
This version is available at https://strathprints.strath.ac.uk/61768/

Strathprints is designed to allow users to access the research output of the University of Strathclyde. Unless otherwise explicitly stated on the manuscript, Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Please check the manuscript for details of any other licences that may have been applied. You may not engage in further distribution of the material for any profitmaking activities or any commercial gain. You may freely distribute both the url (https://strathprints.strath.ac.uk/) and the content of this paper for research or private study, educational, or not-for-profit purposes without prior permission or charge.

Any correspondence concerning this service should be sent to the Strathprints administrator: strathprints@strath.ac.uk
Double-Resonance Magnetometry in Arbitrarily Oriented Fields

Stuart Ingleby
University of Strathclyde
Overview

• Quantum Technology Hub
  – Practical focus: apply QT to sensors

• Design choices
  – Unshielded sensor

• $B_0$ orientation
  – Signal amplitude and phase effects

• Exploitation
  – Demonstrator system
Led Birmingham University
- Includes Strathclyde, Nottingham, Sussex, Southampton, NPL & industry
- Started Jan 2015

Unshielded portable sensor
- Geophysical measurement
- Low size, power requirement
- Sub-pT sensitivity
Unshielded Double Resonance Sensor

- Dynamic range - yes
  - No requirement for µT compensation
- Noise rejection - yes
  - Homodyne detection
  - Polarimetry
  - Gradiometry
- Arbitrary B₀ orientation - ?
  - Dead-zones
  - Heading errors
- Portability - yes
  - Single frequency pump-probe
  - Firmware signal processing
Unshielded Double Resonance Sensor

• Dynamic range - yes
  – No requirement for $\mu$T compensation
• Noise rejection - yes
  – Homodyne detection
  – Polarimetry
  – Gradiometry
• Arbitrary $B_0$ orientation - ?
  – Dead-zones
  – Heading errors
• Portability - yes
  – Single frequency pump-probe
  – Firmware signal processing
**B\(_0\) Orientation: Shielded Test System**

- \(M_x\) configuration
- Paraffin-coated Cs cell
  - Weis group [1]
- \(B_0\) control
  - Software-controlled coils
  - Iterative calibration
- Software modulation & demodulation
  - Lineshape fitting

---

**B\(_0\) Orientation:**

**Shielded Test System**

- \(M_x\) configuration
- Paraffin-coated Cs cell
  - Weis group []
- \(B_0\) control
  - Software-controlled coils
  - Iterative calibration
- **Software modulation & demodulation**
  - Lineshape fitting
**$B_0$ Orientation: Shielded Test System**

- **$B_0$ control**
  - Low-noise current drivers
  - Shield degauss
  - Single-axis calibration [2]
    - 3D calibration [C. O’Dwyer poster]
- **200 nT $B_0$**
  - $\delta |B| = 0.24$ nT
  - $\delta \theta = 0.23$ mrad

**B₀ Orientation: Theory**

- **Pump**
  - Cs D1 4-3
  - σ-polarised
  - 20 µW
    - $\Gamma_{\text{PUMP}} \ll \Gamma$

- **Evolution**
  - $B₀ \gg B_{\text{RF}}$
  - $\Omega_{\text{RF}} \sim \Gamma$

- **Probe**
  - Polarimeter signal
    - Linear dichroism
    - Cancellation of $\mathcal{G}$ absorption
B₀ Orientation: Theory

Multipole moment model [3][4]

- **Pump**
  - Creation of $k = 1, 2…$
  - Equilibrium $q = 0$
    - B₀ frame
- **Evolution**
  - RW frame
    - B₀ // z
    - B_RF(t=0) // -x
  - Obtain $m_{kq}(t)$
- **Probe**
  - Difference in ↑ and ↓

\[
\rho = \sum_{k=0}^{2F} \sum_{q=-k}^{k} m_{k,q} T_{q}^{(k)}
\]

\[
\frac{d}{dt} m_{k,q} = \sum_{q'} \Gamma_{qq'}^{(k)}(m_{k,q'} - m_{k,q}) - \sum_{q'} \Theta_{qq'}^{(k)}(m_{k,q} - m_{k,q'}^{eq})
\]

\[
f(t) = m_{2,0}(t) - m''_{2,0}(t)
= \frac{3}{2} m_{2,0}(t) - \sqrt{\frac{3}{8}} [m_{2,2}(t) + m_{2,-2}(t)]
\]

$B_0$ Orientation: Amplitude

- 4π angular scan
  - 1646 resonance fits
  - 3½ hours
- $R^2 \equiv X^2 + Y^2$
  - Extract $X$ and $Y$ from $f(t)$
- Dead-zones
B₀ Orientation: Phase

- On-resonance phase
  \[ \tan \phi \equiv \frac{X}{Y} \]

- Strong dependence
  - B₀ orientation
  - Bₕ orientation

\[
\tan \phi_{RF_y} = \frac{2 \sin \theta_L \tan \theta_V}{(\sin^2 \theta_L \tan^2 \theta_V - 1) \cos \theta_L \sin \theta_V}
\]
\[
\tan \phi_{RF_z} = \frac{-\sin 2\theta_L \sin \theta_V}{(1 + \cos^2 \theta_L) \sin 2\theta_V}
\]
**B₀ Orientation: Phase**

- **On-resonance phase**
  \[ \tan \phi \equiv \frac{X}{Y} \]

- **Strong dependence**
  - B₀ orientation
  - B_RF orientation

\begin{align*}
\tan \phi_{RFy} &= \frac{2 \sin \theta_L \tan \theta_V}{(\sin^2 \theta_L \tan^2 \theta_V - 1) \cos \theta_L \sin \theta_V} \\
\tan \phi_{RFz} &= \frac{-\sin 2\theta_L \sin \theta_V}{(1 + \cos^2 \theta_L) \sin 2\theta_V}
\end{align*}
Portable Demonstrator System

- Minimal hardware
  - VCSEL
  - MEMS cell
    - Heater PCB
  - Polarimeter PCB
- Component testing
  - FPGA
  - MEMS cell
    - Geometry
    - Buffer gas
Summary

• Understanding $B_0$ orientation effects
  • Model & measurement agree
    – Optimal sensitivity axes
    – Phase-vector information
  • Exploit using signal processing

Strathclyde Magnetometry People

Erling Riis, Aidan Arnold, Paul Griffin, Stuart Ingleby, Dominic Hunter, Carolyn O’Dwyer, Iain Chalmers