Searching for New Physics at the intensity frontier

(at low energies with lots of particles)
Part III

Niklaus Berger

Institut für Kernphysik, Johannes-Gutenberg Universität Mainz

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JG|U

Emmy Noether-Programm
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DFG

Overview

Why and where to search for new physics:

- Triumph and tragedy of the Standard Model

Proton decay:

- Watching lots of water

Proton radius, neutron lifetime:

- Puzzling discrepancies

Muon magnetic moment:

- Measuring and calculating at the precision limit

The electric dipole moment of the neutron:

- Particles in a bottle

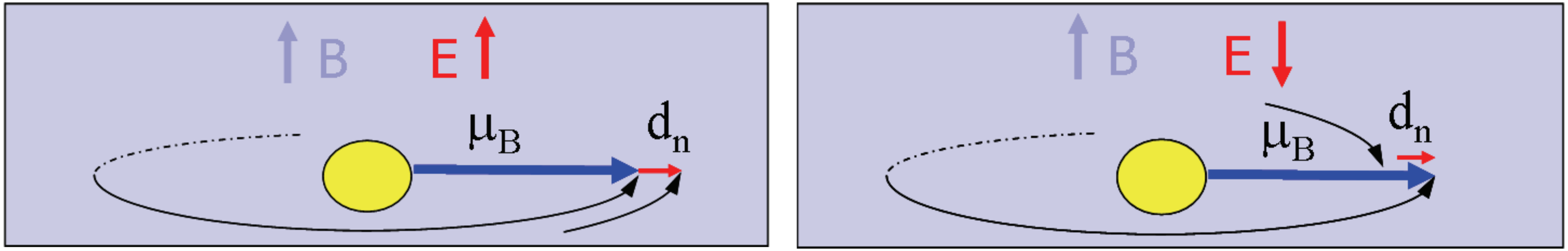
The weak mixing angle:

- New Physics in tiny differences between left- and right-handed

Neutron Electric Dipole Moment

P. Schmidt-Wellenburg

Measure the difference of precession frequencies in parallel/anti-parallel fields:



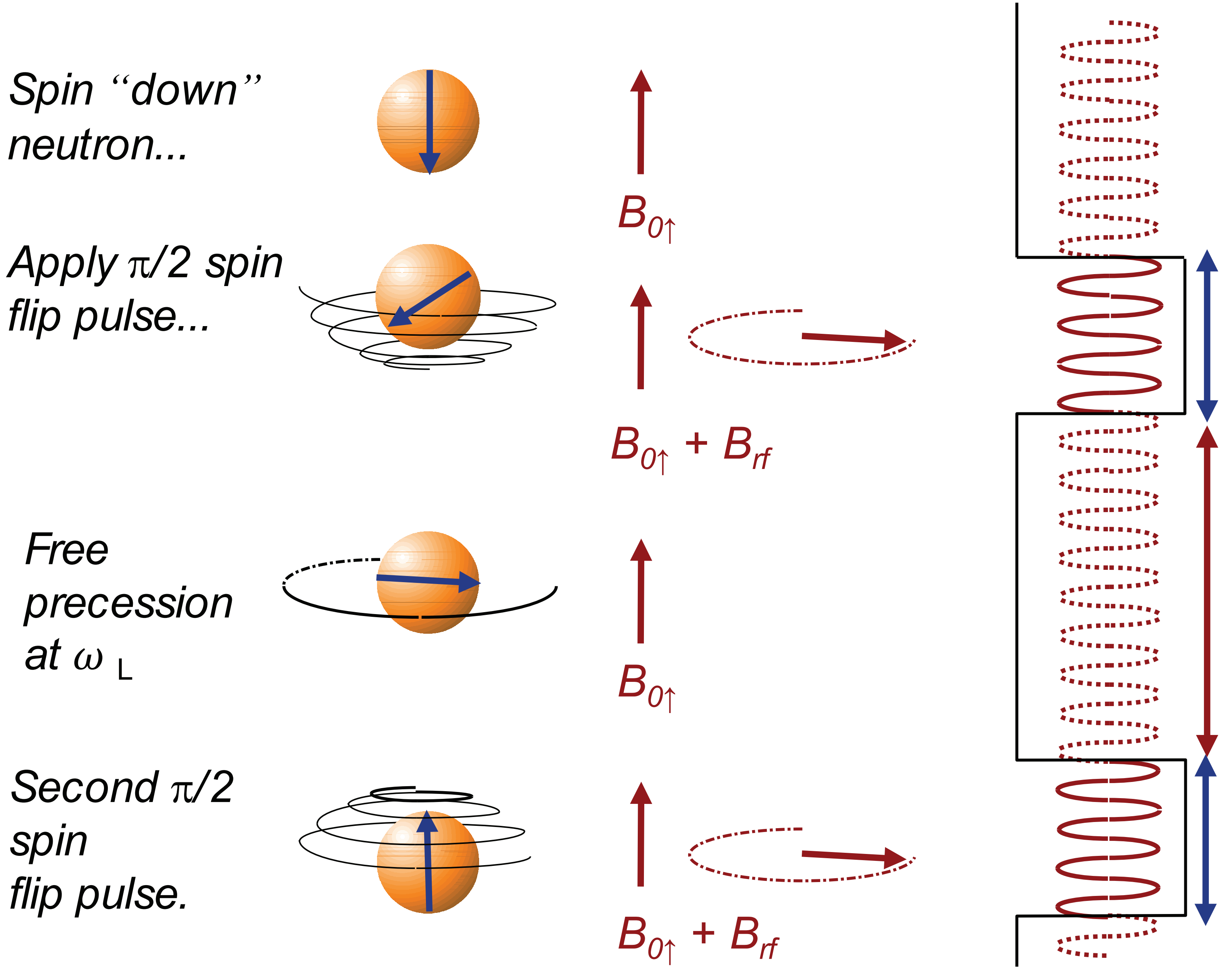
$$\hbar \Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)$$

for $d_n < 10^{-26}$ → $\Delta\omega$ < 60 nHz

$\omega_L \approx 30$Hz for $B_0 = 1\mu$T

Ramsey-Technique

P. Schmidt-Wellenburg



Ramsey-Technique

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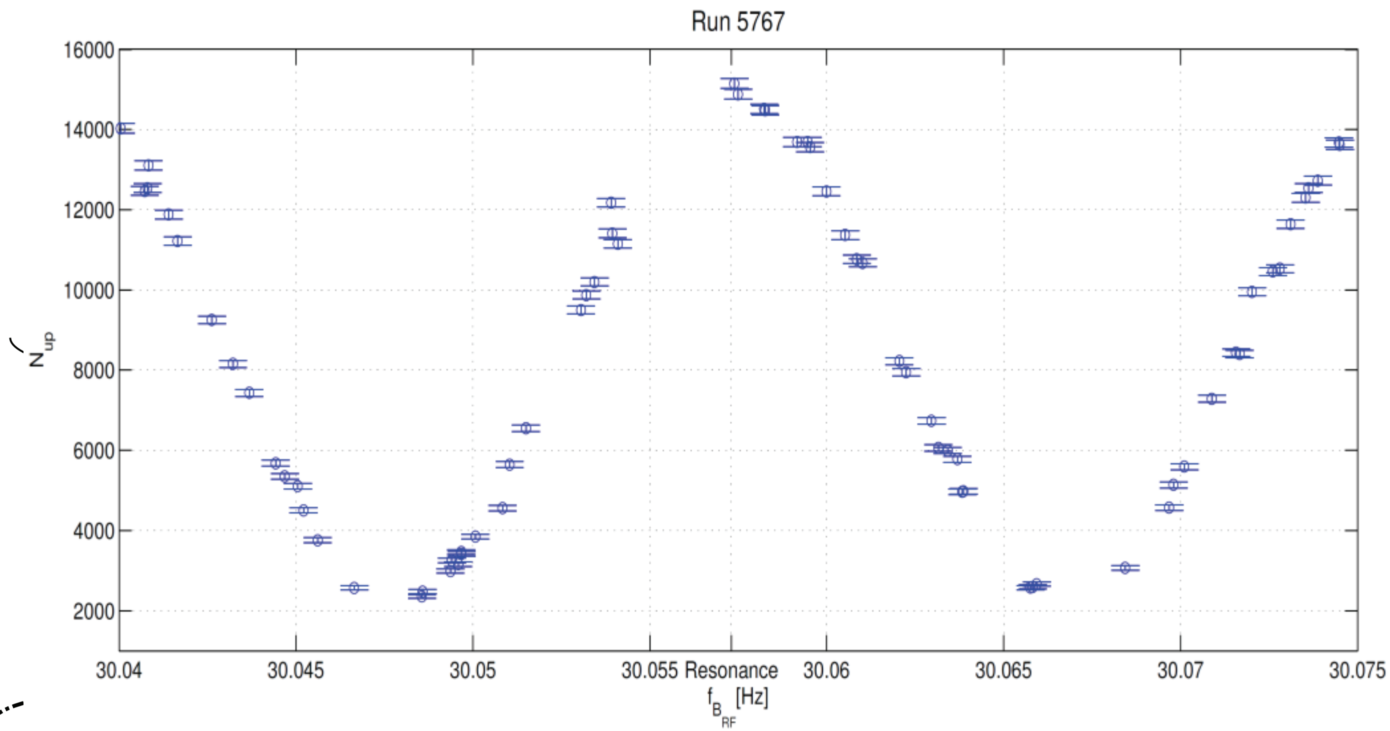
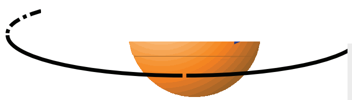
Spin "down" neutron...

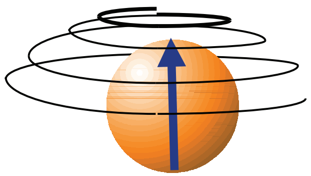
Apply π/2 spin flip pulse...



Free precession at ω L



Second π/2 spin flip pulse.



Sensitivity: $$\sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}}$$

α Visibility of resonance

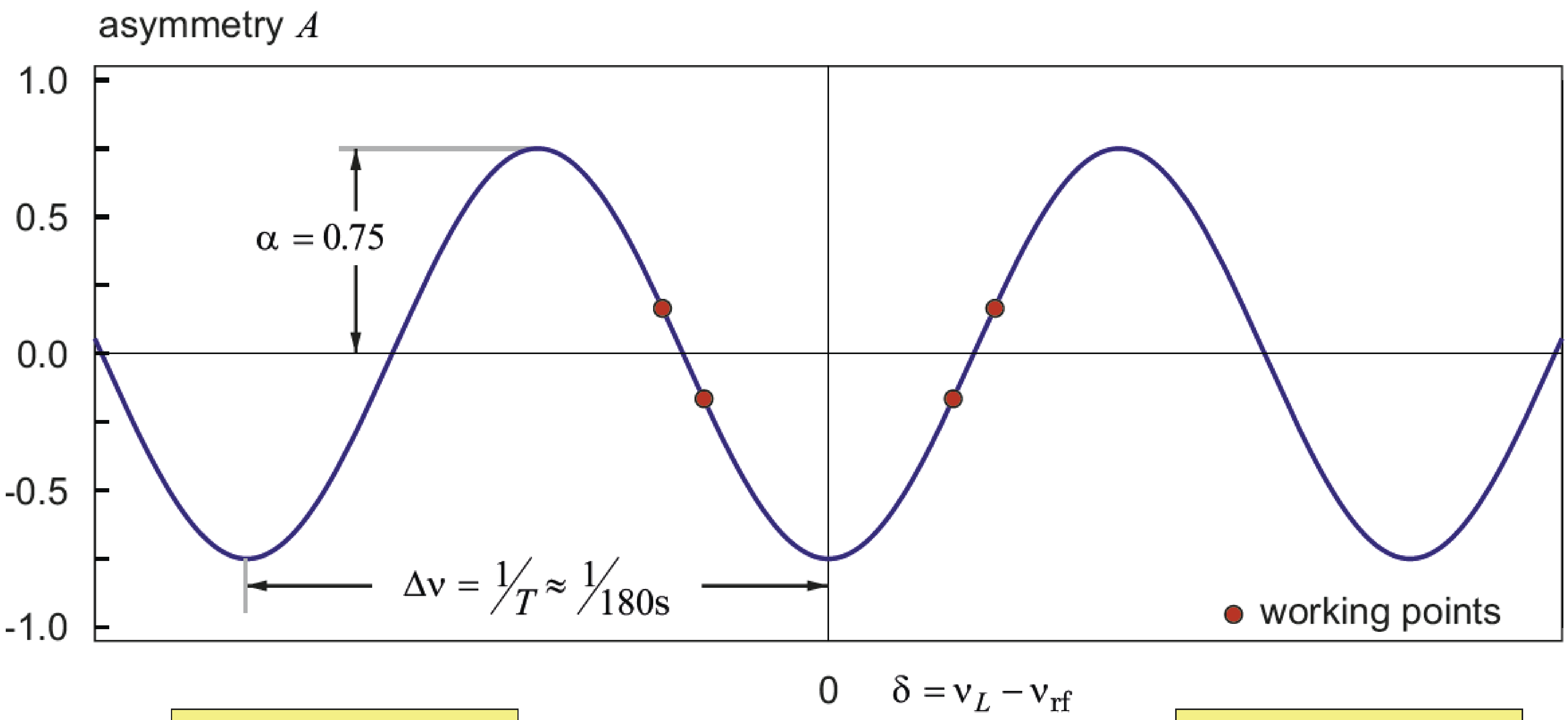
T Time of free precession

N Number of neutrons

E Electric field strength

Ramsey-Technique

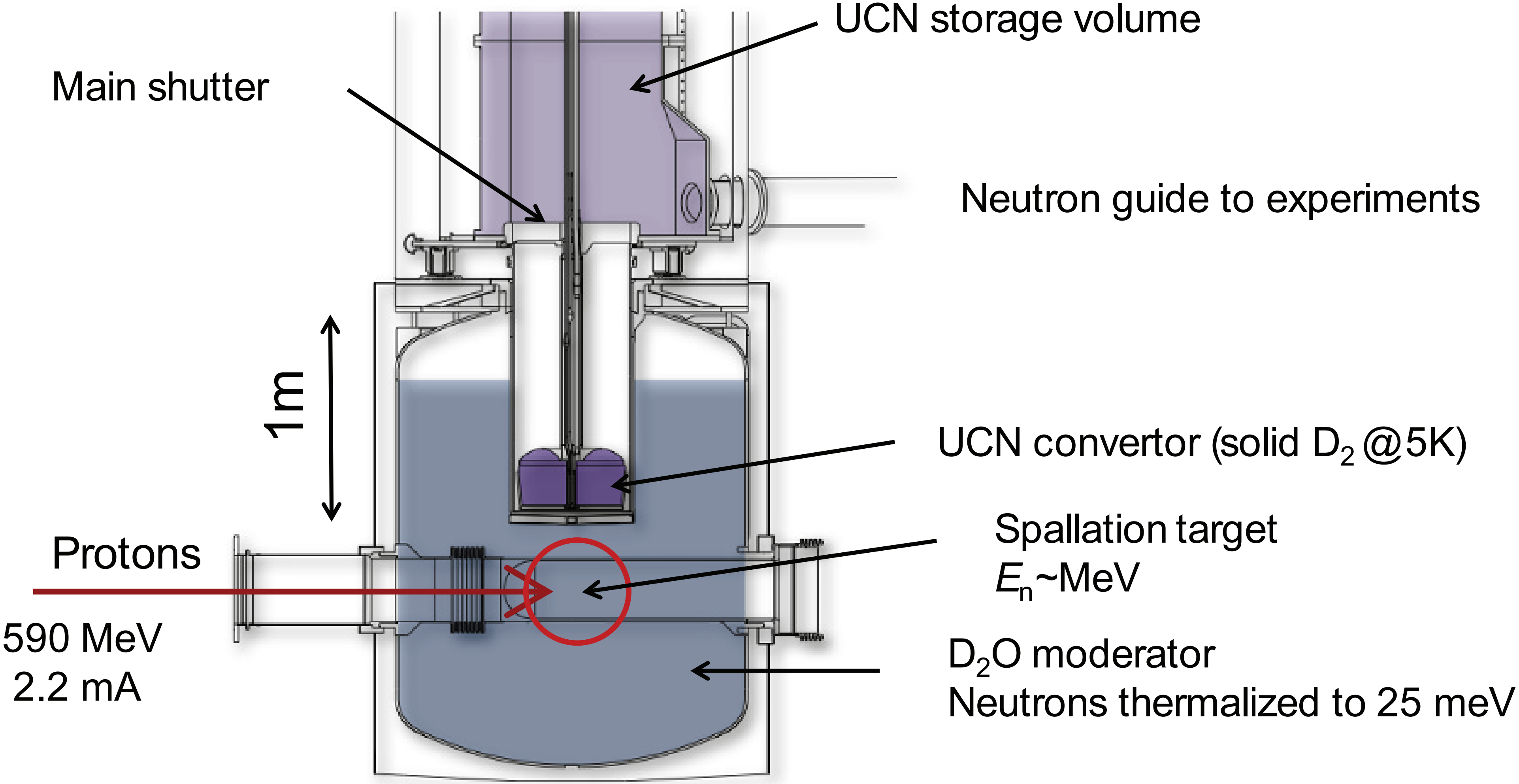
G. Bison



$$A = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

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

PSI UCN Source



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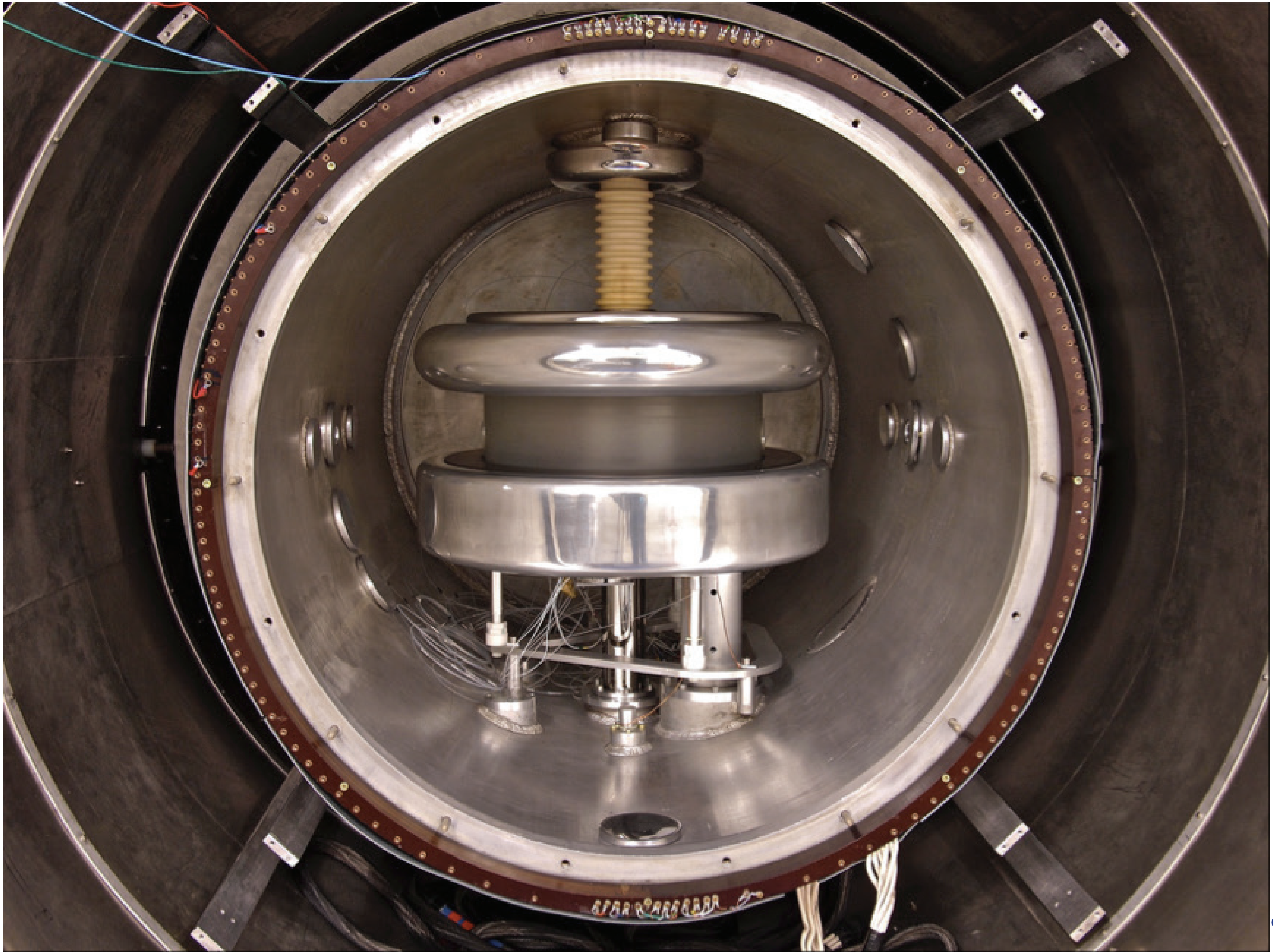
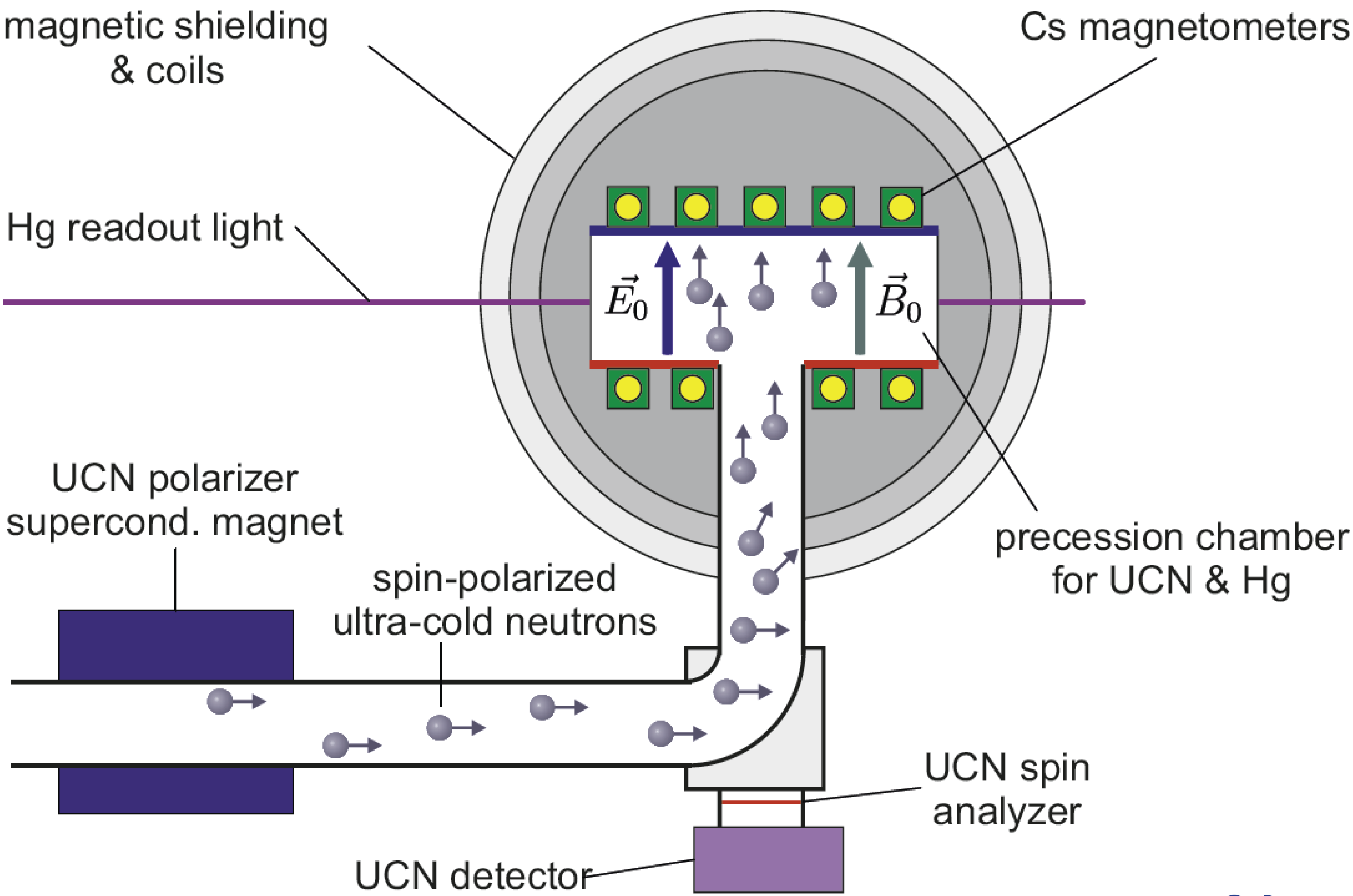
PSI UCN Experiment




magnetic shielding & coils
Cs magnetometers
Hg readout light
$\vec{E}_0$
$\vec{B}_0$
UCN polarizer supercond. magnet
spin-polarized ultra-cold neutrons
precession chamber for UCN & Hg
UCN spin analyzer
UCN detector

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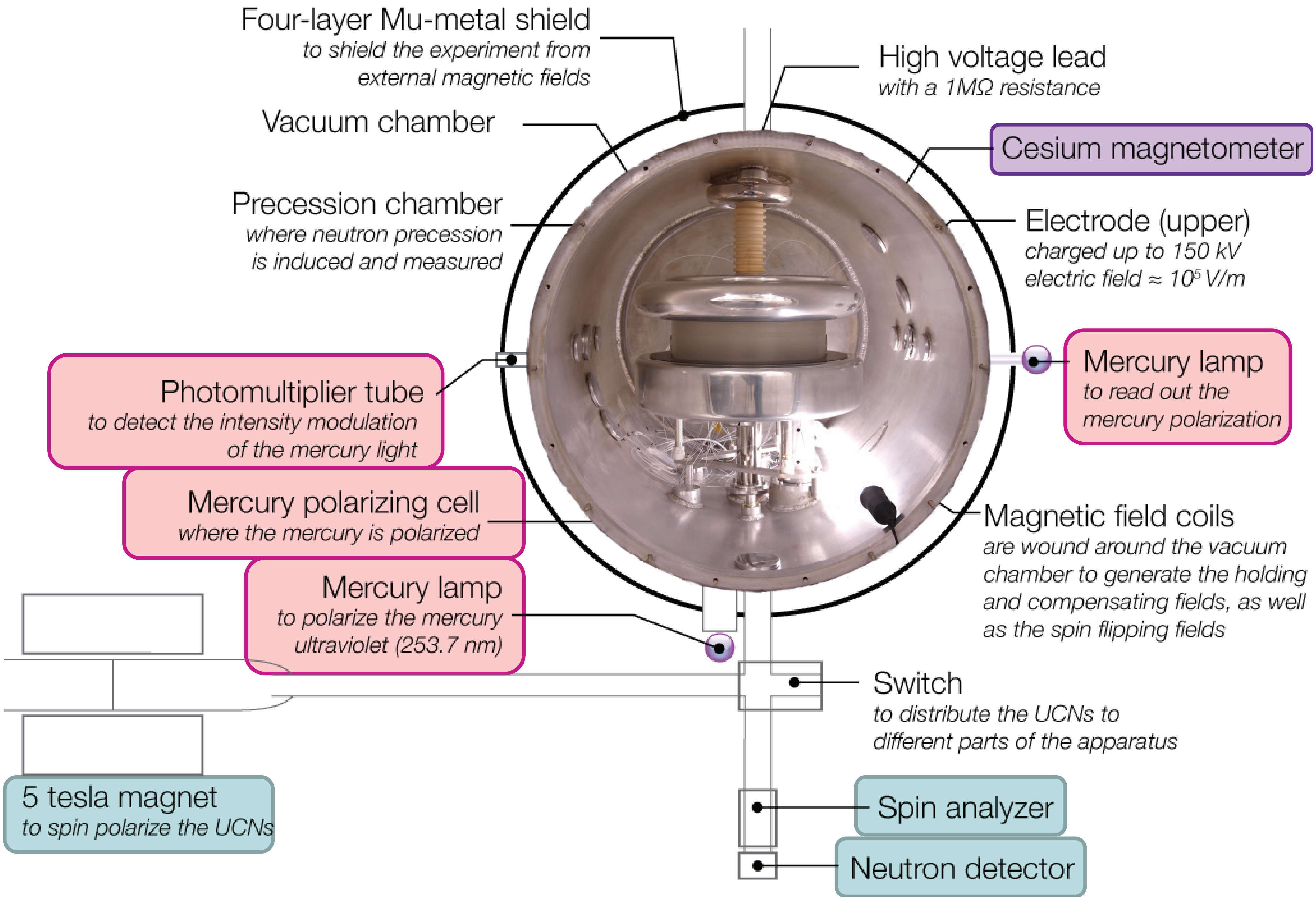
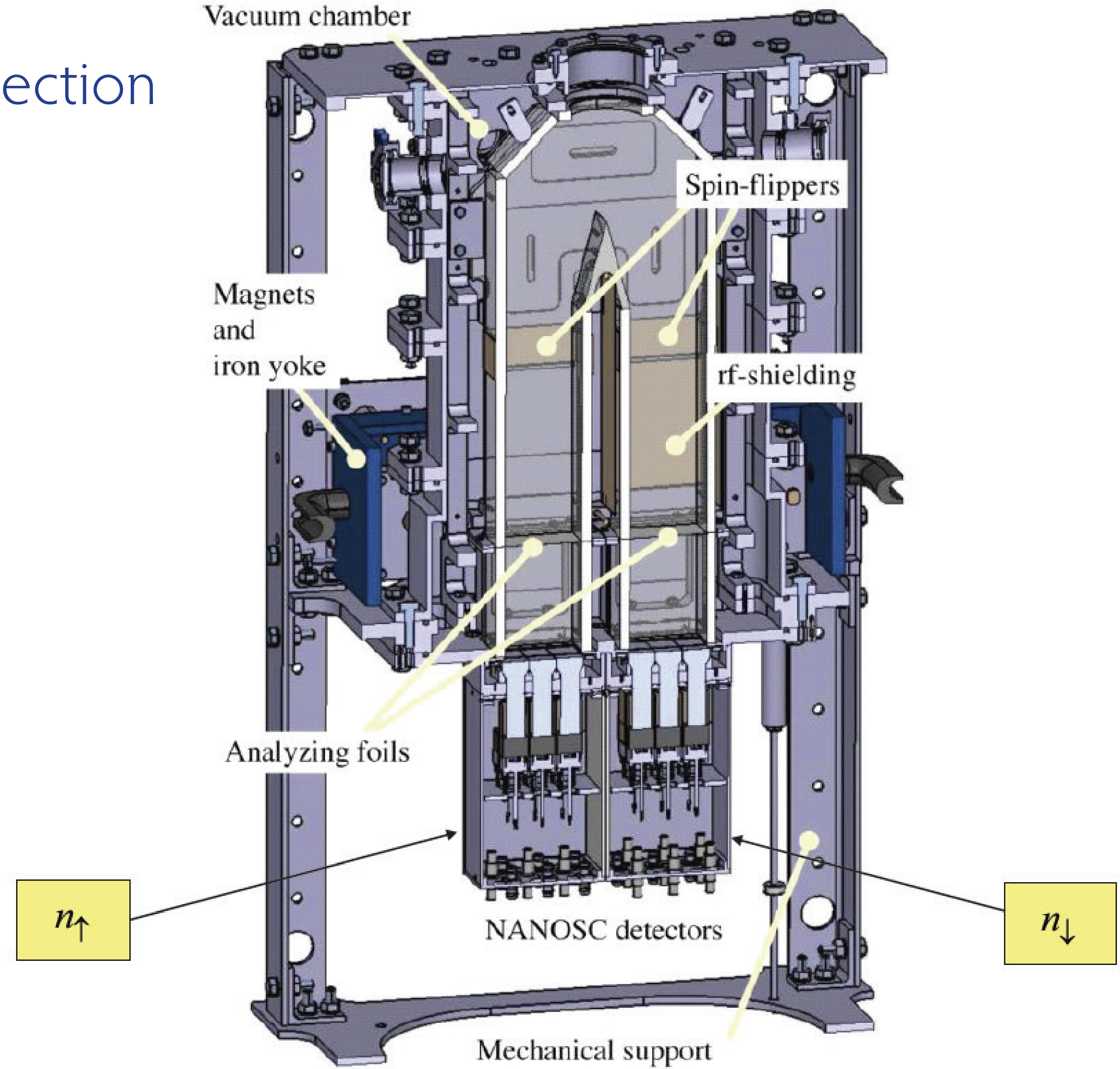

Four-layer Mu-metal shield
to shield the experiment from external magnetic fields
High voltage lead
with a 1MΩ resistance
Vacuum chamber
Cesium magnetometer
Precession chamber
where neutron precession is induced and measured
Electrode (upper)
charged up to 150 kV
electric field ≈ 10⁵ V/m
Photomultiplier tube
to detect the intensity modulation of the mercury light
Mercury lamp
to read out the mercury polarization
Mercury polarizing cell
where the mercury is polarized
Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields
Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)
Switch
to distribute the UCNs to different parts of the apparatus
5 tesla magnet
to spin polarize the UCNs
Spin analyzer
Neutron detector

Neutron Detection



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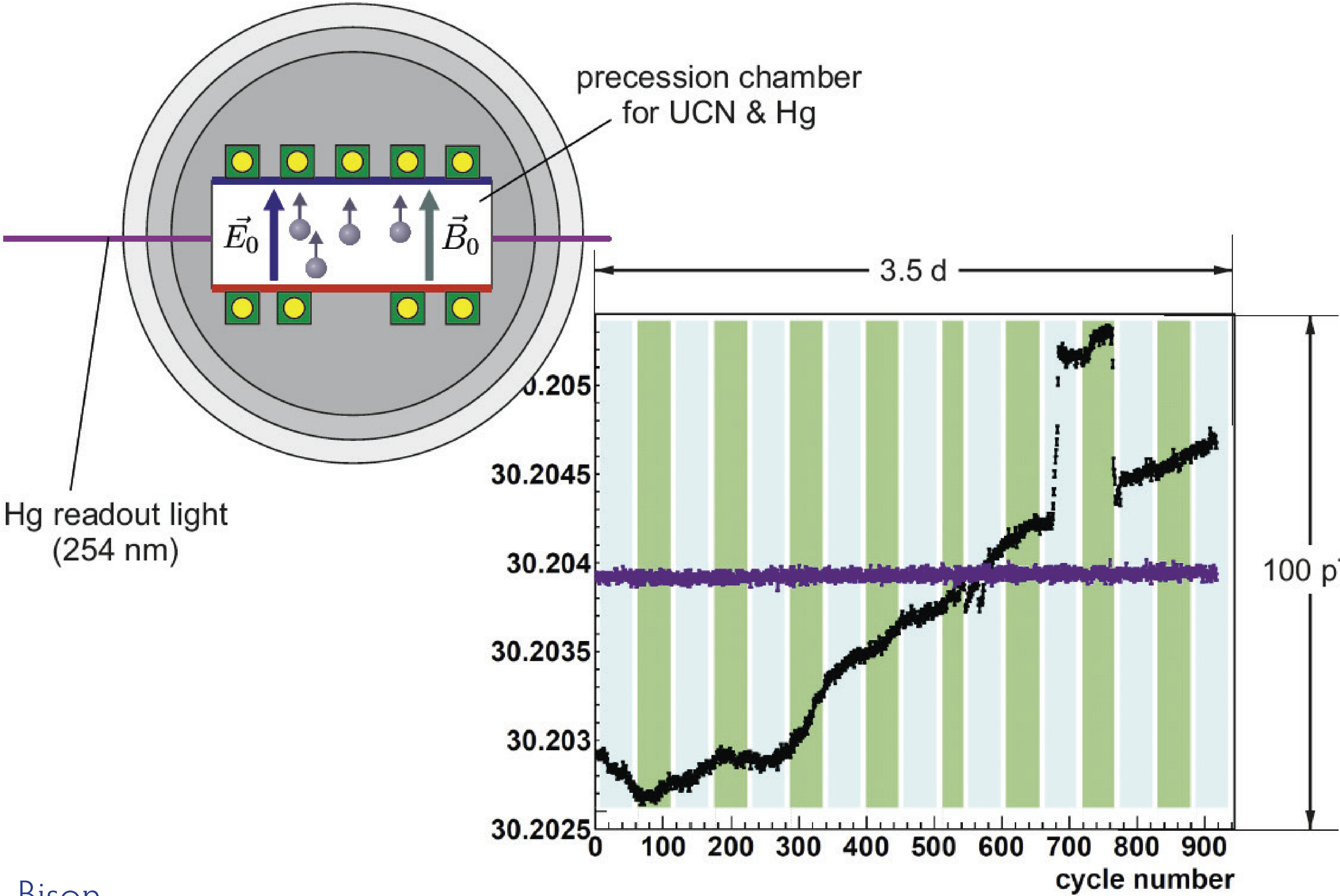
Magnetic Field Correction



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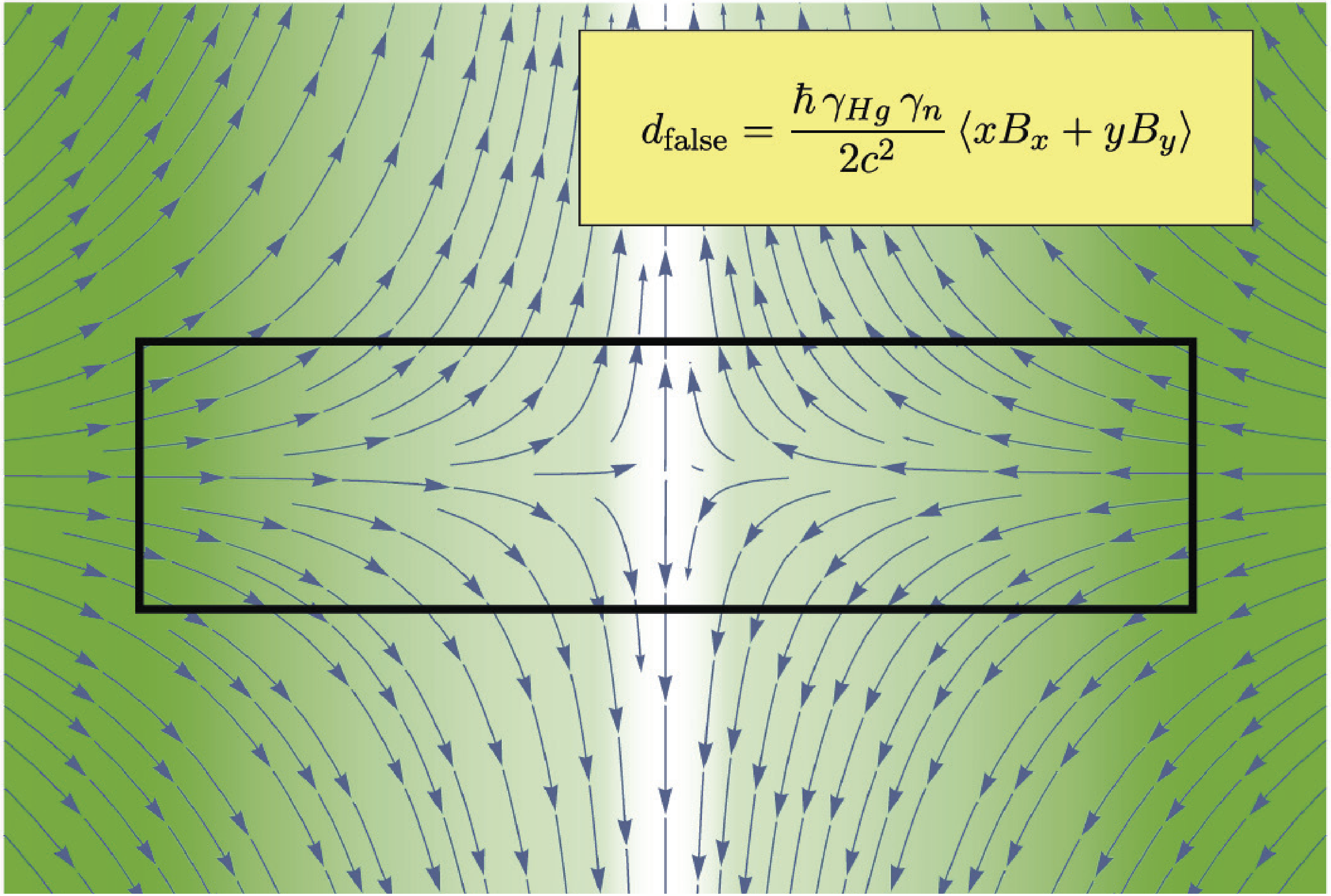
False EDM due to magnetic gradients



$$d_{\text{false}} = \frac{\hbar \gamma_{Hg} \gamma_n}{2c^2} \langle x B_x + y B_y \rangle$$

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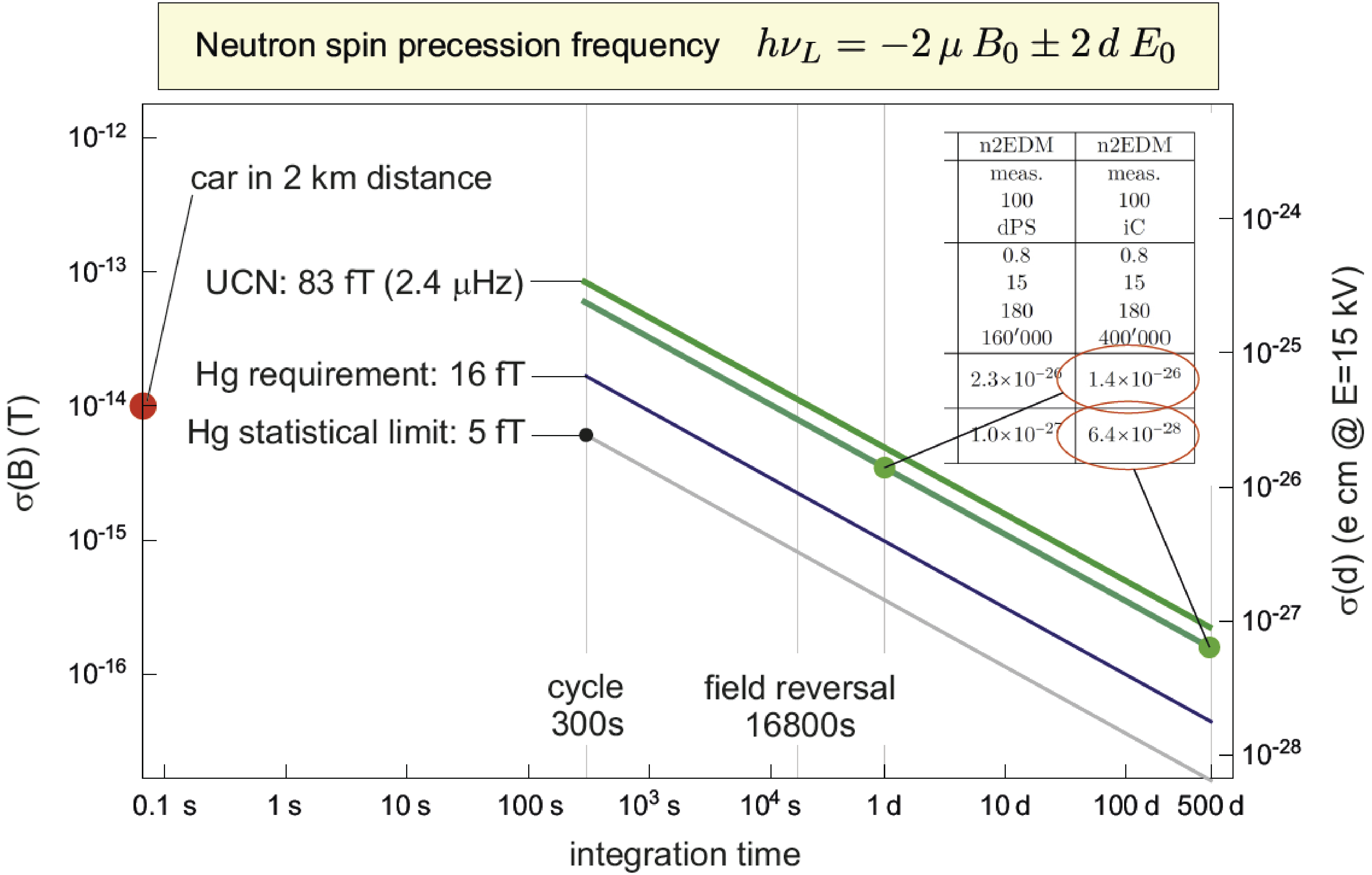
Magnetometer performance



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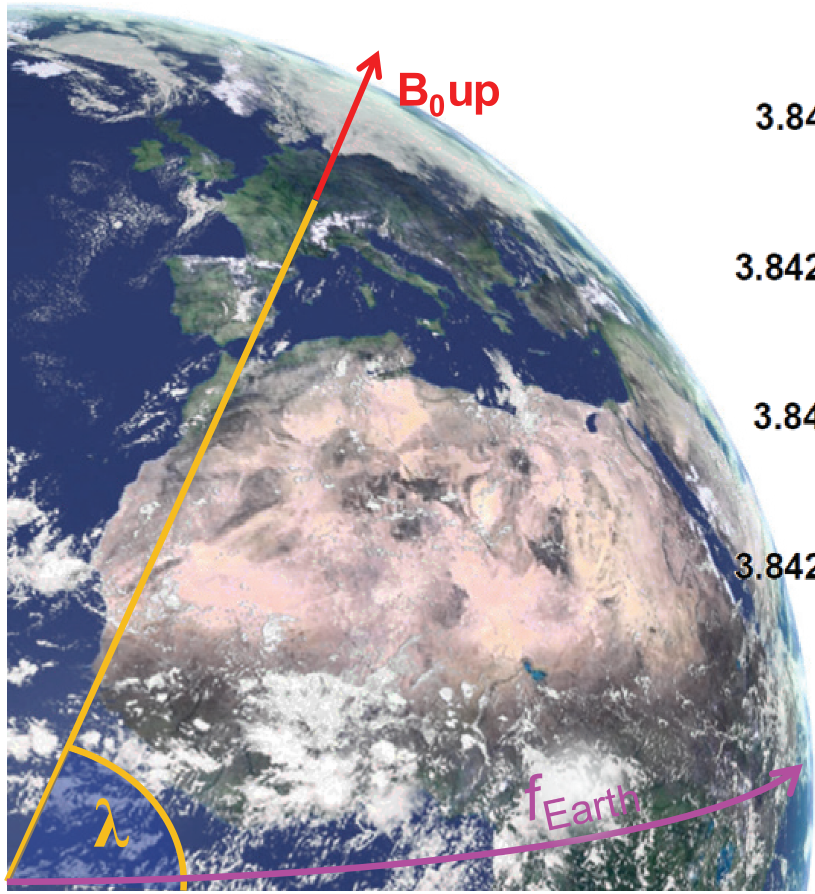
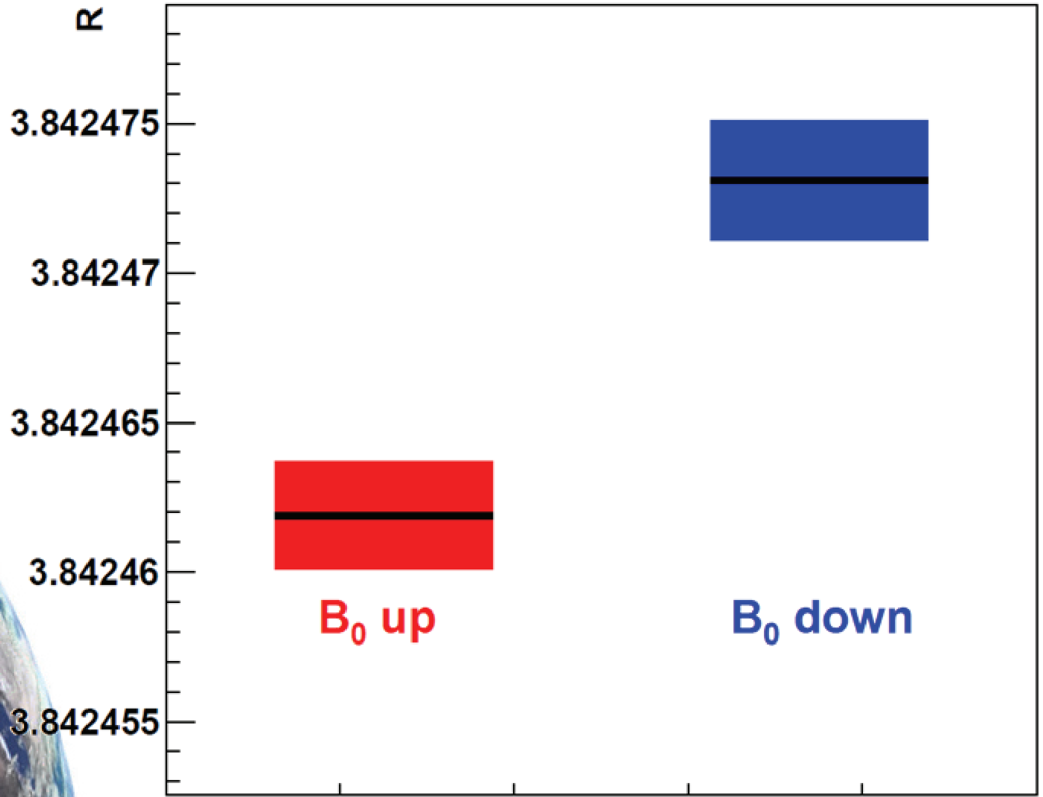
Earth rotation correction

$$\delta_{\mathrm{Earth}} = \mp\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(\frac{f_{\mathrm{Earth}}}{f_{\mathrm{n}}} + \frac{f_{\mathrm{Earth}}}{f_{\mathrm{Hg}}}\right)\sin(\lambda)$$

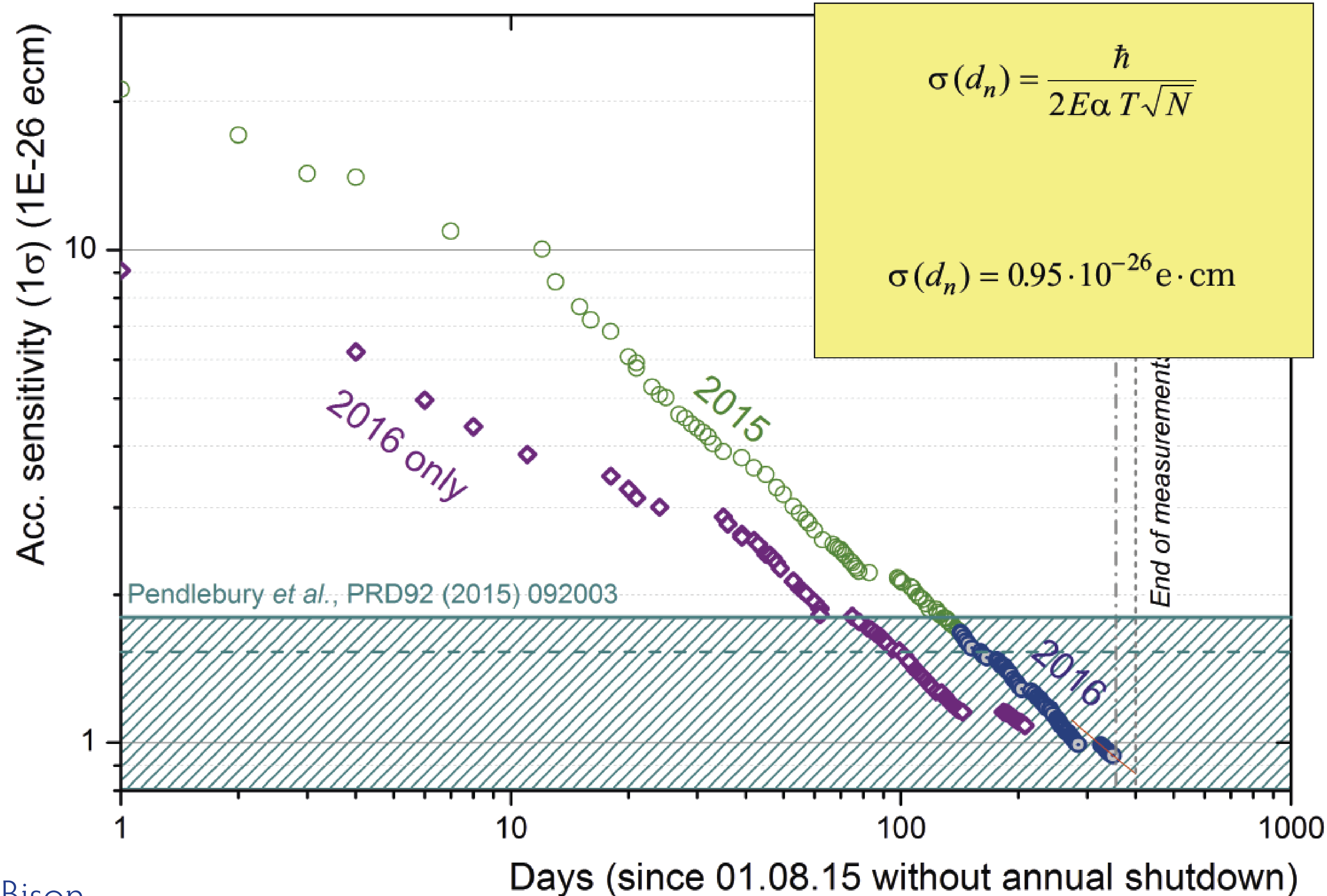
$$= \mp 5.3\times 10^{-6}$$





P. Schmidt-Wellenburg

PSI accumulated statistics



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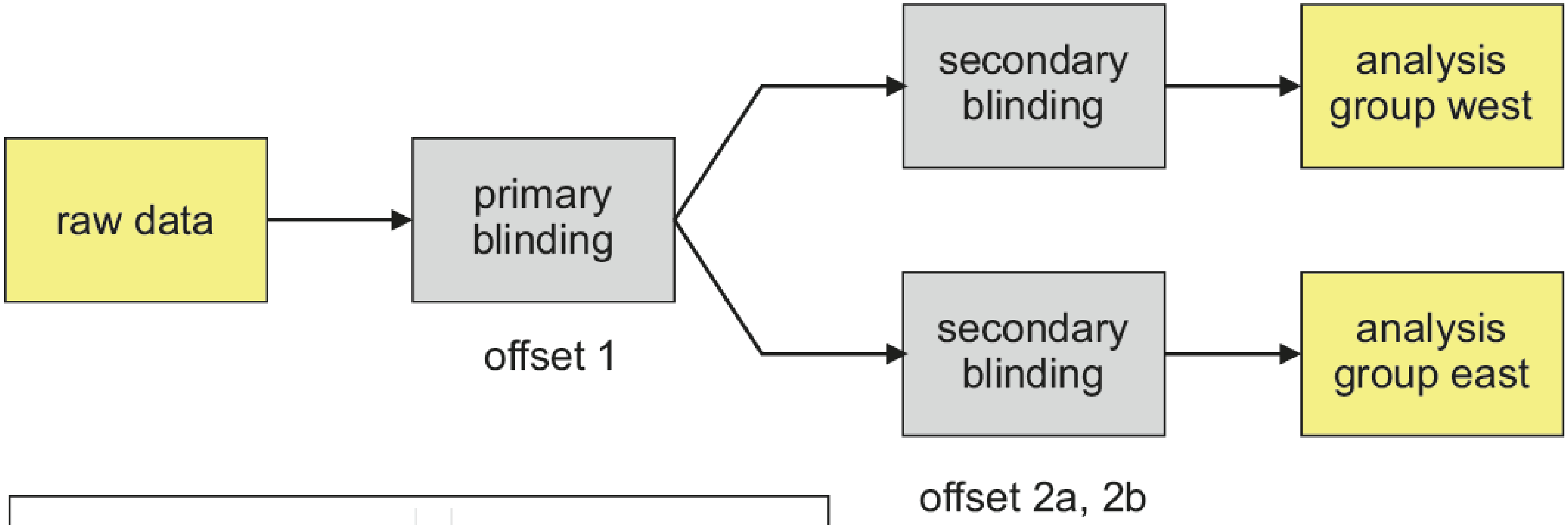
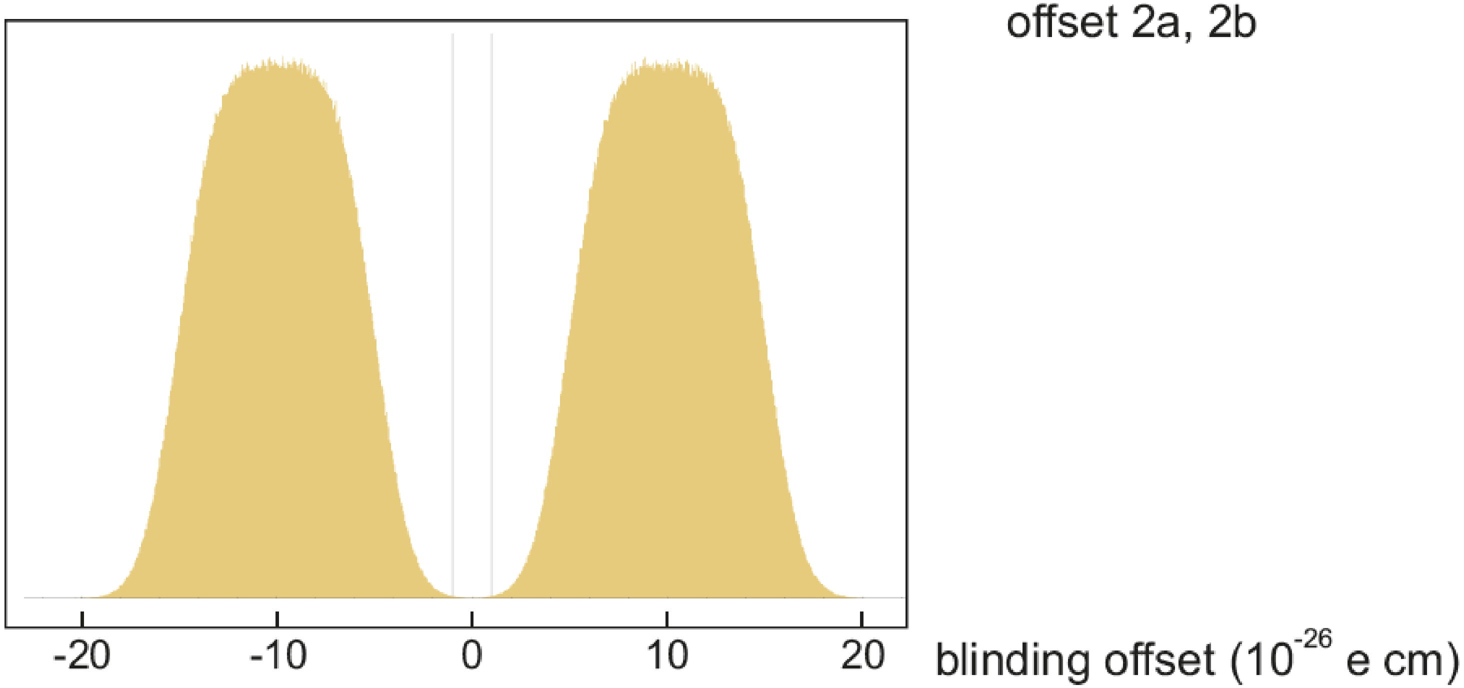
Data blinding





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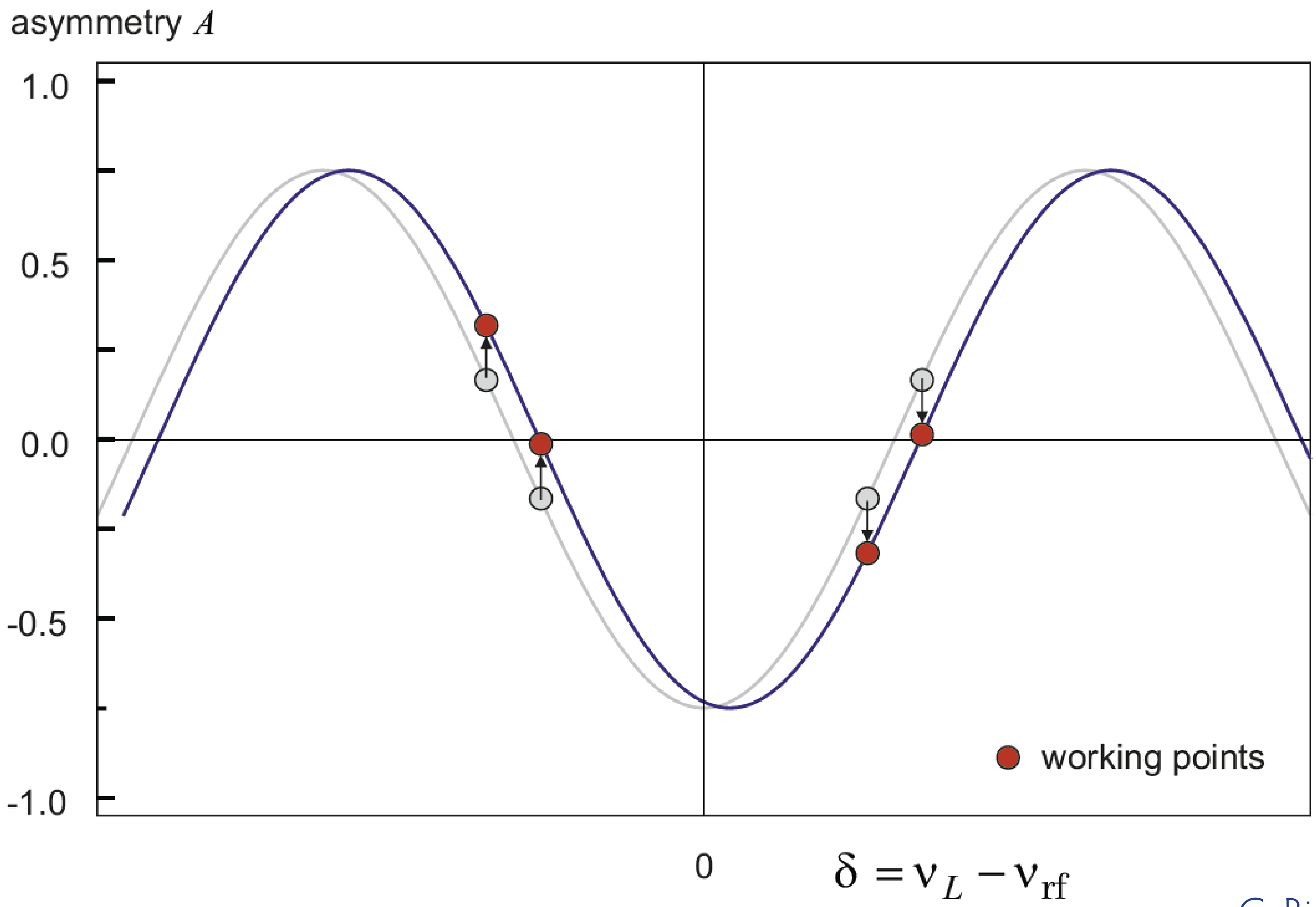
Data blinding



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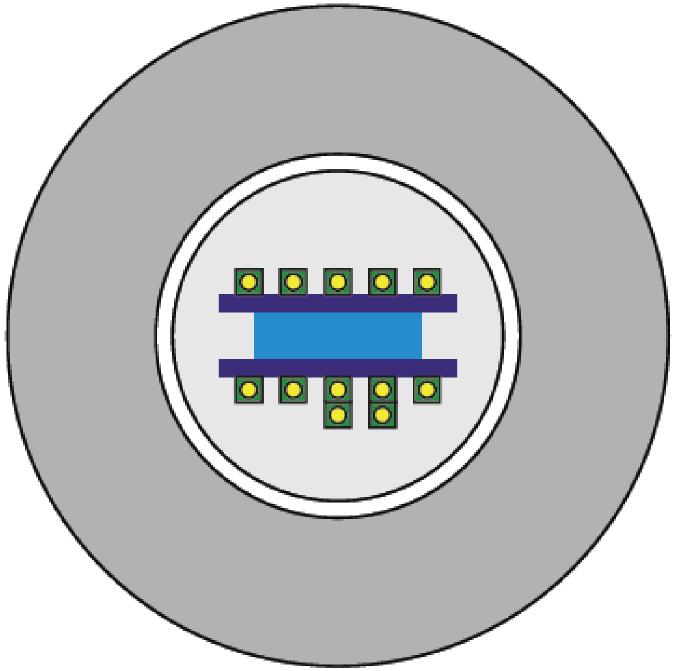
What next?

nEDM - now



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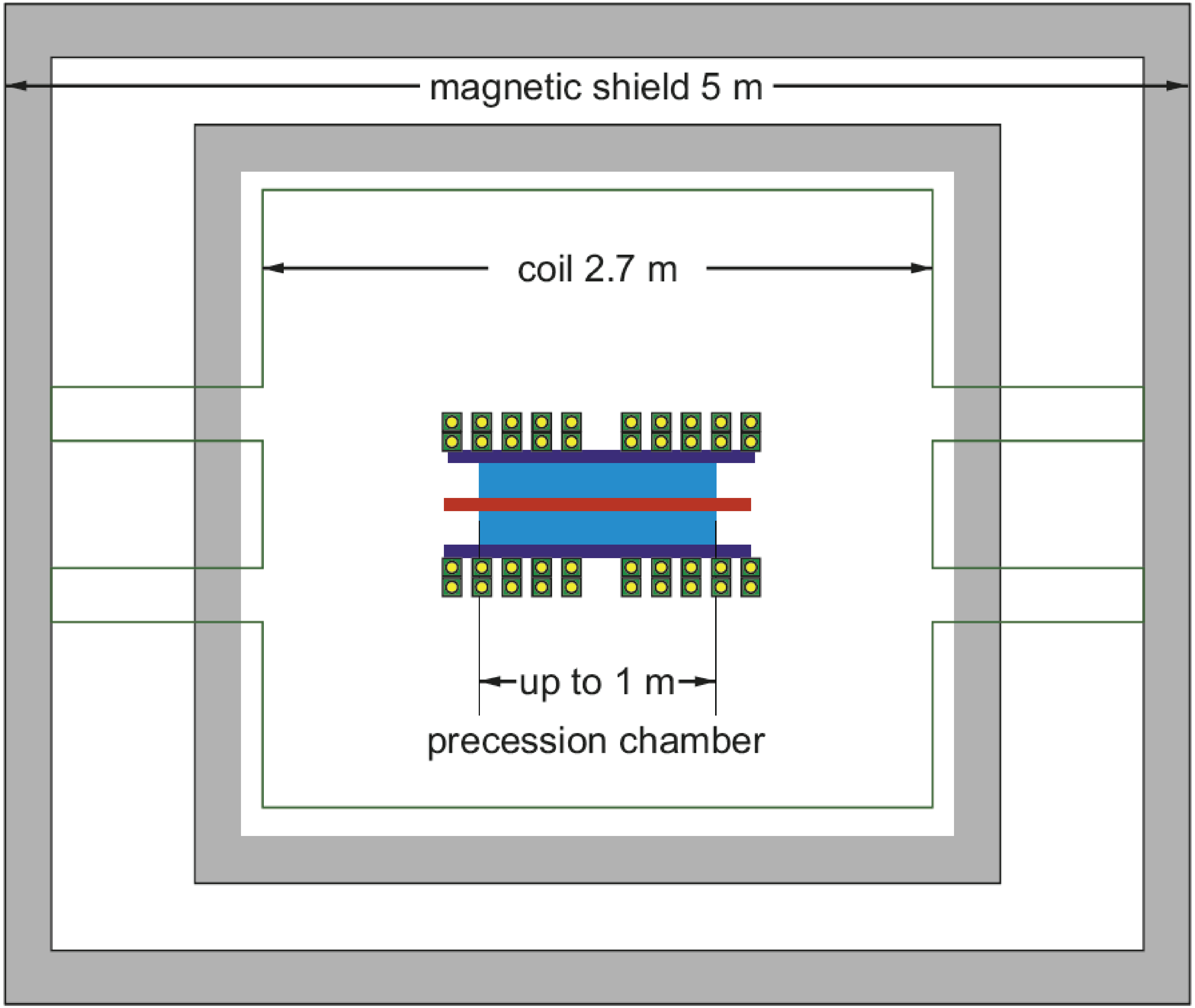
nEDM2



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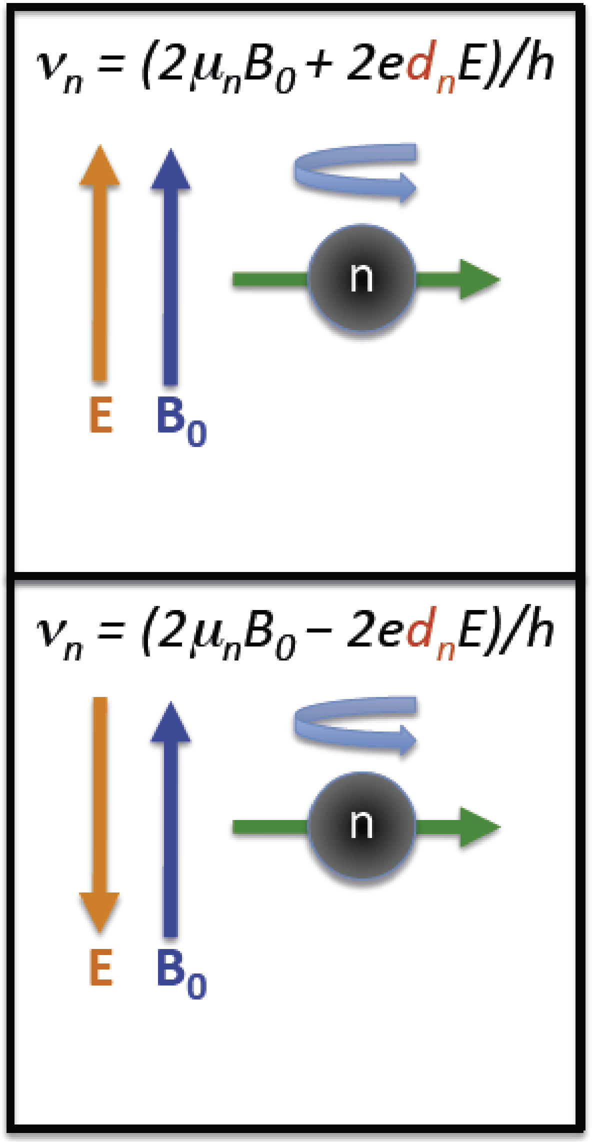
Or do it somewhat differently

nEDM Measurement Principle

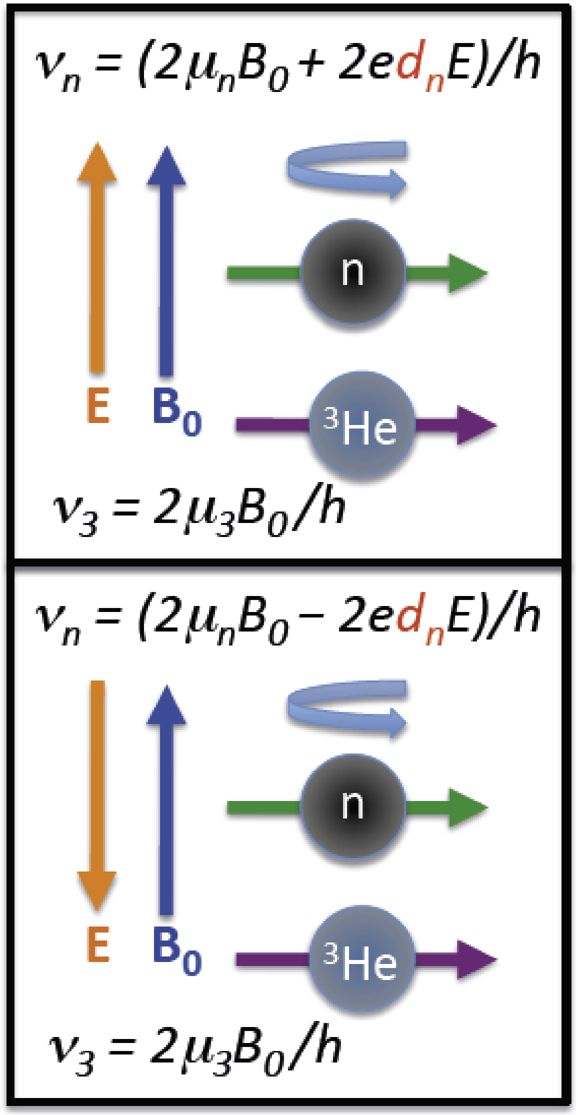


- Non-zero d_n causes the precession frequency to be slightly different for **E** and **B** parallel vs. anti-parallel
- For E = 75 kV/cm and $d_n = 5\times10^{-28}$ e-cm,
  $\Delta\nu = 36$ nHz
  Equivalent to $\Delta B_0 = 1.2$ fT
- Statistical uncertainty:

$$\delta d_n \propto \frac{1}{|\vec{E}| T \sqrt{N_{UCN}}}$$

S. Clayton

Dual Role of Polarized Helium-3



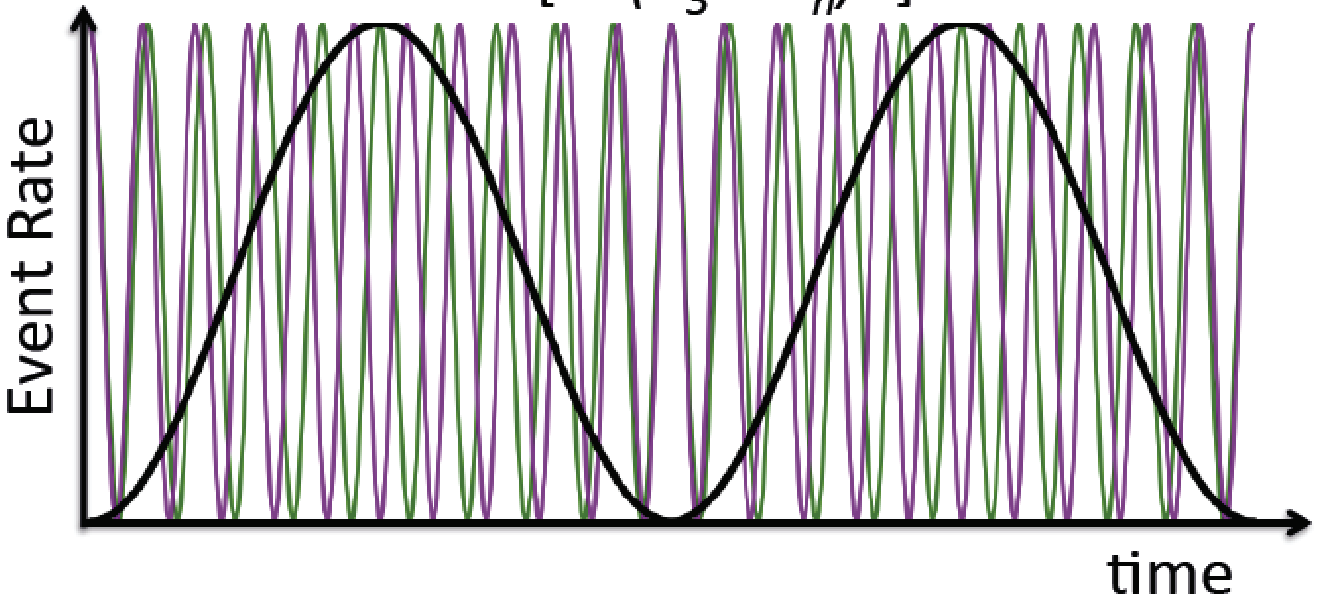
Co-magnetometer:

- Measure ^{3}He precession frequency ν_3 to correct ν_n for B-field shifts.
- Negligible ^{3}He EDM

Neutron spin analyzer:

- Highly spin-dependent capture reaction, n+^{3}He→p + T + 764 keV,

$1+\sin[2\pi(\nu_3 - \nu_n)\, t]$



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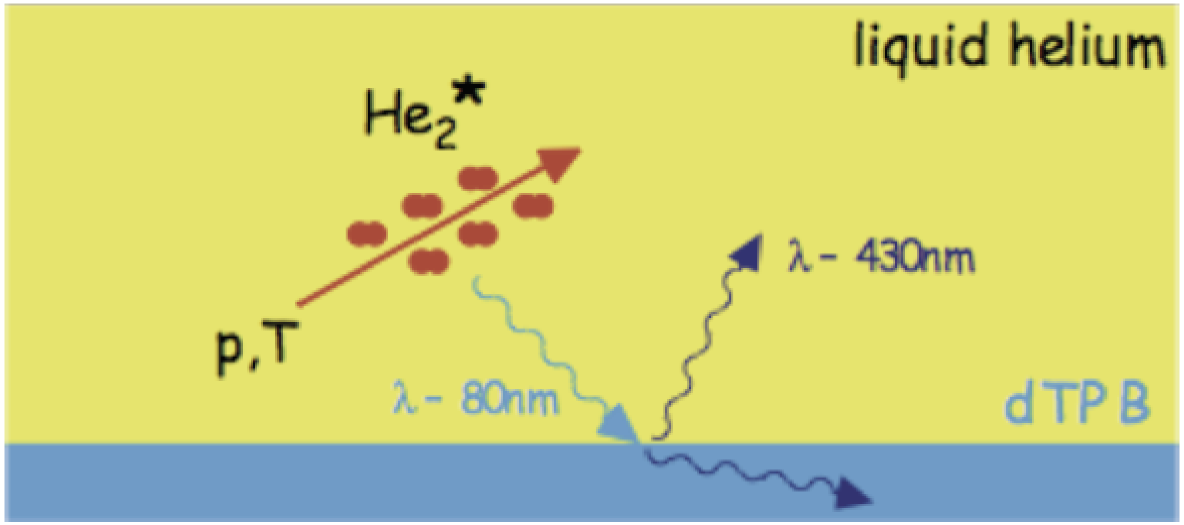
Detection of n+3He→ p+T

- Neutron absorption on ^{3}He is highly spin dependent ($\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$)
- Reaction products of n+^{3}He→p+t generates UV scintillation light (80 nm) in LHe.
- The UV light will be downconverted by a wavelength shifter and detected by PMTs.



Spin dependent n-^{3}He absorption reaction provides a measurement of the difference of the neutron precession frequency and the ^{3}He precession frequency.

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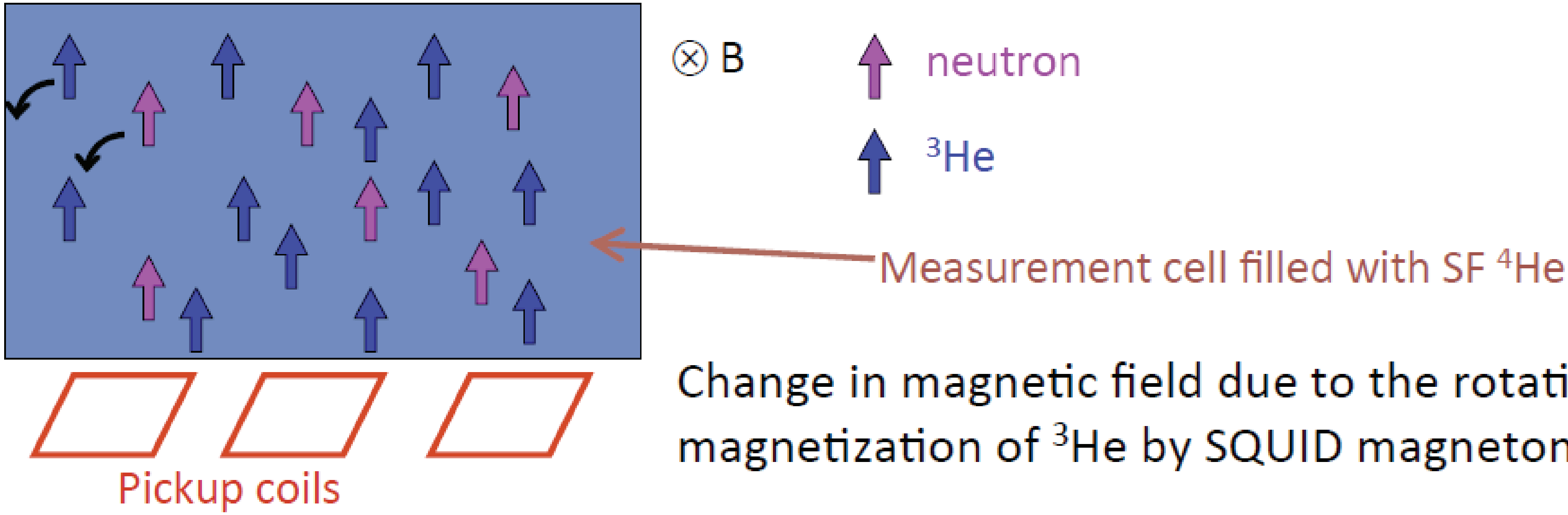
Free Precession Method

A dilute admixture of polarized ^3He atoms is introduced to the bath of SF ^4He ($x = N_3/N_4 \sim 10^{-10}$ or $\rho_{3He} \sim 10^{12}$/cc) as comagnetometer



Change in magnetic field due to the rotating magnetization of ^3He by SQUID magnetometers

Signature of EDM appears as a shift in $\omega_3 - \omega_n$ corresponding to the reversal of ***E*** with respect to ***B***, corrected by ω_3.

3He concentration needs to be adjusted to maximize the sensitivity

- Low concentration ➔ small BR for capture events, weak SQUID signals
- High concentration ➔ short storage time

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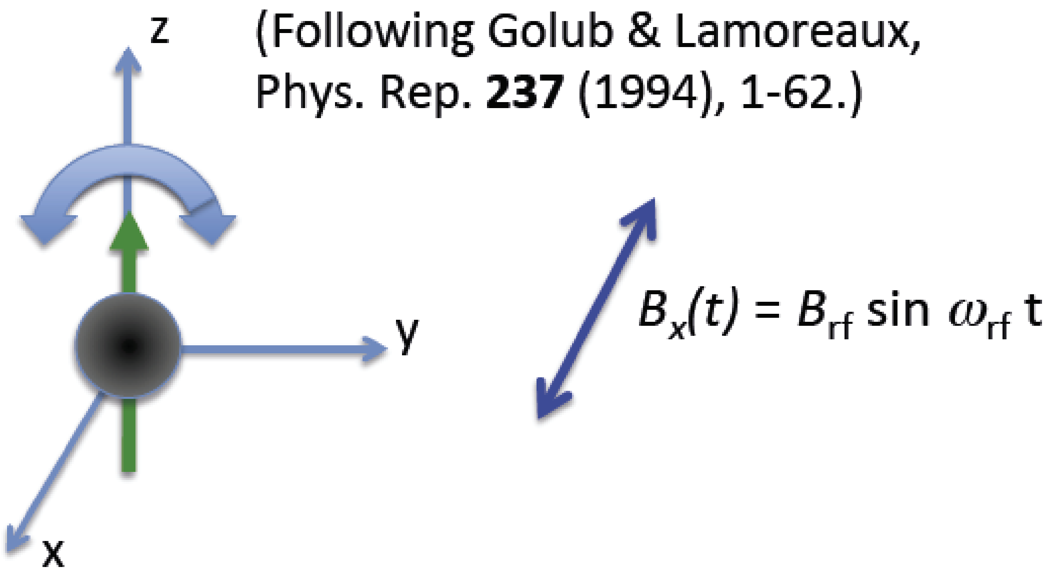
Spin Dressing

(Following Golub & Lamoreaux, Phys. Rep. **237** (1994), 1-62.)



- Apply oscillating B-field in *x*-direction
- Spin precesses with $\omega(t) = \gamma B_x(t)$
- Angle with *z*-axis: $\theta(t) = \gamma (B_{rf}/\omega_{rf}) \cos \omega_{rf} t$

$$\langle \cos\theta(t) \rangle_T = \frac{1}{T} \int_T \mathrm{d}t \cos\left[(\gamma B_{rf}/\omega_{rf}) \cos \omega_{rf} t\right] = J_0(\gamma B_{rf}/\omega_{rf})$$

- Thus, the spin responds to a small B-field along *z*-axis with

$$\gamma_{eff} = \gamma_0 J_0(X)$$

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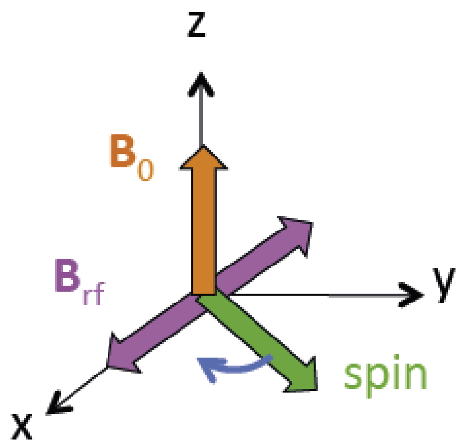
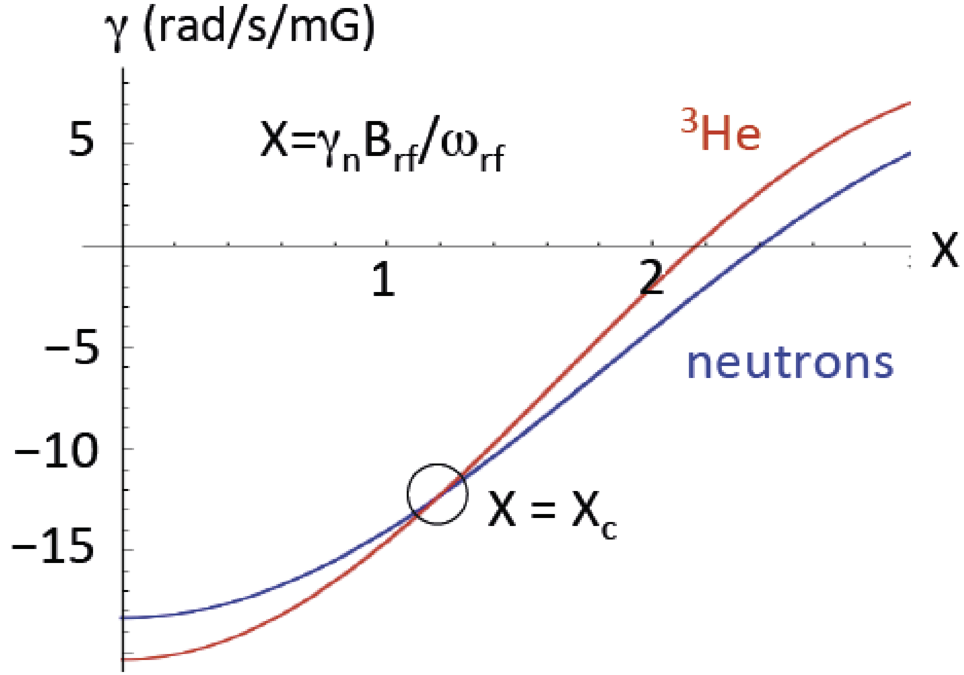
Dressed Spin Method for nEDM





A strong non-resonant RF field

$$\mathbf{B_{rf}} \perp \mathbf{B_0},\ B_{rf} >> B_0,\ \omega_{rf} >> \omega_0$$

$$\gamma' = \gamma J_0\left(\gamma B_{rf}/\omega_{rf}\right) = \gamma J_0(X)$$

- Can tune the dressing parameter ($X = \gamma_n B_{rf}/\omega_{rf}$) until the relative precession between ^{3}He and neutrons is zero ($X = X_c$).

$$d_n = \frac{\hbar}{2E}\left[2\pi(f_s^{\uparrow} - f_s^{\downarrow}) - \frac{(\gamma_3' - \gamma_n')}{\gamma_3'} 2\pi(f_3^{\uparrow} - f_3^{\downarrow})\right]$$

scintillation signals

= 0 at at "critical dressing"

^{3}He precession frequency

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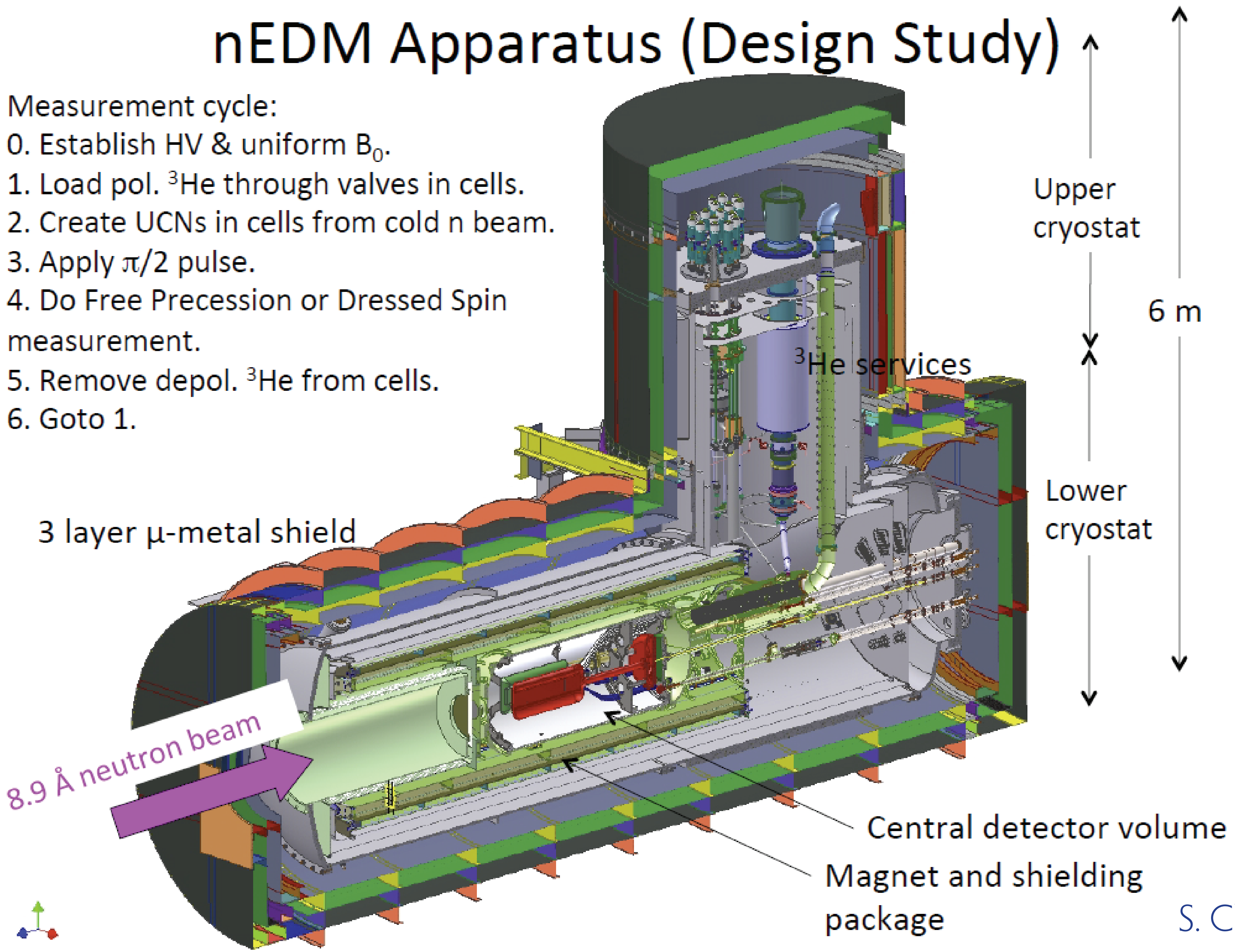
nEDM Apparatus (Design Study)

Measurement cycle:
0. Establish HV & uniform B_0.
1. Load pol. ^{3}He through valves in cells.
2. Create UCNs in cells from cold n beam.
3. Apply $\pi/2$ pulse.
4. Do Free Precession or Dressed Spin measurement.
5. Remove depol. ^{3}He from cells.
6. Goto 1.



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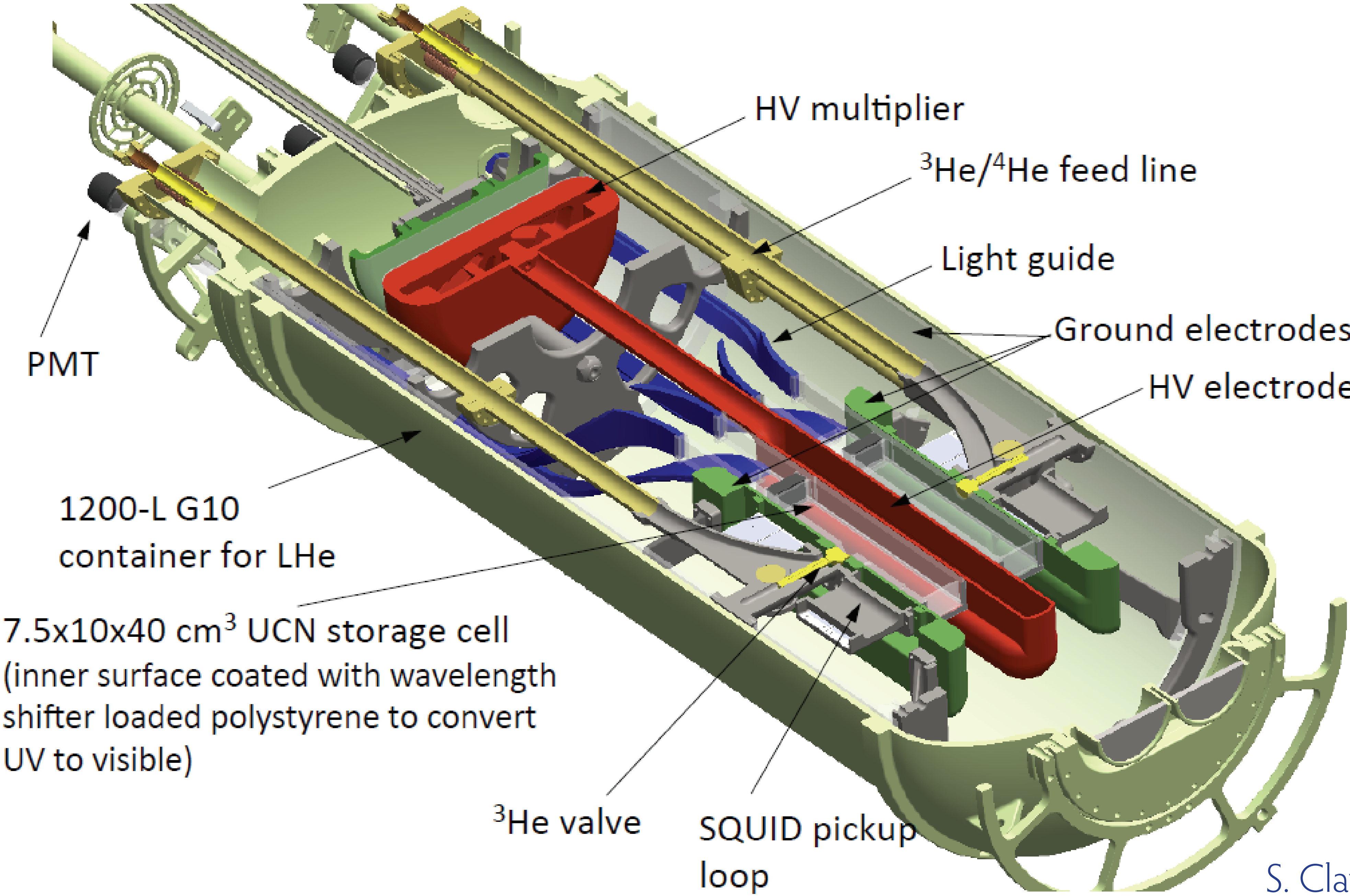
Central Detector System (Design Study)



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Projected Systematic Uncertainties

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Error Source	Projected systematic error (e-cm)	Comments
Linear vxE	$< 2 \times 10^{-28}$	Uniformity of B_0
Quadratic vxE	$< 0.5 \times 10^{-28}$	E field reversal to 1%
Pseudomagnetic field effects	$< 1 \times 10^{-28}$	π/2 pulse, compare two cells
Uncompensated leakage current effects (gravitational offset)	$< 0.2 \times 10^{-28}$	Leakage current < 1 nA
vxE from rotational UCN flow	$< 1 \times 10^{-28}$	Uniformity of E, damping time of the rotational motion of UCN
Heat from leakage currents	$< 1.5 \times 10^{-28}$	Leakage current on the inner surface of the cell wall correlated with the E field direction
Miscellaneous	$< 1 \times 10^{-28}$	