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Optical magnetometry for the TUCAN nEDM experiment

Wolfgang Klassen

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NRC · CNRC

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:

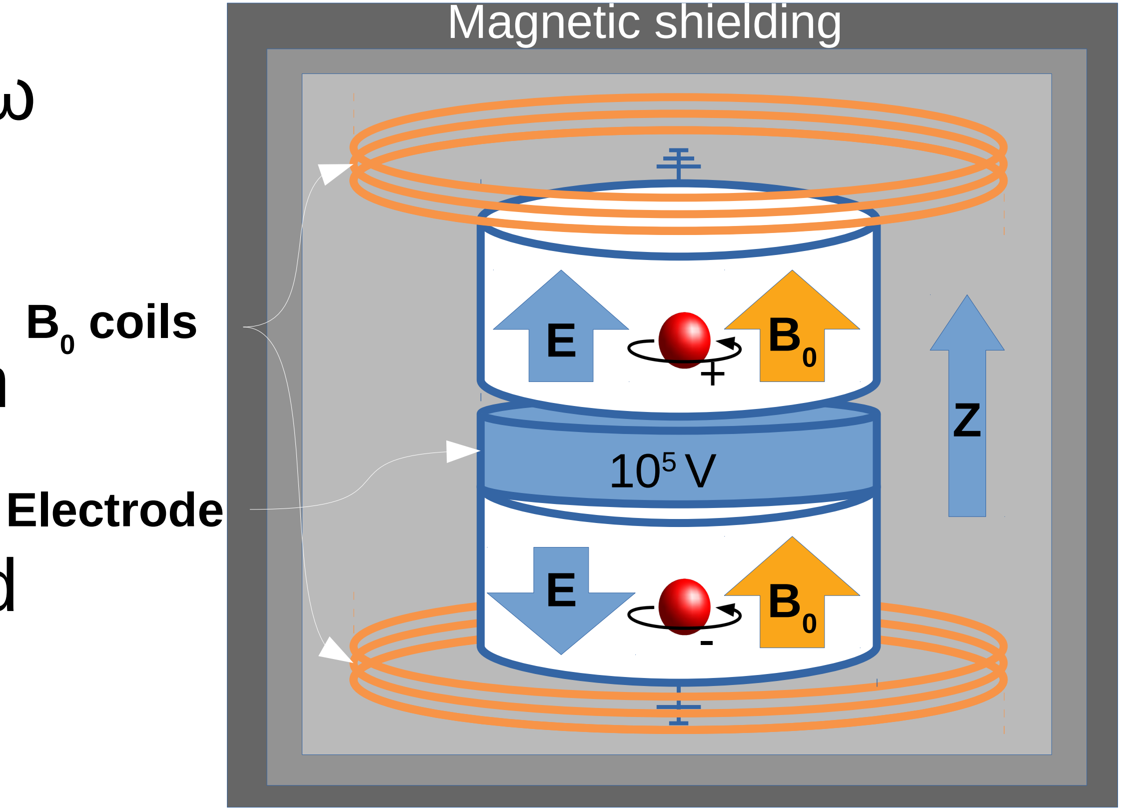
$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4E}$$

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

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

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

* C. Abel et al. *Magnetic field uniformity in neutron electric dipole moment experiments*. In:Phys.Rev.A99.4 (2019), p. 042112

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

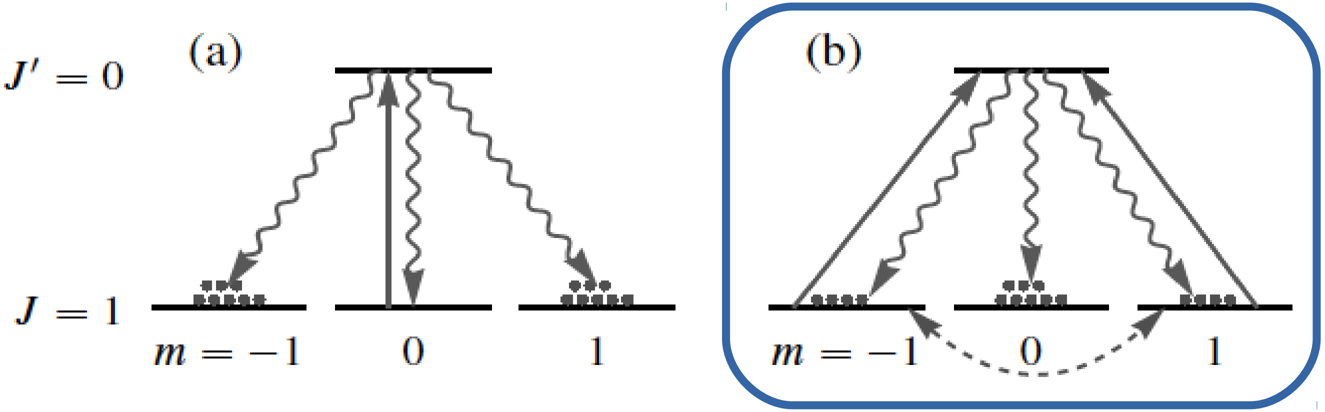
Want to calculate

Known from positions of sensors

Optical magnetometry: NMOR

non-linear magneto-optical rotation

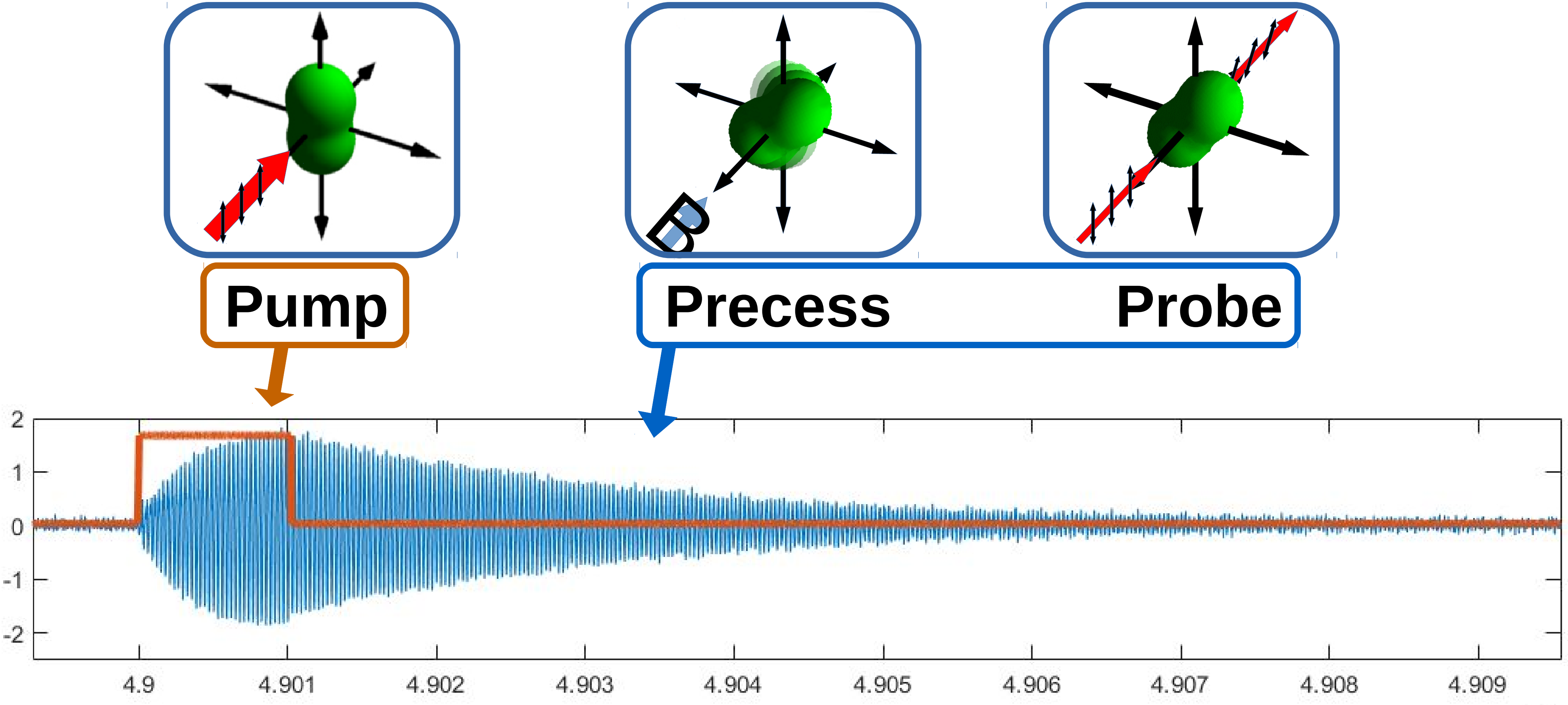
- Manifests in alkali vapour (Cs) excited by resonant light
- Atoms can be polarized by light
- Polarized atoms interact with magnetic fields
- Effectively couples magnetic field to light



Optical pumping rearranges the magnetic sub-level occupation

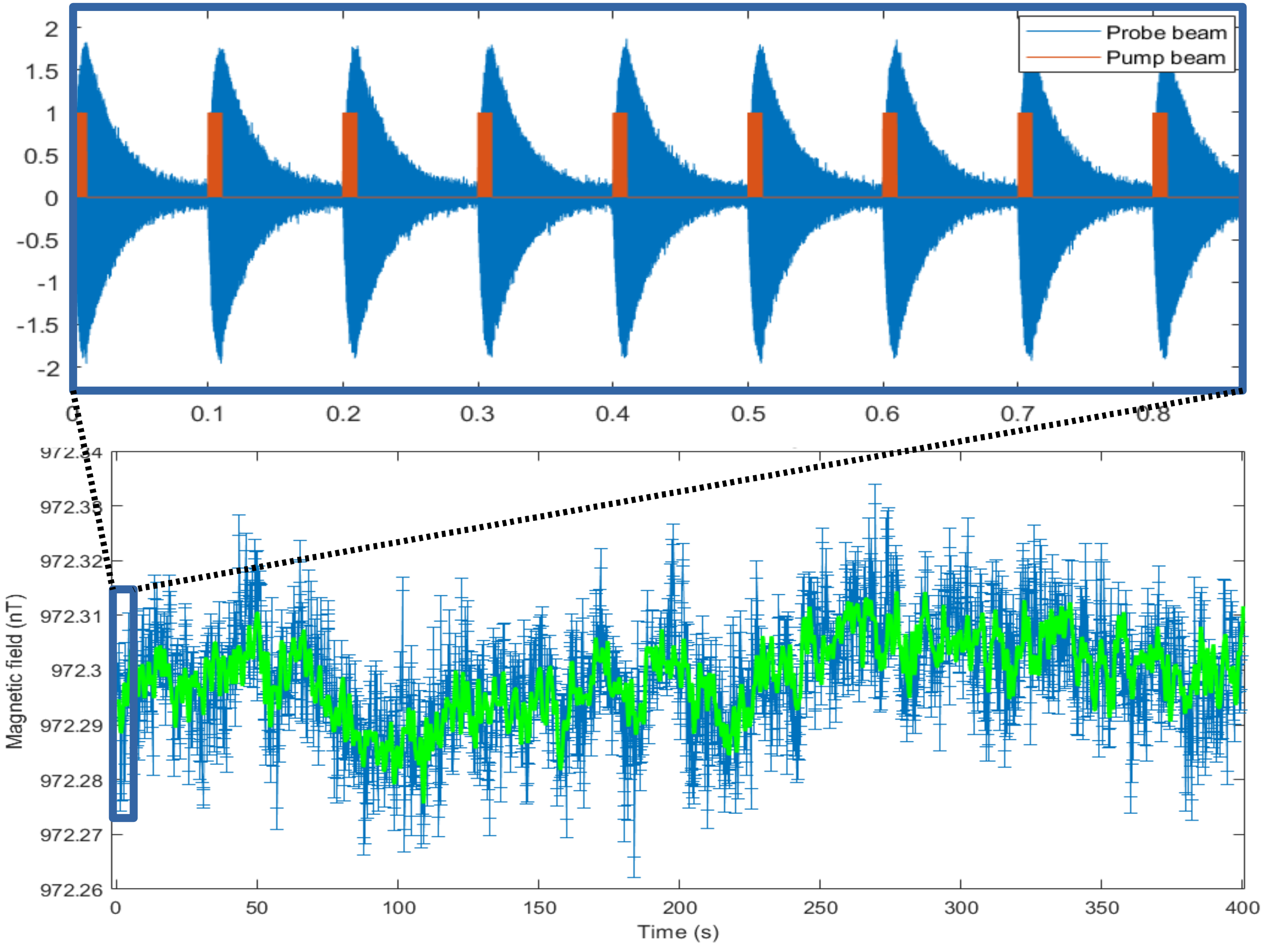
TUCAN configuration: FID (FSP?)

free induction decay



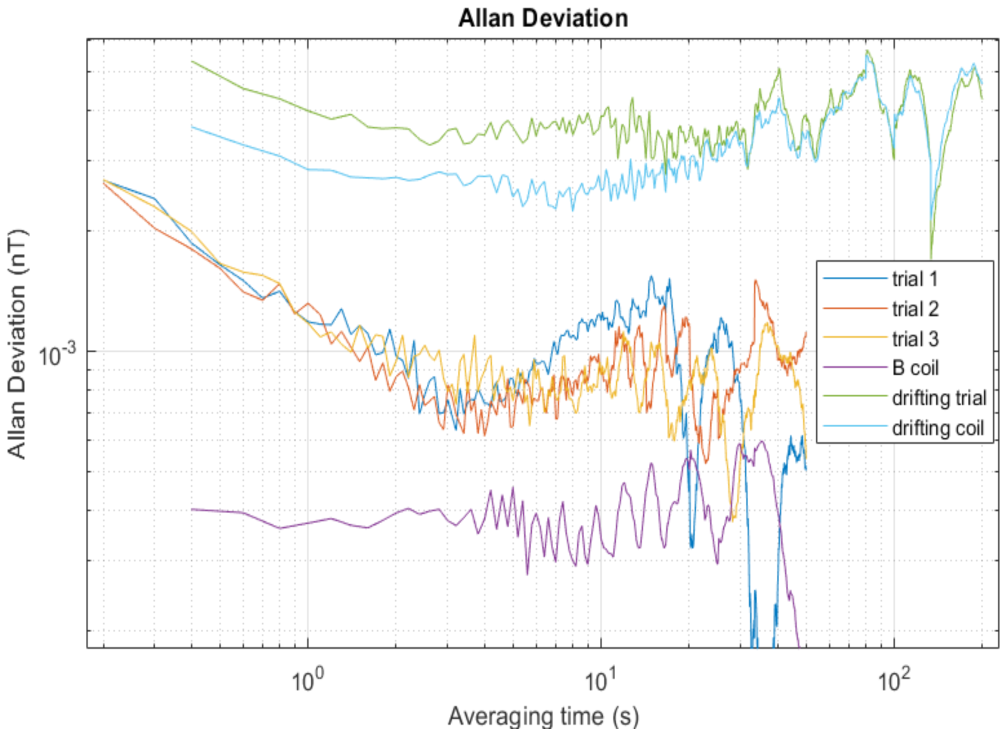
We use Cs atoms, we know **precisely** how fast they precess in a magnetic field

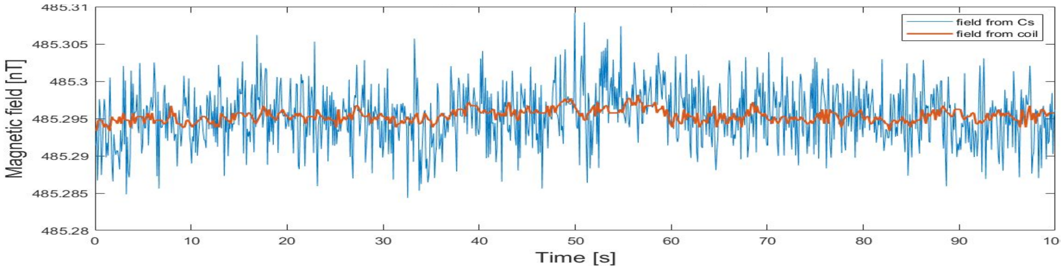
Measuring fields at UofW



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

Proof-of-concept performance

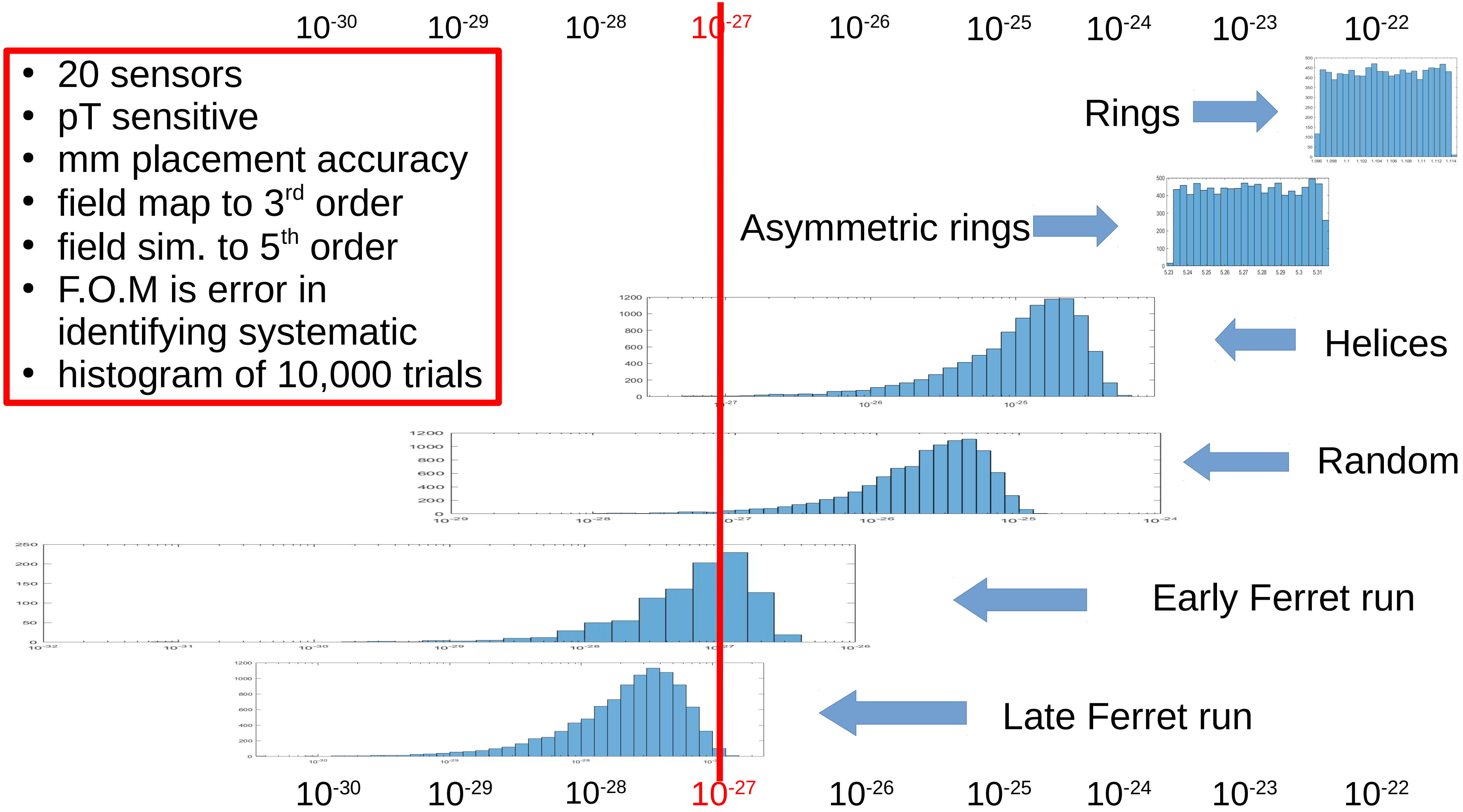




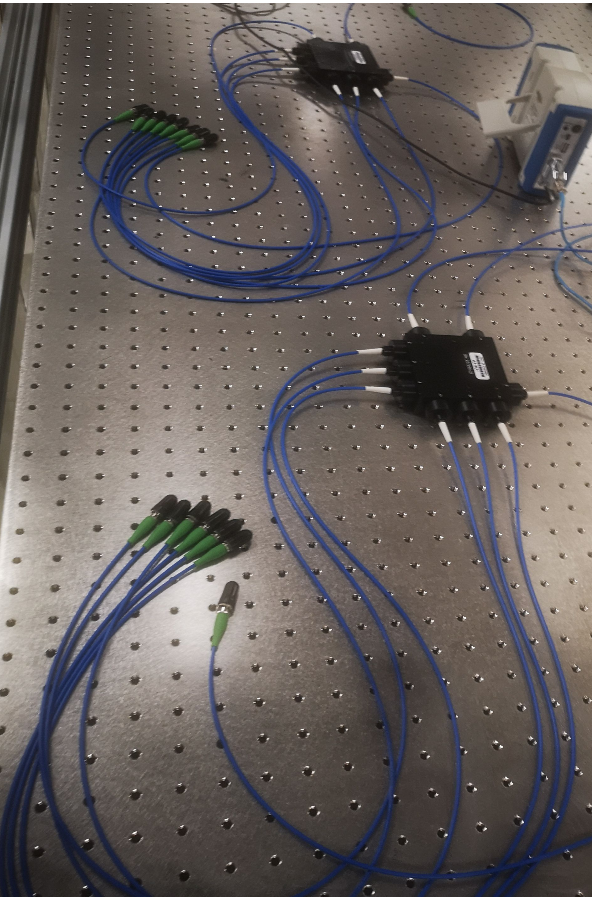
- sub-pT performance after 3-4 s integration
- Monte Carlo simulations indicate that this level of precision can adequately map our field

How to deploy sensors? Genetic Algorithm

- 20 sensors
- pT sensitive
- mm placement accuracy
- field map to 3rd order
- field sim. to 5th order
- F.O.M is error in identifying systematic
- histogram of 10,000 trials

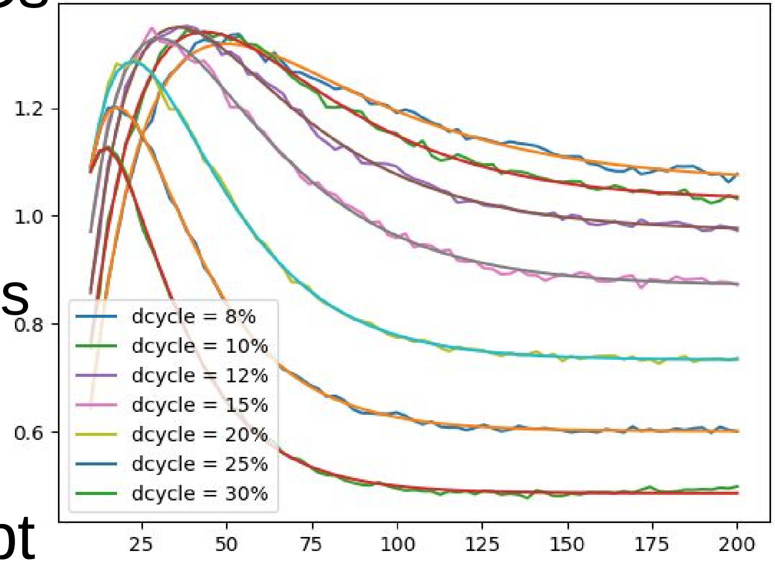


Current development



Fibre splitters being set up and tested at UofW

- Characterizing coated Cs cells for fibre coupled prototype
  - Automatically characterize T1, T2, Cs vapour pressure
- Going from free space coupled proof-of concept to fibre coupled prototype
  - prototype manufactured by SWS in Santa Fe



Automatically optimizing parameters to maximize the amplitude of FIDs to characterize T2 for the custom made Cs cells. These cells get sent to SWS to be placed in the final sensors

Questions?