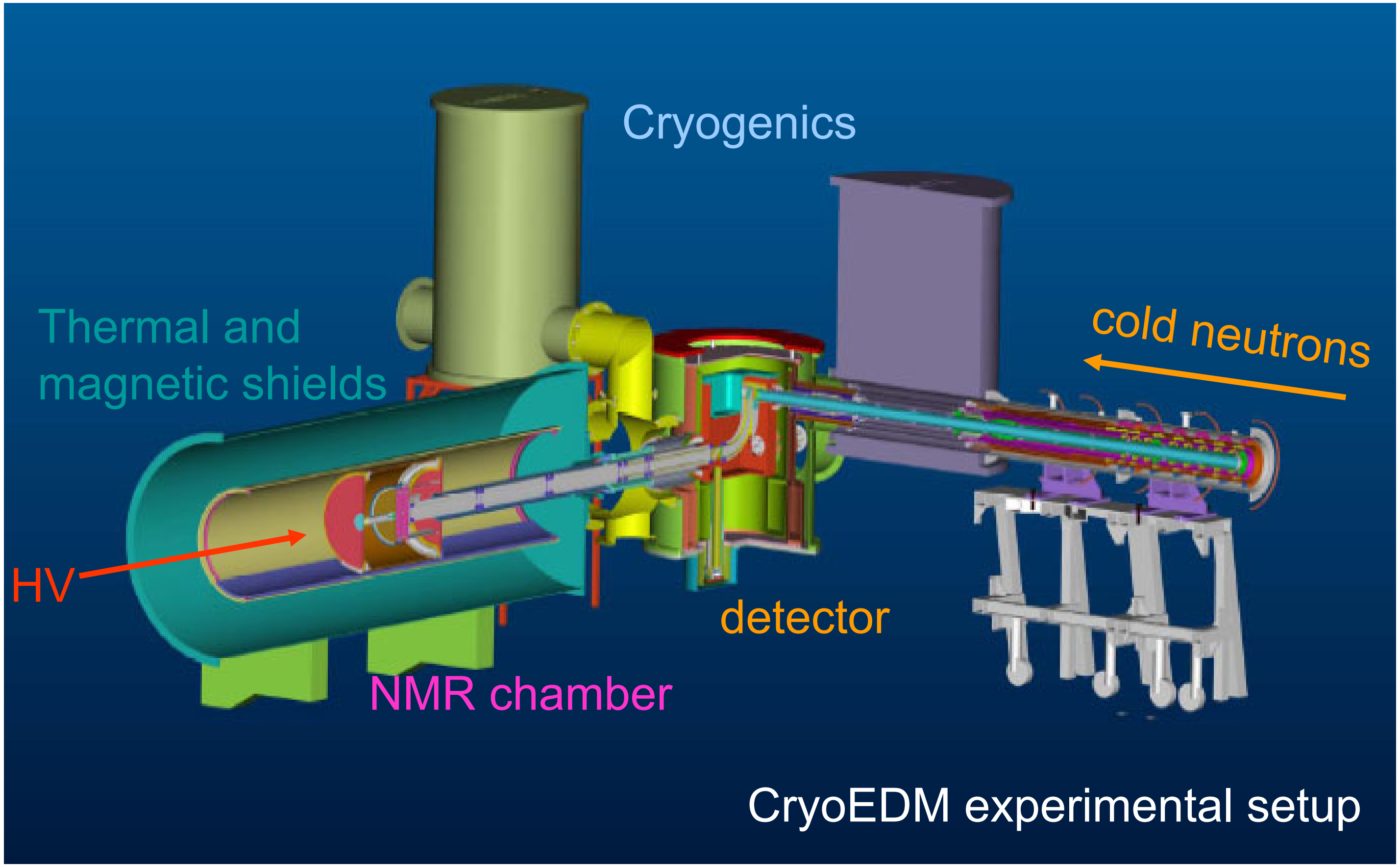
Summary

- nEDM key way to investigate T-violation and distinguish between various models, RT result already constraining SUSY ($\Phi_{CP}<10^{-2}$)
- Improvements (x100):
  - ↑N: better guides, He-II
  - ↑E: He-II dielectric
  - ↑α: better polarising
  - ↑T: He-II, UCN

- Aiming for 10^{-27} ecm by end 2006 and 10^{-28} ecm (further improvement to guides to increase N) by 2008.

End

- www.neutronEDM.org



CryoEDM experimental setup

Spare slides

- Problems
- Ramsey fields
- Setup
- Ramsey Chamber shinanogans

A fraction of the problems!!!

- Actual lifetime of the neutron (losses)

  hydrogen sub-layer, very pure He-4, extreme tolerances (Cu guides, fitting and electrode-insulator fitting in cells), depolarisation…

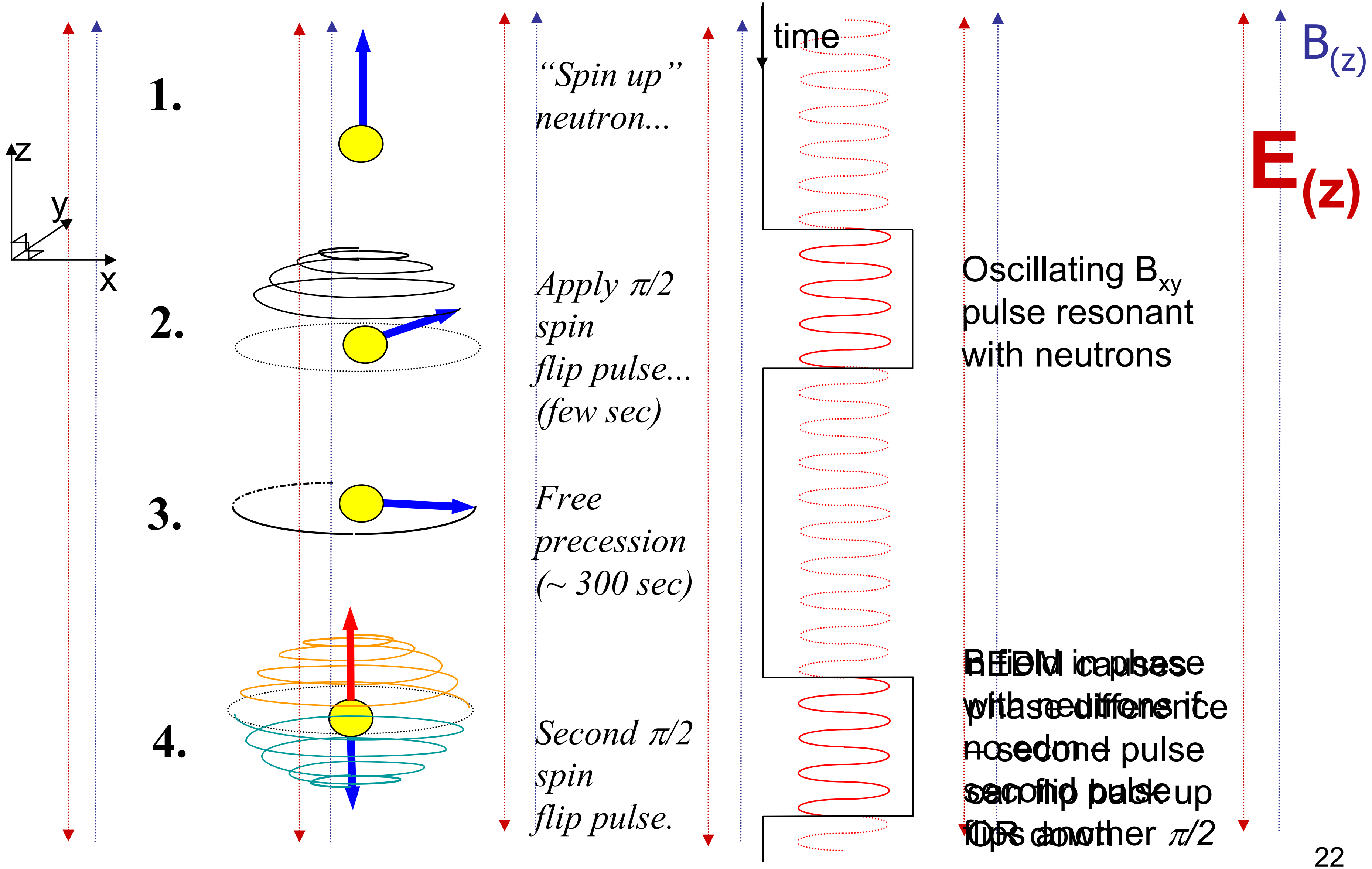
- Magnetic issues (non-uniformities)

  geometric phase effects (radial component to B-field combined with **E**x**v** effects), avoiding st. st., external perturbations, mu-metal hysteresis, leakage currents, HV feedback and ripple etc…

- General issues

  Different materials – thermal contractions, investigating high voltage discharge in He-II…, residual **E**x**v** effects

“Ramsey’s Oscillating Fields”



1. *“Spin up” neutron…*

2. *Apply $\pi/2$ spin flip pulse… (few sec)*

3. *Free precession (~ 300 sec)*

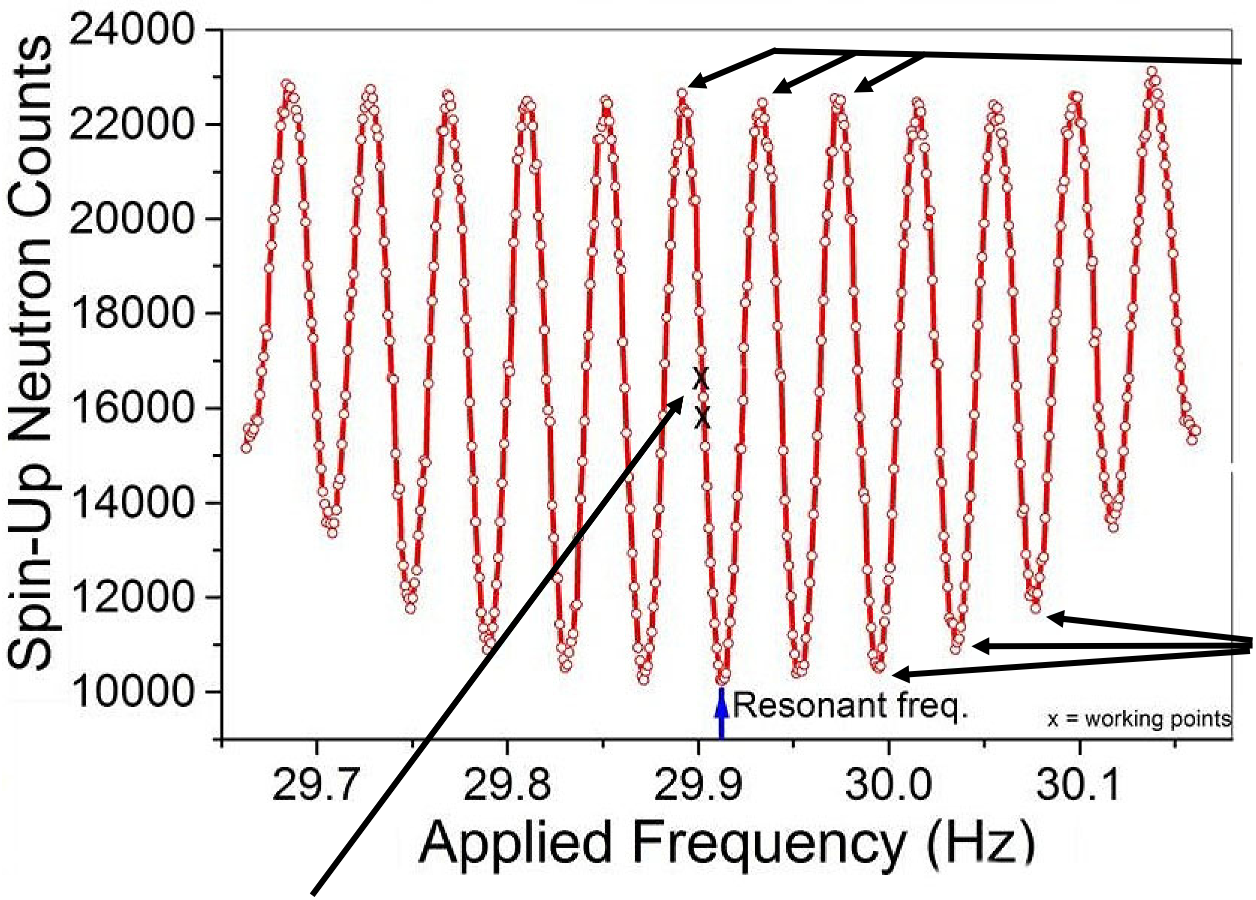
4. *Second $\pi/2$ spin flip pulse.*

Oscillating B_{xy} pulse resonant with neutrons

BField in phase
with neutrons if
no edm –
second flip pulse
flips down

nEDM causes
phase difference
second pulse
can flip back up
for another $\pi/2$

Ramsey Oscillatory Fields II



Off resonance by (2n−1)π

Off resonance by 2nπ

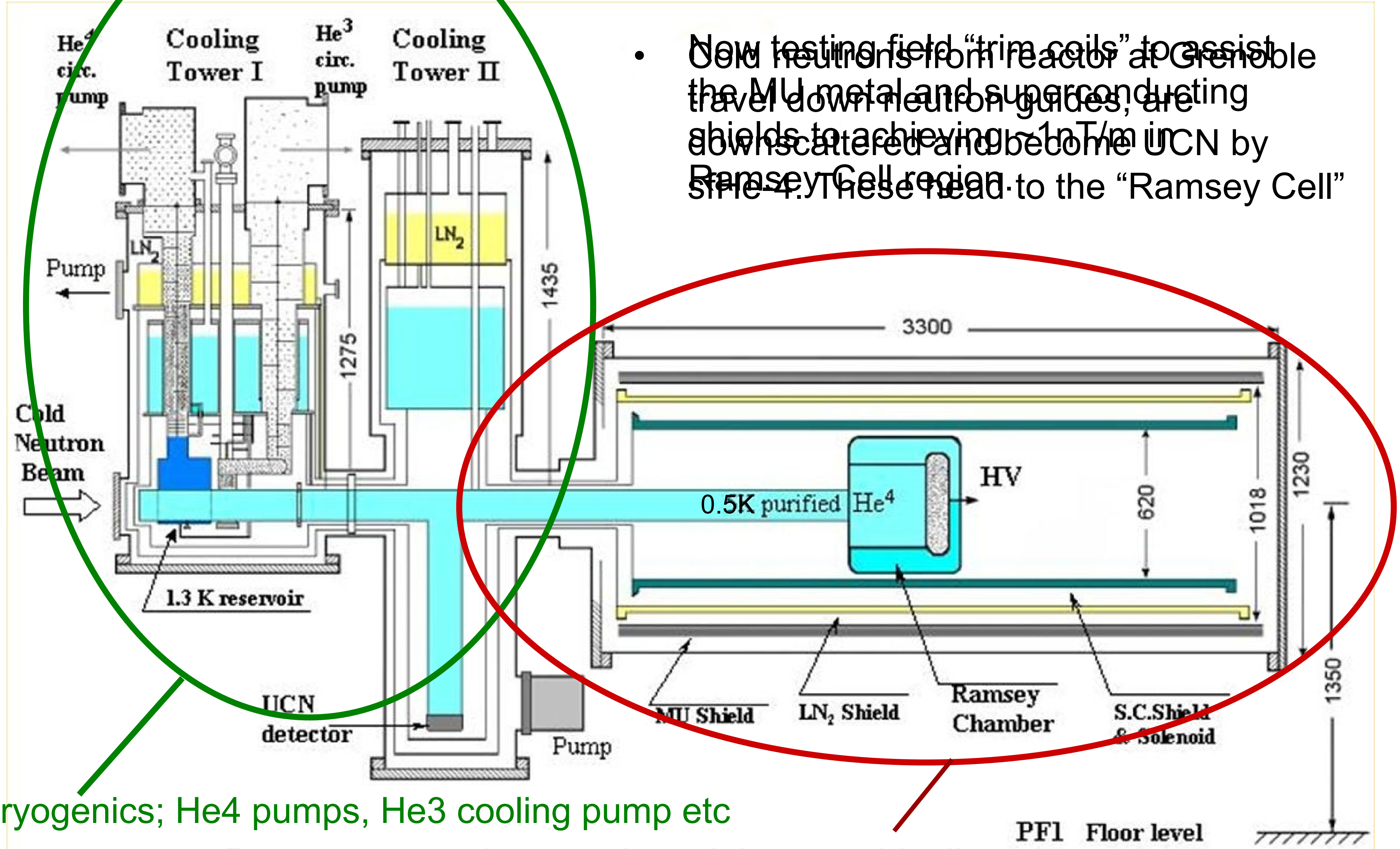
Working points i.e. where rate of change of neutron count as function of frequency is maximal ➔ small extra off resonance <u>due to an nEDM</u> (and many other things ☹) gives large change in neutrons counted.

Similar curve for spin-down counts, reverse troughs and peaks

The experiment – core setup

- Cold neutrons from reactor at Grenoble travel down neutron guides, are downscattered and become UCN by sfHe-4. These head to the “Ramsey Cell”

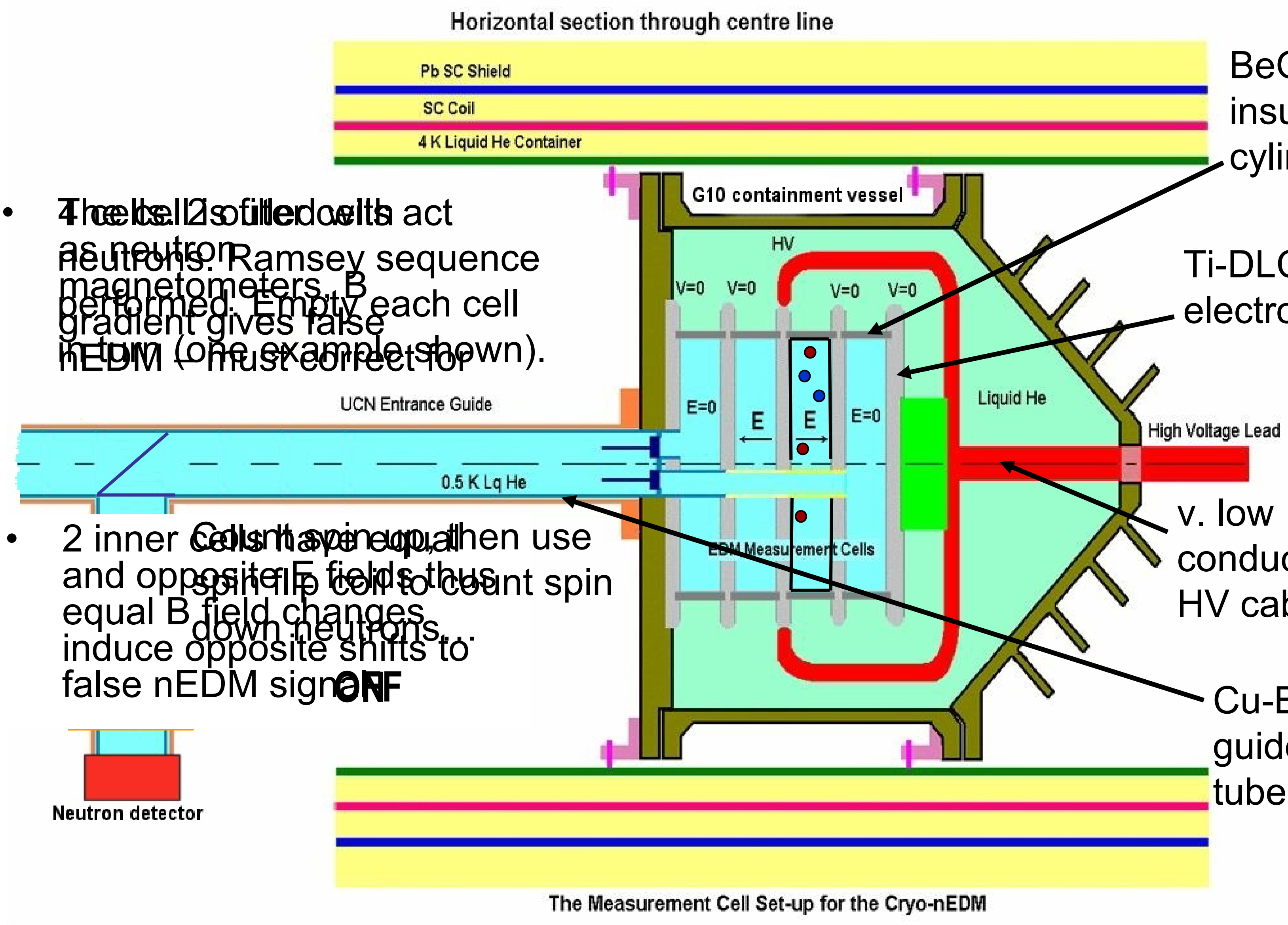
- Now testing field “trim coils” to assist the MU metal and superconducting shields to achieving ~1nT/m in Ramsey Cell region.



cryogenics; He4 pumps, He3 cooling pump etc

Ramsey cell and magnetic and thermal shielding

The Ramsey Cell



The Measurement Cell Set-up for the Cryo-nEDM

BeO insulating cylinders

Ti-DLC electrodes

v. low conductance HV cable

Cu-Be guide tubes

- The cell is filled with neutrons. Ramsey sequence performed. Empty each cell in turn (one example shown).
- 4 cells. 2 outer cells act as neutron magnetometers. B gradient gives false nEDM – must correct for
- Count spin up, then use spin flip coil to count spin down neutrons…
- 2 inner cells have equal and opposite E fields thus equal B field changes induce opposite shifts to false nEDM signal

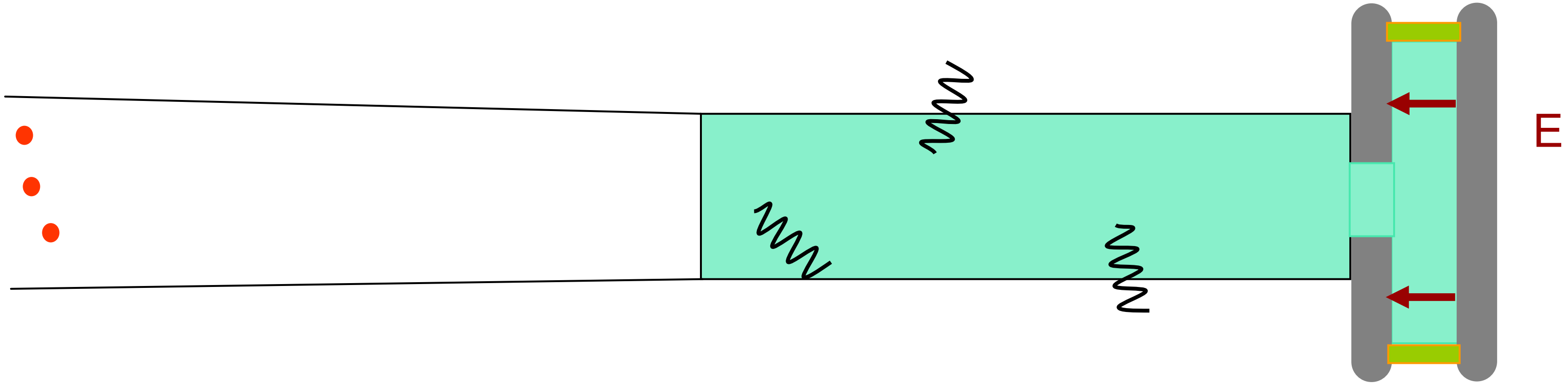
ON

OFF

Superfluid Helium-4

$$\delta(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

1) Cold neutrons (0.89nm) lose all energy by phonon emission in superfluid He ➔ UCN.
2) High dielectric strength, will accept the extreme electric field necessary across it without breakdown.



Can produce a large number N of UCN

Can sustain E~100KV/cm.