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Optical magnetometry for the TUCAN nEDM experiment

Wolfgang Klassen

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THE UNIVERSITY OF BRITISH COLUMBIA

THE UNIVERSITY OF WINNIPEG

Motivation

- The Hamiltonian of the neutron:

Does this exist?
Lets measure it!

$$H = \hbar\omega = -\mu \mathbf{B} \cdot \mathbf{S} - d\mathbf{E} \cdot \mathbf{S}$$

- To measure d, take advantage of the behaviour of **B**, **E**, and **S**:

$$h\omega_{\uparrow\uparrow} = 2\mu_n B + 2d_n E$$ Parallel

$$h\omega_{\uparrow\downarrow} = 2\mu_n B - 2d_n E$$ Anti-parallel

- and solve for:

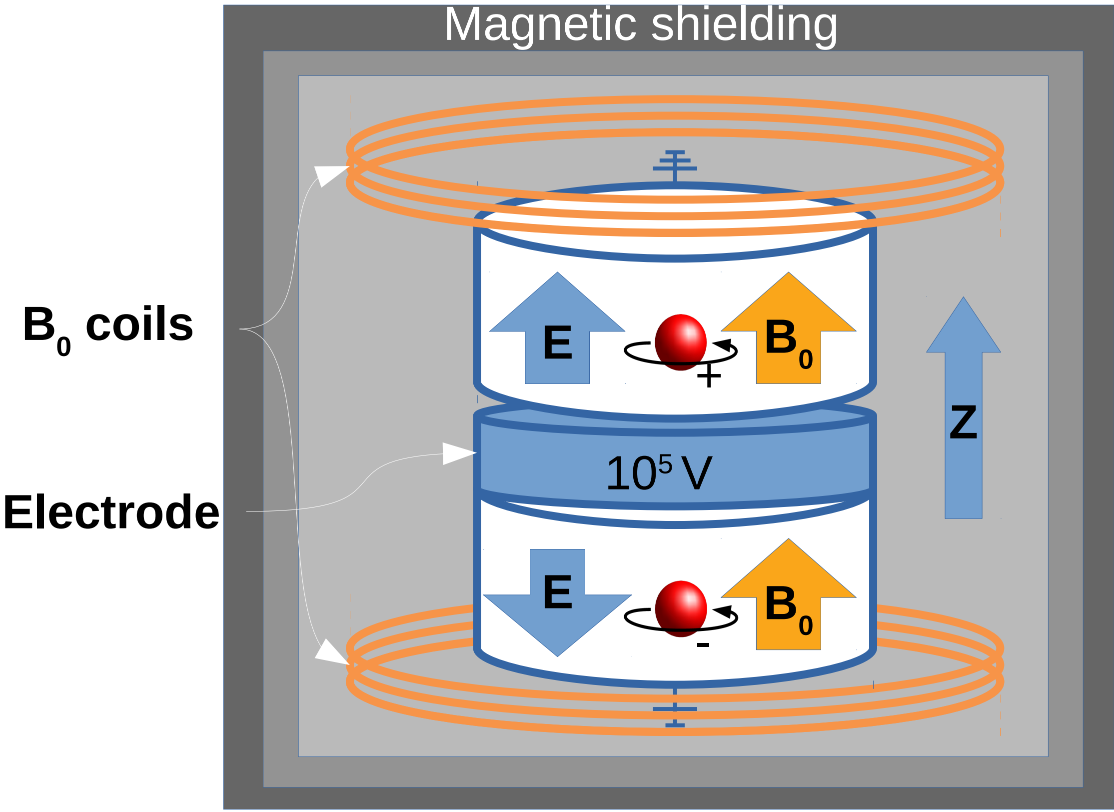
$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4E}$$

$$d_n(standard\ model) \sim 1 \times 10^{-31} \mathrm{e \cdot cm}$$

$$d_n(upper\ bound) = 1 \times 10^{-26}\ \mathrm{e \cdot cm}$$

The TUCAN experiment

- 2 chambers allows us to measure both values of ω simultaneously
- Working equation relies on **identical E&B** in both chambers, **B** = 1μT
- Gradients in general, and vertical gradients especially will effect our measurement of d_n



Magnetometry: field decomposition

- In order to measure and control magnetic fields we need a sensible way to describe them
- Like Fourier decomposition, we can describe the field in terms of the relative contributions of orthogonal functions

$$\begin{pmatrix} B_x(\vec{r}) \\ B_y(\vec{r}) \\ B_z(\vec{r}) \end{pmatrix} = \sum_{l,m} \boxed{G_{l,m}} \begin{pmatrix} \Pi_{x,l,m}(\vec{r}) \cdot \hat{i} \\ \Pi_{y,l,m}(\vec{r}) \cdot \hat{j} \\ \Pi_{z,l,m}(\vec{r}) \cdot \hat{k} \end{pmatrix}$$

Fully describes the field up to order ℓ

Magnetometry: measuring fields

$$
\begin{bmatrix} B_x(x_1,y_1,z_1) \\ \vdots \\ B_y(x_1,y_1,z_1) \\ \vdots \\ B_z(x_1,y_1,z_1) \\ \vdots \\ B_z(x_n,y_n,z_n) \end{bmatrix}
=
\begin{bmatrix}
0 & 0 & 1 & y_1 & 0 & \frac{-1}{2}x_1 & z_1 & x_1 & 2x_1y_1 & 2y_1z_1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \\
1 & 0 & 0 & x_1 & z_1 & \frac{-1}{2}y_1 & 0 & -y_1 & x_1^2-y_1^2 & 2x_1z_1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \\
0 & 1 & 0 & 0 & y_1 & z_1 & x_1 & 0 & 0 & 2x_1y_1 \cdots \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \\
0 & 1 & 0 & 0 & y_n & z_n & x_n & 0 & 0 & 2x_ny_n \cdots
\end{bmatrix}
\cdot
\begin{bmatrix} G_{0-1} \\ G_{00} \\ G_{01} \\ G_{1-2} \\ G_{1-1} \\ G_{10} \\ G_{11} \\ G_{12} \\ G_{2-2} \\ G_{2-1} \\ \vdots \end{bmatrix}
$$

$<<B_z$

$<<B_z$

$$\vec{B}_z = T_z \cdot \vec{g}.$$

$$\vec{g} = pinv(T_z) \cdot \vec{B}_z \approx pinv(T_z) \cdot \overrightarrow{B_{mod}}$$

Measured by sensors

Want to calculate

Known from positions of sensors

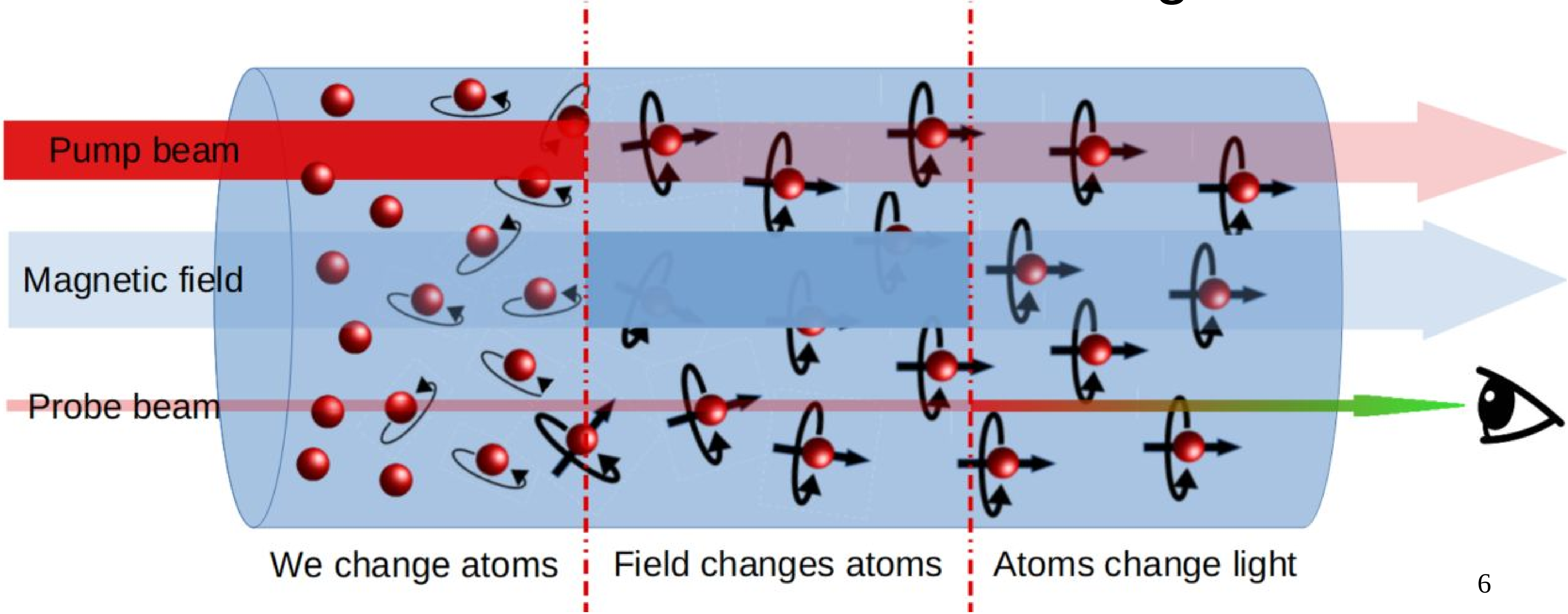
How to measure B?

- Can’t disturb the magnetic field
  - no metal components, no currents
- Can’t realistically be cryogenic
  - no SQUIDs
- Co-magnetometer can only measure 1st order gradient
  - need multiple sensors to measure higher orders
- Needs to be very sensitive

Optical magnetometry: NMOR

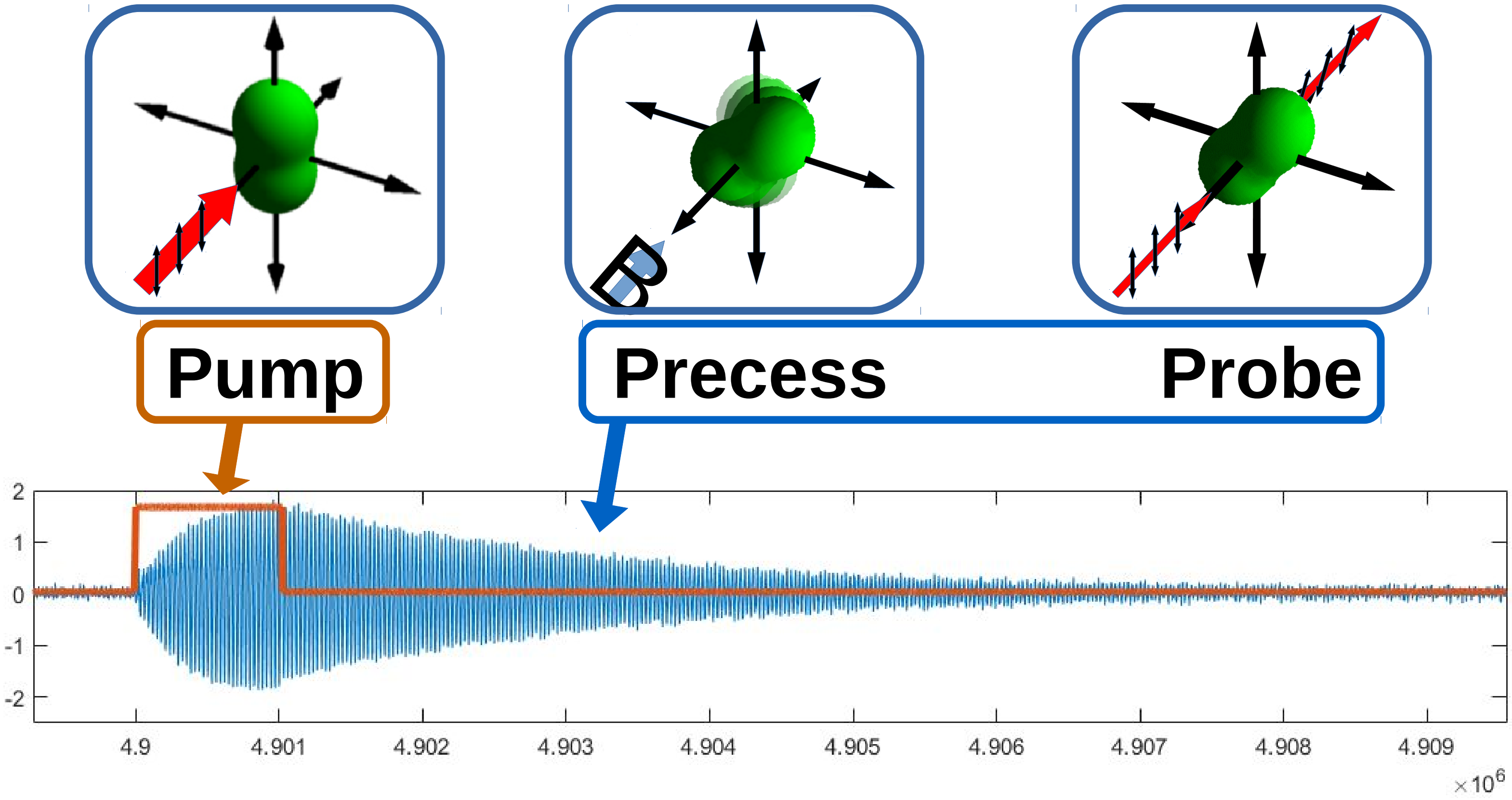
non-linear magneto-optical rotation

- We use lasers to measure magnets



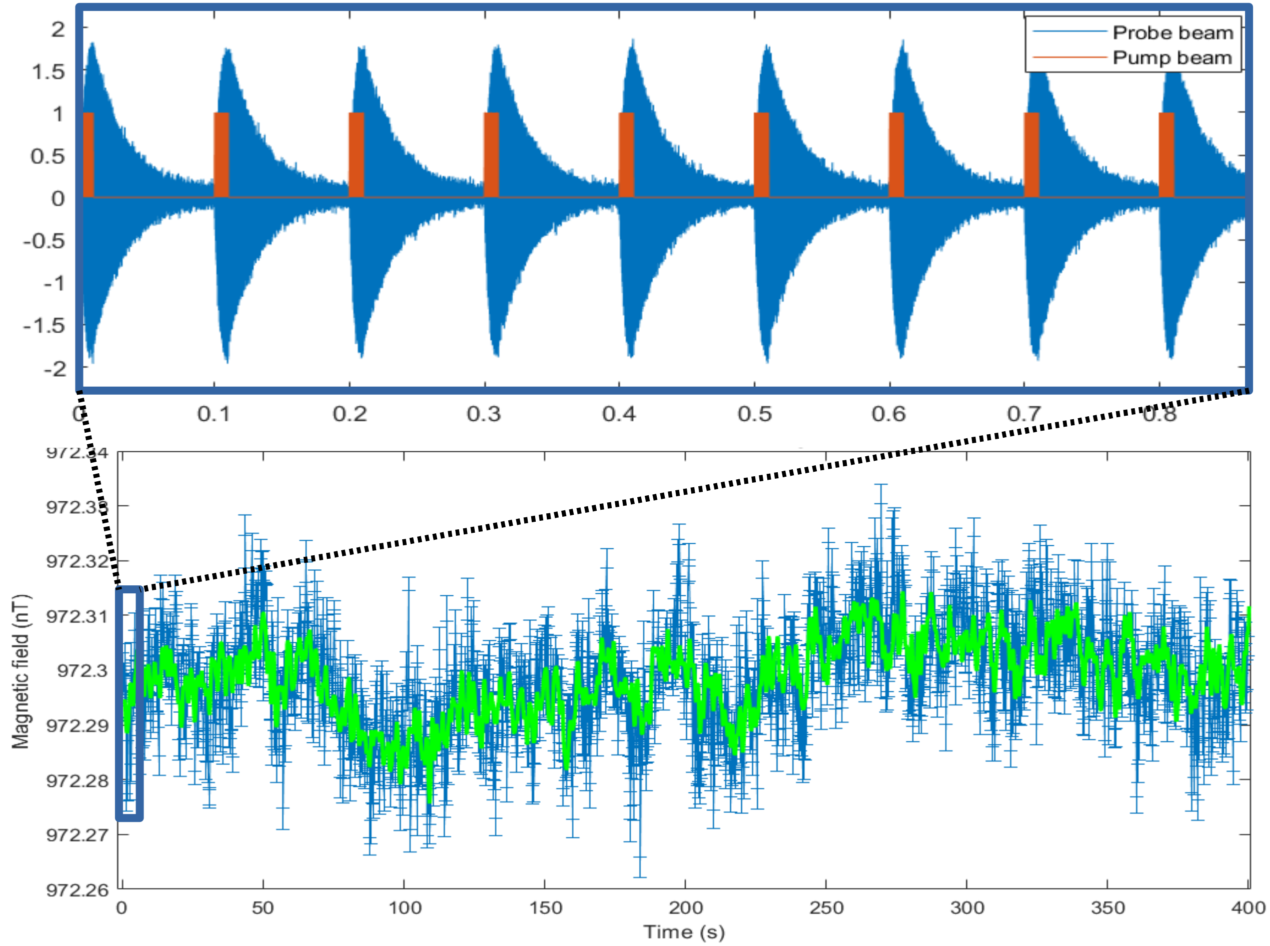
TUCAN configuration: FID

free induction decay



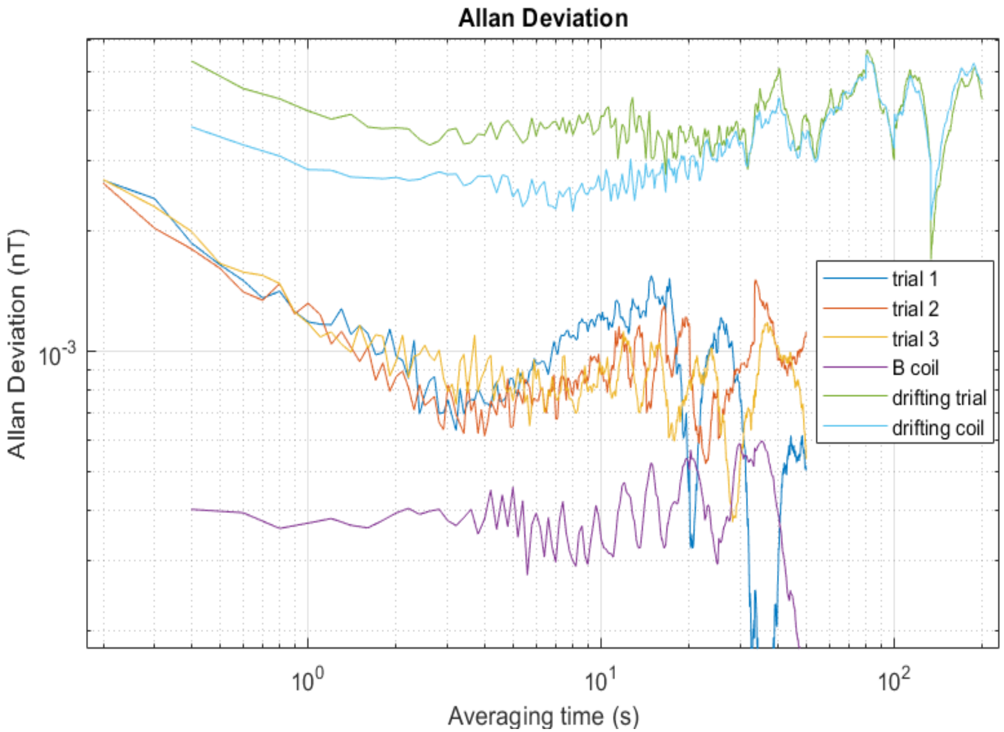
We use Cs atoms, we know **precisely** how fast they precess in a magnetic field

Measuring fields at UofW



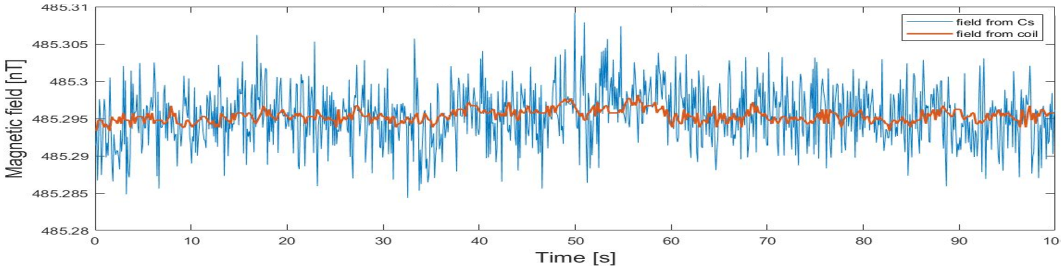
- Can clearly see drifts in the coil current generating the test field
- Well correlated with FID frequency measurement

Prototype performance



- sub-pT performance after 3-4 s integration
- Is this good enough?
- Which $G_{l,m}$'s do we care about?

$$d^{false}_{Hg\to n} = 2.6\times 10^{-27}G_{10} + 6.5\times 10^{-26}G_{20} + 9.5\times 10^{-25}G_{30} + 6.7\times 10^{-24}G_{40} - 9.5\times 10^{-23}G_{50}$$



Monte Carlo simulations

Position error built in — Position error added

$$T_x, T_y, T_z = f(x, y, z)$$

Position error built in — Position error built in — Exactly defined

$$\begin{bmatrix} \vec{B}_x \\ \vec{B}_y \\ \vec{B}_z \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \cdot [\vec{g}]$$

Field error and offset added

Position error built in
Transverse field error added

$$B_{mod} = \sqrt{B_x^2 + B_y^2 + B_z^2}$$

The value of g recovered by a realistic system of magnetometers

Exactly defined

Field, position, and offset errors built in

$$\vec{g} \cong pinv(T_z) \cdot \overrightarrow{B_{mod}}$$

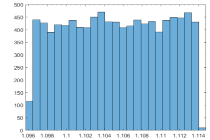
$$error = \left| d_{false}(g_{simulated}) - d_{false}(g_{recovered}) \right|$$

How to deploy sensors? Genetic Algorithm

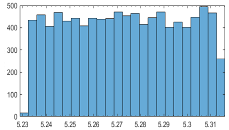
10^{-30} 10^{-29} 10^{-28} 10^{-27} 10^{-26} 10^{-25} 10^{-24} 10^{-23} 10^{-22}

- 20 sensors
- pT sensitive
- mm placement accuracy
- field map to 3rd order
- field sim. to 5th order

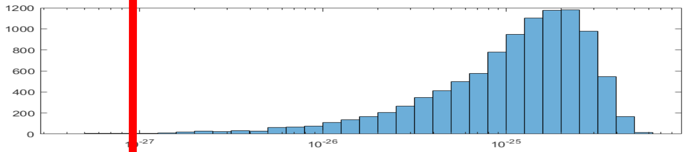
Rings



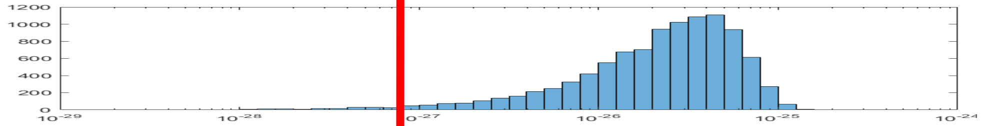
Asymmetric rings

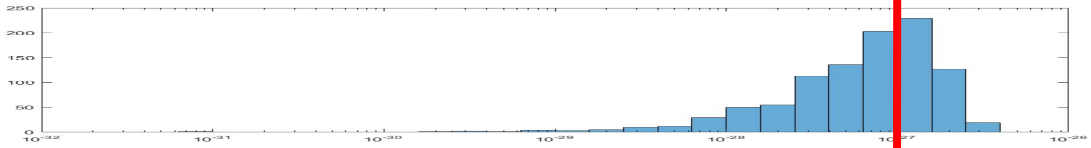


Helices

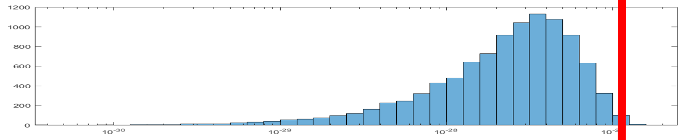


Random





Early Ferret run

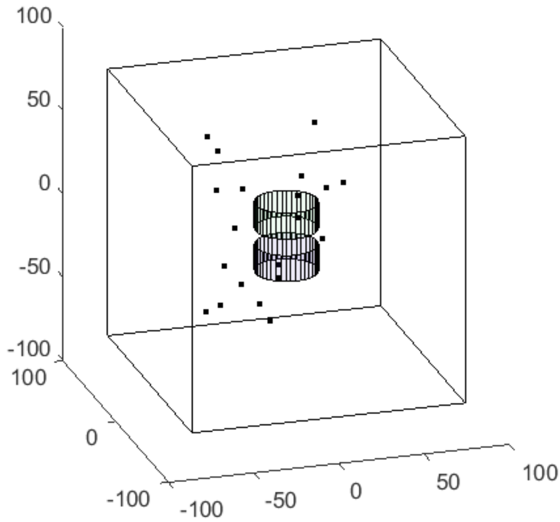


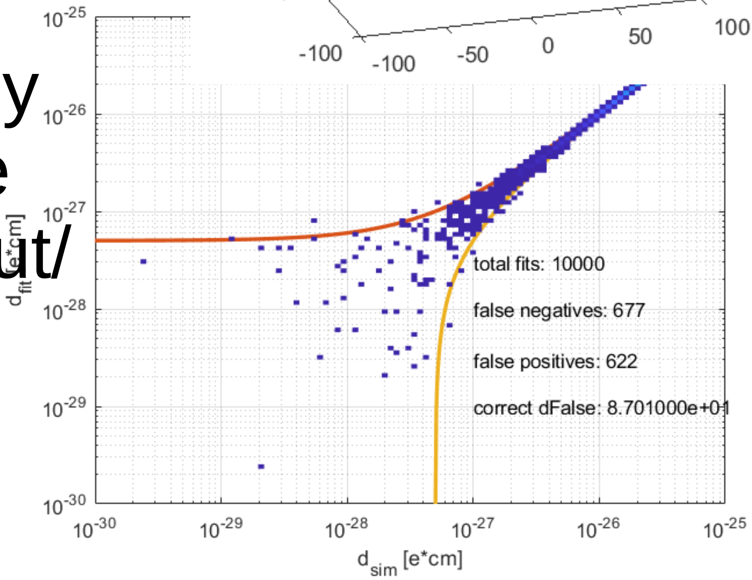
Recent Ferret run

10^{-30} 10^{-29} 10^{-28} 10^{-27} 10^{-26} 10^{-25} 10^{-24} 10^{-23} 10^{-22}

Advantages of using Ferret

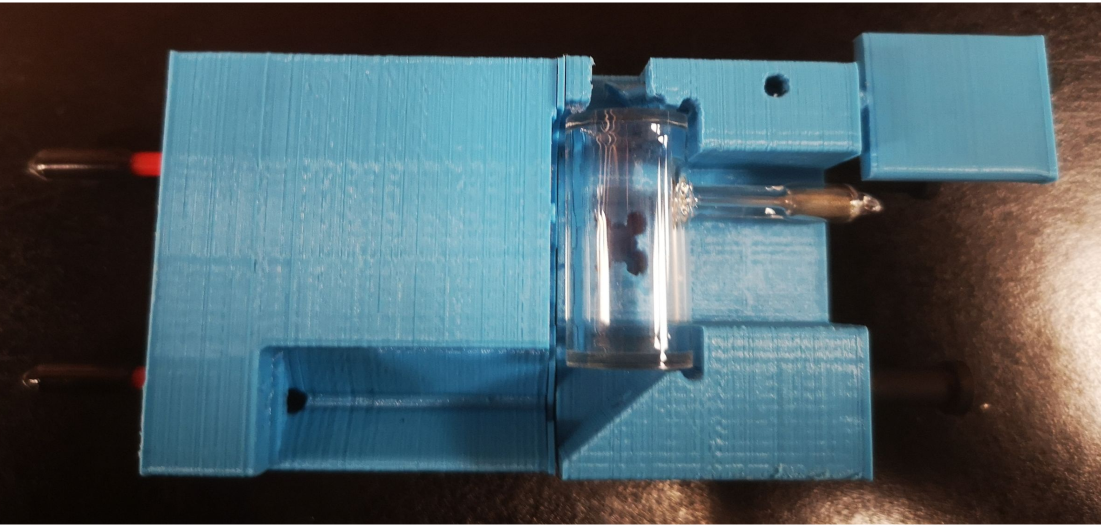
- Can account for changing keep-out zones
- Can find solutions robust against:
  - Any single sensor dying
  - Any single sensor being deliberately mis-placed by some relatively large margin (e.g to avoid a new pipe/strut/ cable/vacuum hose being placed)
  - Sensor tilt angles





Further development

- Setting up fibre optics in our lab at UofW
- Contracted Southwest Sciences to build prototype mag-heads, as well as final design



- Ultimately will have 25-30 sensors made

Early prototype clamshell
for sensor design

Questions?