A New Limit on the Neutron Electric Dipole Moment

Nicholas J. Ayres on behalf of the Neutron Electric Dipole Moment collaboration at PSI

nEDM2021

15 February 2021

Overview

- Apparatus
- Datataking
- Analysis & Systematics
- Result!

How to measure an EDM?

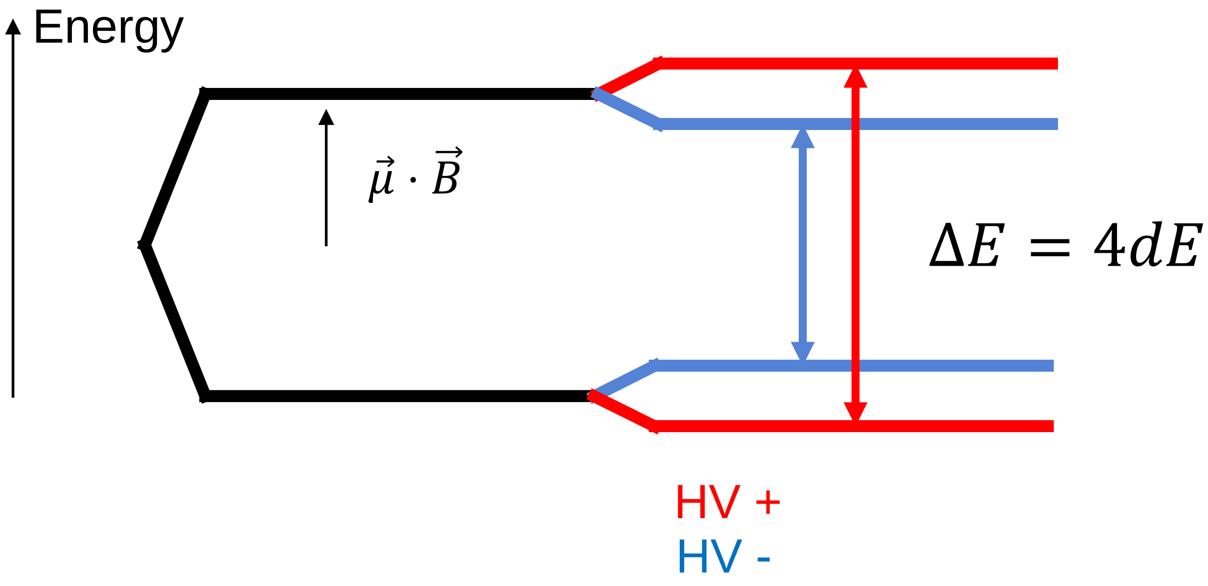
$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Magnetic Dipole Moment

Electric Dipole Moment

Measure Larmor frequency of particles in B and E fields

Look for change when reversing E while controlling B



$$d_n = \frac{1}{4E}\left(h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$

The Measurement Principle

- Store ultracold neutrons in (anti-)parallel E and B fields

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

- Measure neutron frequency with Ramsey Technique
- Measure shift correlated with E

$$d_n = \frac{1}{4E}\left(h\left(f_\mathrm{n}^{\uparrow\uparrow} - f_\mathrm{n}^{\uparrow\downarrow}\right) - \mu_\mathrm{n}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$

- Correct B drift with Hg comagnetometer

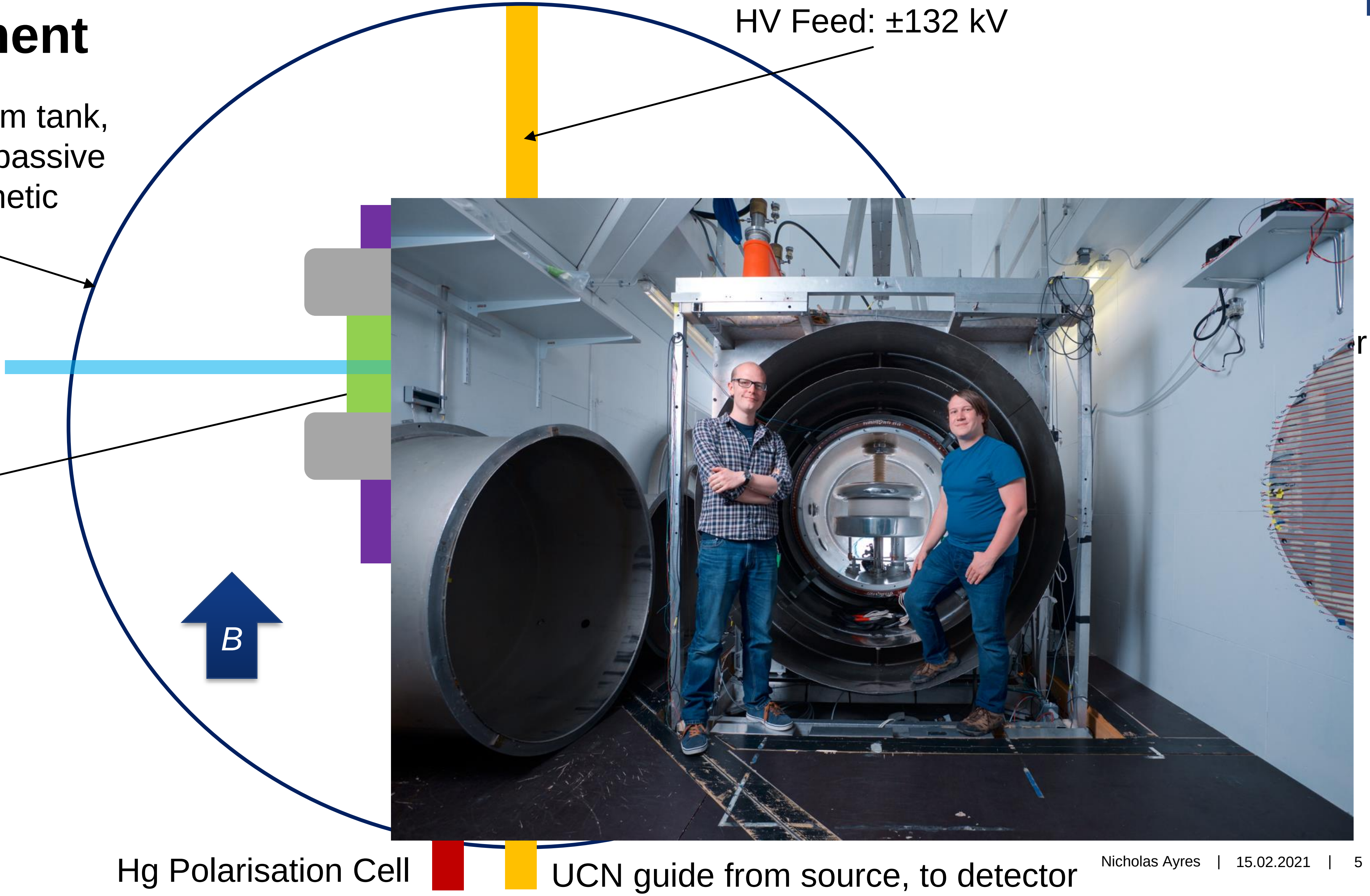
$$\mathcal{R} = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} \quad \Rightarrow \quad d_n = \frac{h\left|f_\mathrm{Hg}\right|}{4E}\left(\mathcal{R}^{\uparrow\uparrow} - \mathcal{R}^{\uparrow\downarrow}\right)$$

The Experiment

B coil wound on vacuum tank, within 4-layer μ-metal passive shield and active magnetic shield

HV Feed: ±132 kV

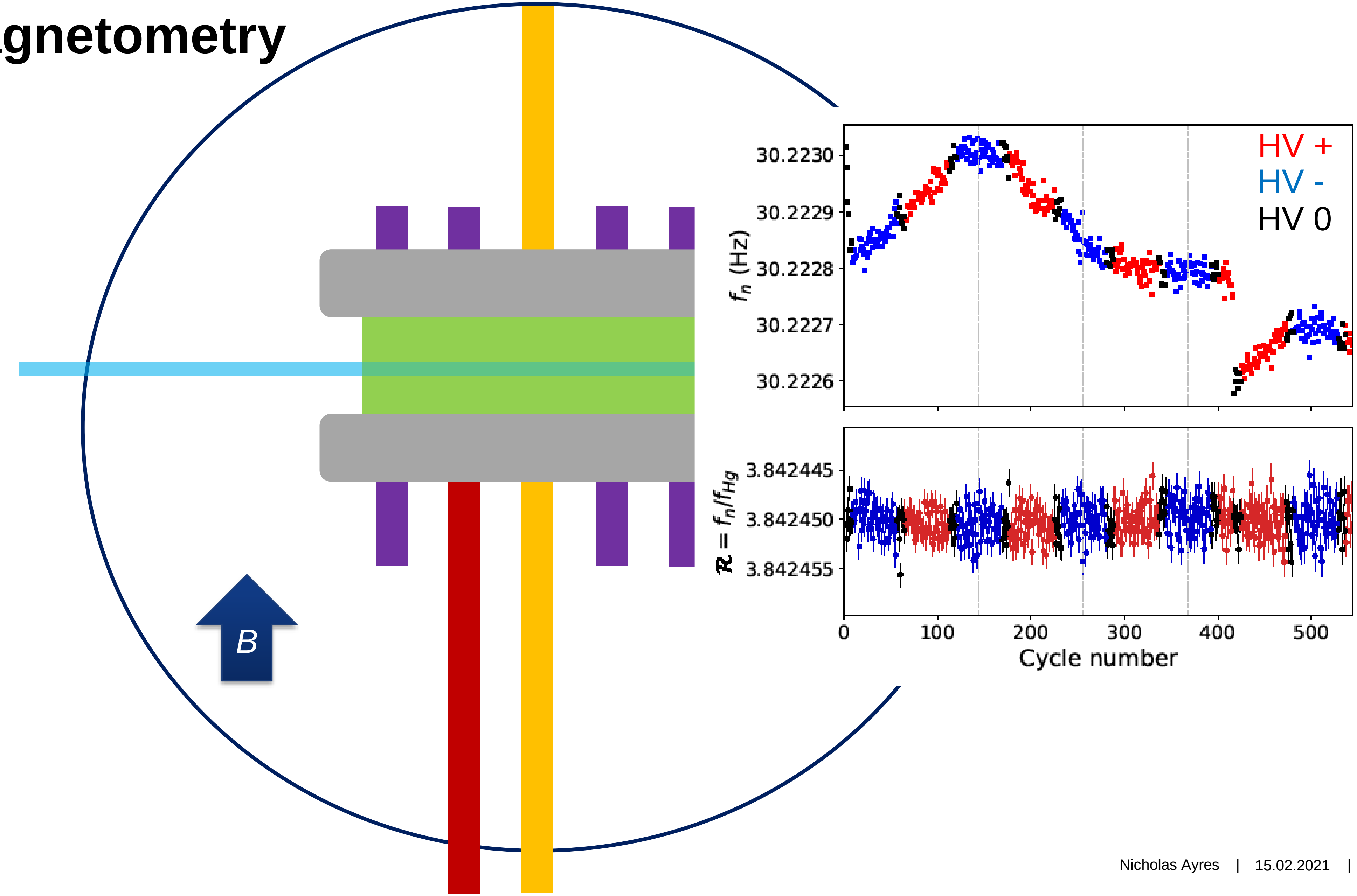
UCN + Hg Precession Chamber



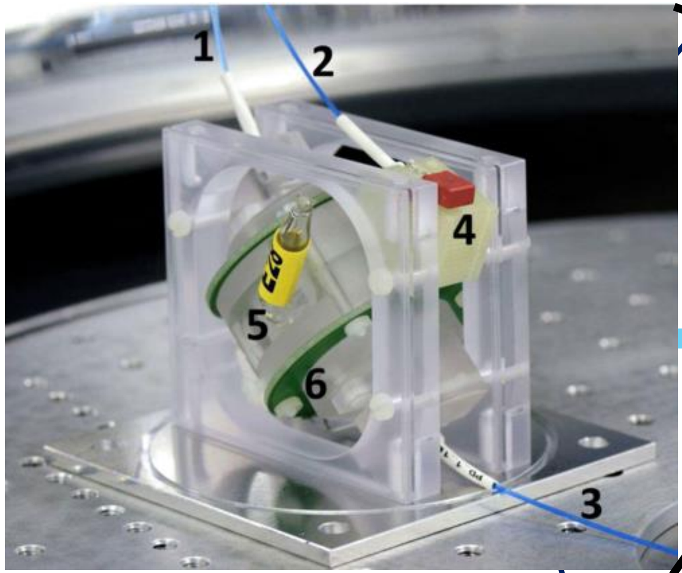
Hg Polarisation Cell

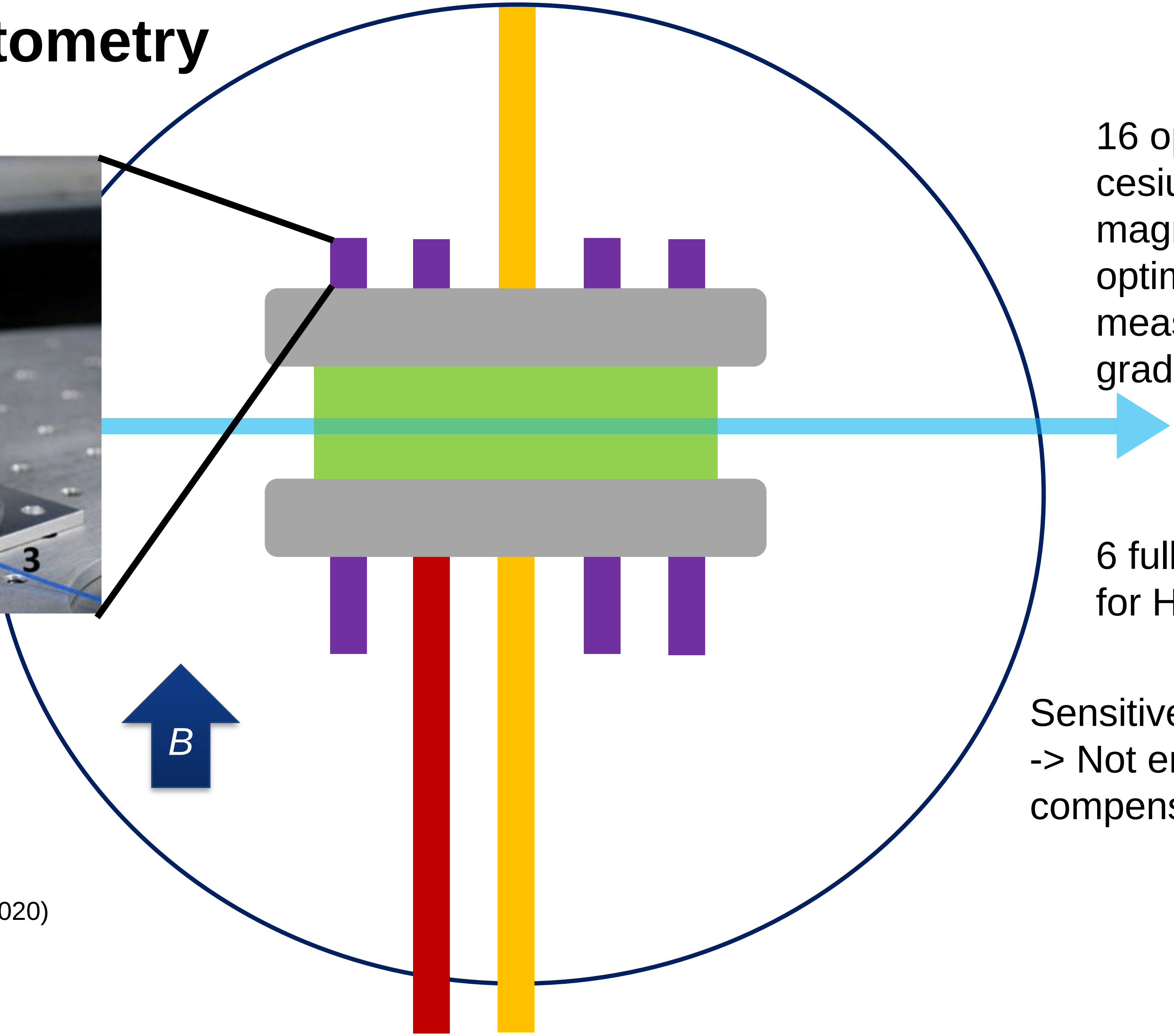
UCN guide from source, to detector

Mercury Magnetometry



Cesium Magnetometry





16 optically pumped cesium vapour magnetometers for optimisation and online measurement of field gradients

6 fully optically coupled for HV electrode

Sensitive but not so accurate -> Not enough to compensate false EDM alone

C. Abel *et al.* Phys. Rev. A **101**, 053419 (2020)

Datataking Summary and Timeline

Ancient History: take over Sussex-RAL-ILL apparatus and move to PSI
“Ship of Theseus” upgrade programme

2014

2015 and earlier: commissioning and test measurements

2015

2016

2017

January-April 2017: Field mapping

2018

October 2017: Start dismounting nEDM

2019

November 2019: Final unblinding

ing

Raw Statistical Sensitivity 1 x 10^{-26} e cm

Performance Benchmark

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

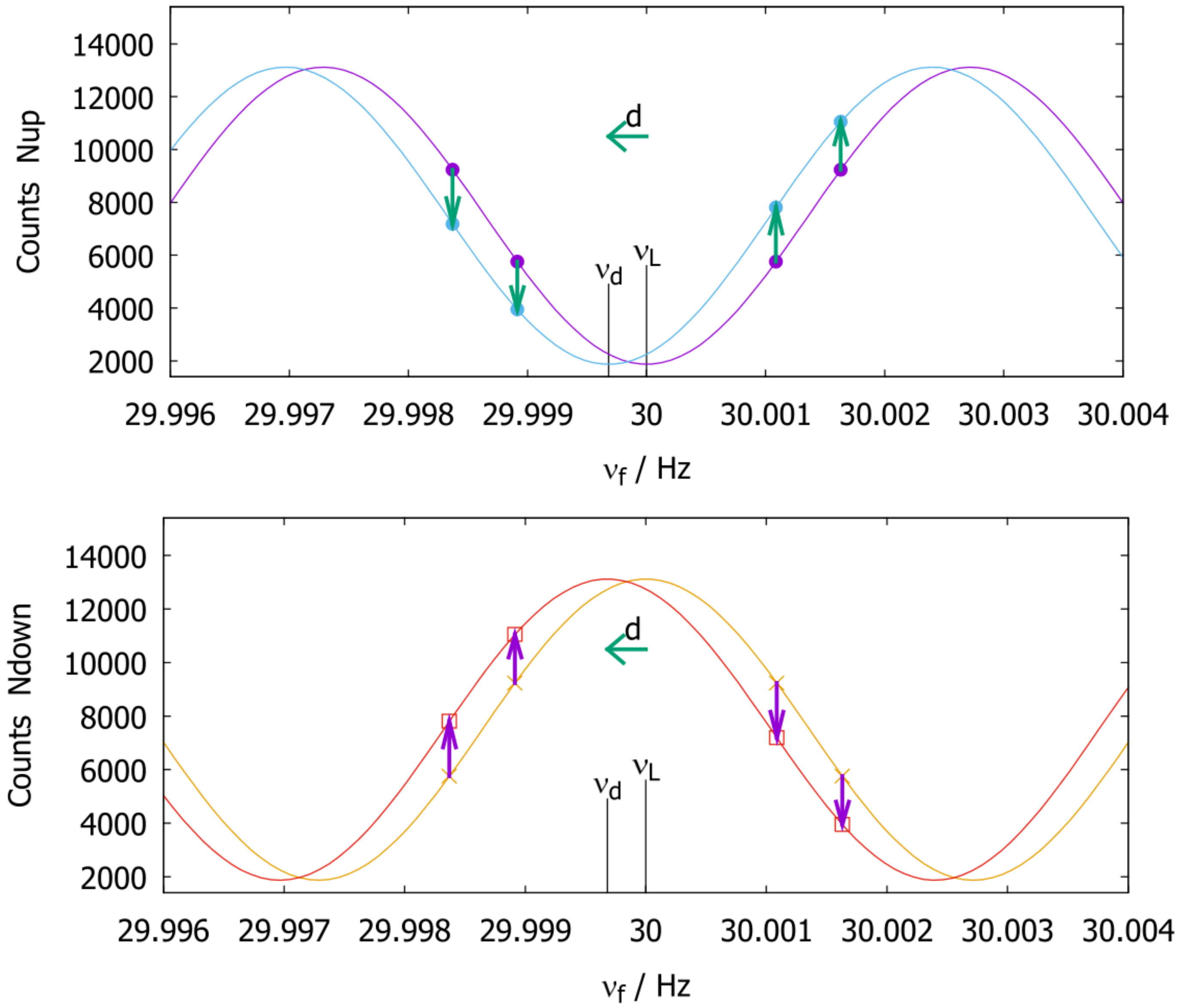
Neutron Visibility
Average = 0.76

E = 11kV/cm

Precession
time 180s

Average 11,400
neutrons per cycle
Up to 288 cycles/day

Data Blinding

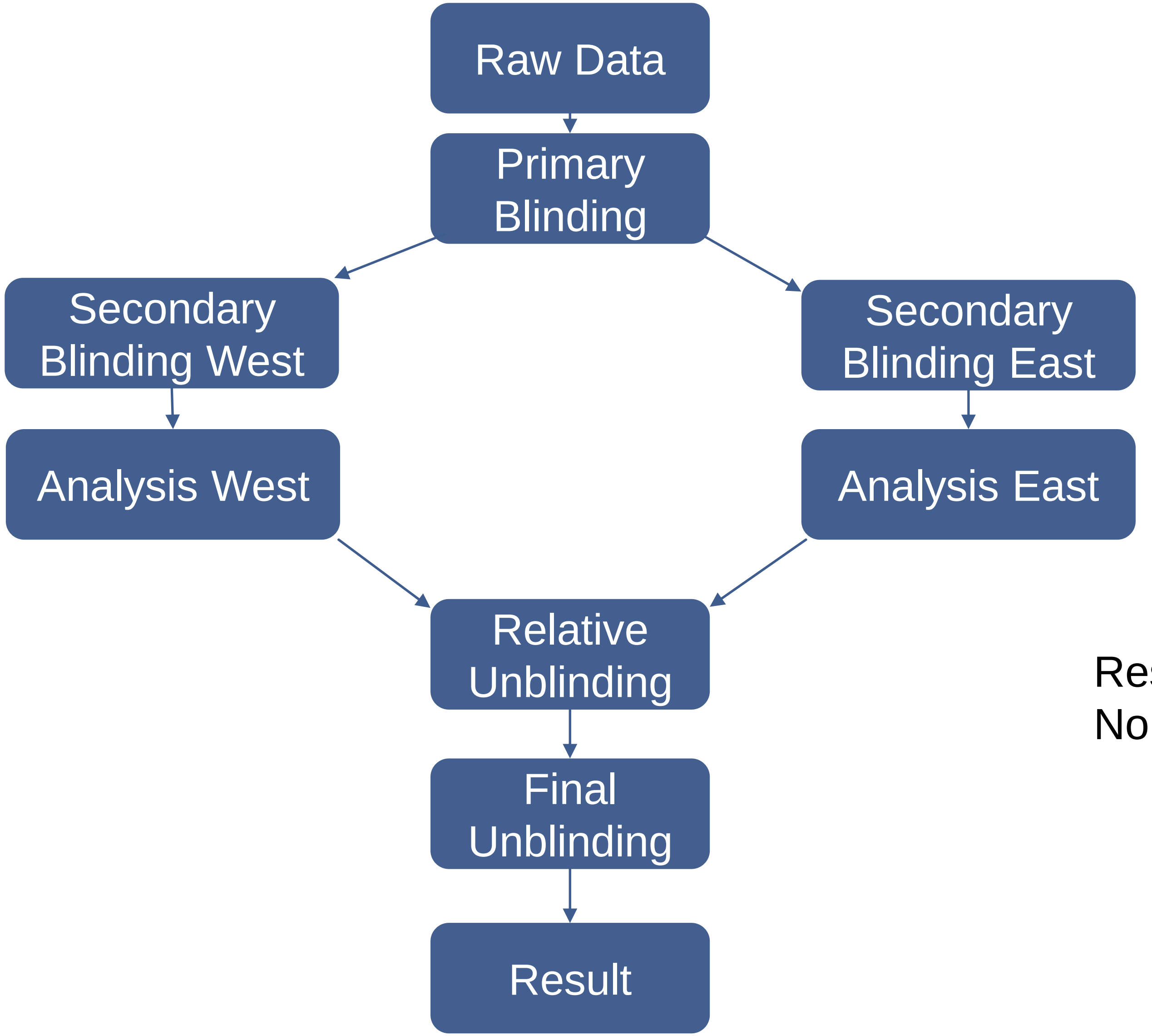


Concept: add an *E*-field dependant shift to the neutron frequency by moving counts between detectors

First nEDM measurement using data blinding

arXiv 1912.09244 (submitted to EPJ A)
J. Krempel talk nEDM2017

Quality Assurance and (Un)-blinding Strategy



Restricted communication
No shared code

PRL **124**, 081803
arXiv 1912.09244 (submitted to EPJ A)

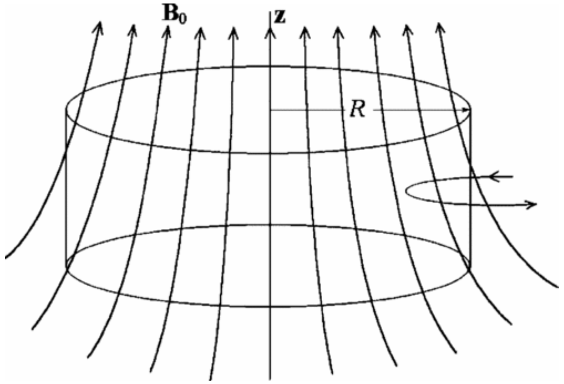
Analysis Strategy

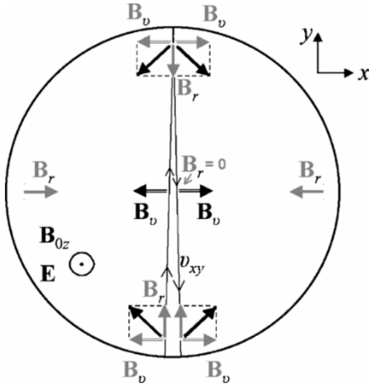
- Two parallel analysis groups converged on roughly the same scheme

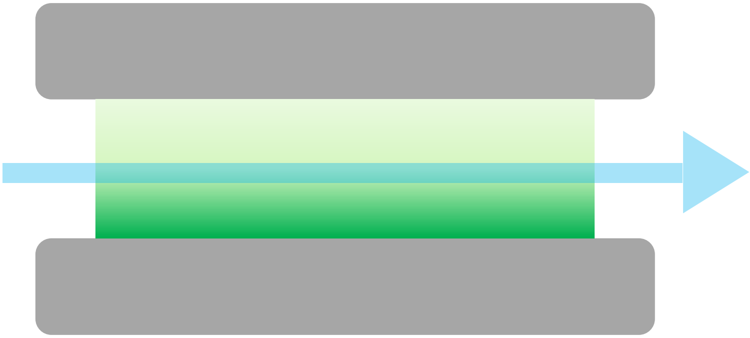
- Measure neutron counts up/down
- Control magnetic field state with mercury and cesium magnetometers
- Fit the Ramsey curve, then invert to infer *n*-Hg freq ratio each cycle

- Fit *n*-Hg freq ratio versus electric field to find an EDM
- Correct some systematics with field mapping data
- Use “Crossing Lines” to control leading systematic

Leading Systematic: False EDMs and Gravitational Shift







Conspiracy between vertical gradient and motional magnetic field from Lorentz transform of *E* into Hg atom frame causes *E*-correlated frequency shift

Slow UCN hang at the bottom of the chamber
Shifts $\mathcal{R}$ shift proportional to vertical gradient

$$d^{\mathrm{false}}_{\mathrm{n}\leftarrow\mathrm{Hg}} = \frac{G_{1,0}}{1\ \mathrm{pT/cm}} * 4.4 * 10^{-27}\mathrm{e\ cm}$$

$$\mathcal{R} = \mathcal{R}_0\left(1 + G_{1,0}\frac{\Delta h}{B_0}\right) \qquad \Delta h \approx 0.35\ \mathrm{cm}$$

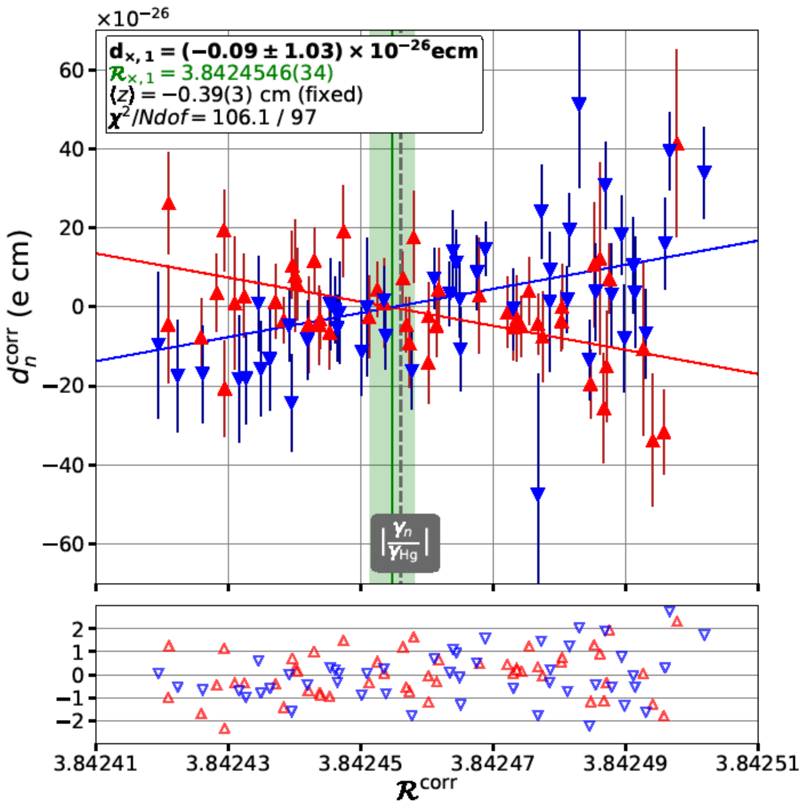
To first order these are proportional, but more complicated fields can cause a “phantom” effect

PRA **99**, 042112 (2019)

False EDMs and Crossing Lines Analysis

- Cesium magnetometer absolute accuracy too poor to use as sole measure of vertical gradient
- Use the gravitational shift to measure the vertical gradient
- Similar concept to that used on previous generation Sussex-RAL-ILL experiment

?



B Up B Down

Phantom Fields

- What happens if the field is more complicated?
- Consider a “cubic” vertical gradient mode “$G_{3,0}$”

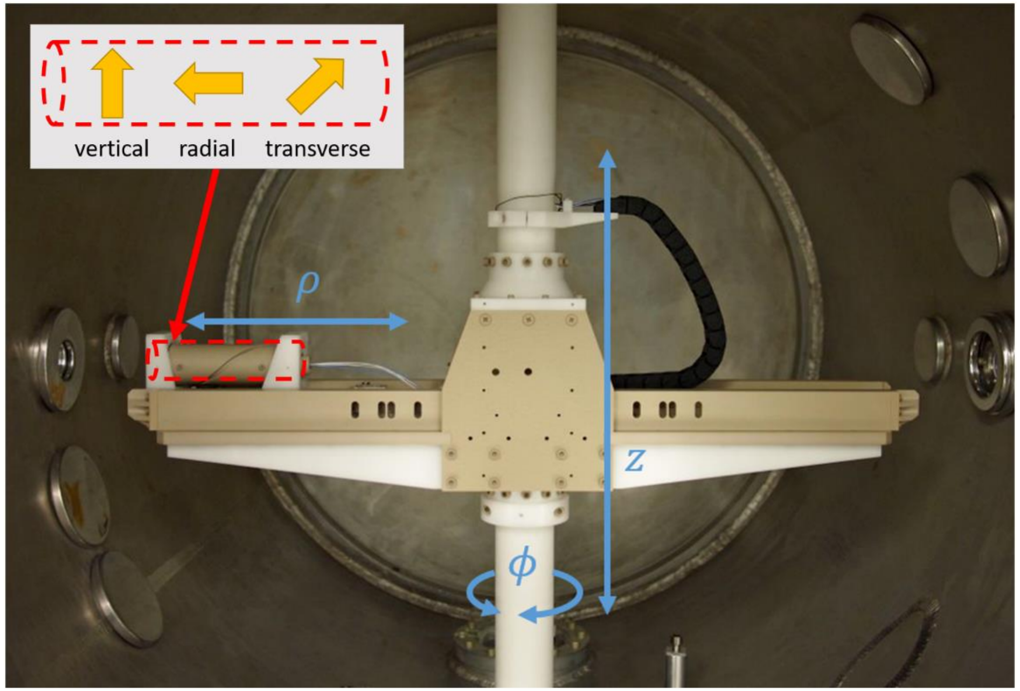
*cylindrical coordinates

$$\vec{B} = G_{3,0}\begin{pmatrix} \frac{3}{8}\rho^3 - \frac{3}{2}z^2\rho \\ 0 \\ z^3 - \frac{3}{2}\rho^2 z \end{pmatrix}$$

- Vertical component causes gravitational shift, radial causes false EDM
- 2/3 of the false EDM is compensated by crossing lines, but “phantom” remains

Magnetic Field Mapping

- Crossing lines analysis fixes the strongest effect, but phantom remains
  - Measure field offline at thousands of points
  - Decompose field into basis of 63 modes
  - Apply corrections to each run before crossing lines analysis



- Reduce effect from phantom fields from 70% of stat. uncert. to 10%
- Control effect of transverse inhomogeneities to 5% of stat. uncert.

PhD Thesis N. J. Ayres
PhD Thesis L. Ferraris-Bouchez
Article to appear on arXiv in coming days

Additional Systematics

Effect	Shift (x10^{-28} e cm)	Error (x10^{-28} e cm)
Error on $\langle z \rangle$	...	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	−0.1	0.1
Local dipole fields	...	4
$v \times E$ UCN net motion	...	2
Quadratic $v \times E$	...	0.1
Uncompensated G drift	...	7.5
Mercury light shift	...	0.4
Inc. scattering ^{199}Hg	...	7
TOTAL	69	18

Included in Crossing Lines Fit (Error on $\langle z \rangle$, Higher-order gradients, Transverse field correction)

Dedicated mapping measurements (Higher-order gradients, Transverse field correction)

Constrained with measurement at PTB Berlin (Local dipole fields)

Cs Magnetometers (Uncompensated G drift)

Not anticipated at design, bear in mind for next time (Inc. scattering ^{199}Hg)

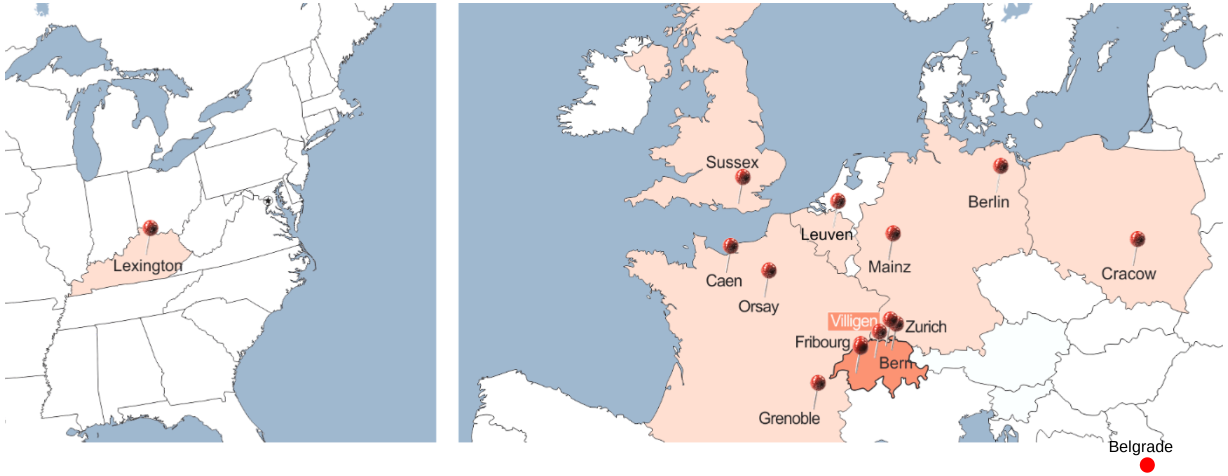
Total systematic error **0.18 x 10^{-26} e cm**
Factor 5 improvement on previous measurement
Only 20% of statistical error

The PSI nEDM Collaboration

- ~55 active experimenters
  - 84 authors on the result
  - 34 PhD Theses

- The strategy:
  - Phase 1: achieve a new world limit using a totally renovated version of the previous Sussex-RAL-ILL apparatus –done!
  - Phase 2: **n2EDM**: a totally new double chamber apparatus to allow for a new measurement on the $d_n \sim 10^{-27}$ e cm scale

Collaboration Meeting, Mainz TRIGA Reactor, November 2019



New nEDM Measurement

- Previous Measurement: $(-0.2 \pm 1.5_{\text{stat}} \pm 1.0_{\text{sys}}) \times 10^{-26}$ e cm
  - Infer $|d_n| < 3 \times 10^{-26}$ e cm (90% CL)
  - J. M. Pendlebury *et al.* Phys. Rev. D **92**, 092003 (2015)

- New Measurement: $(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}$ e cm
  - Infer $|d_n| < 1.8 \times 10^{-26}$ e cm (90% CL)
  - C. Abel *et al.* PRL **124**, 081803 (2020)

Many Thanks