Double-Resonance Magnetometry in Arbitrarily Oriented Fields

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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

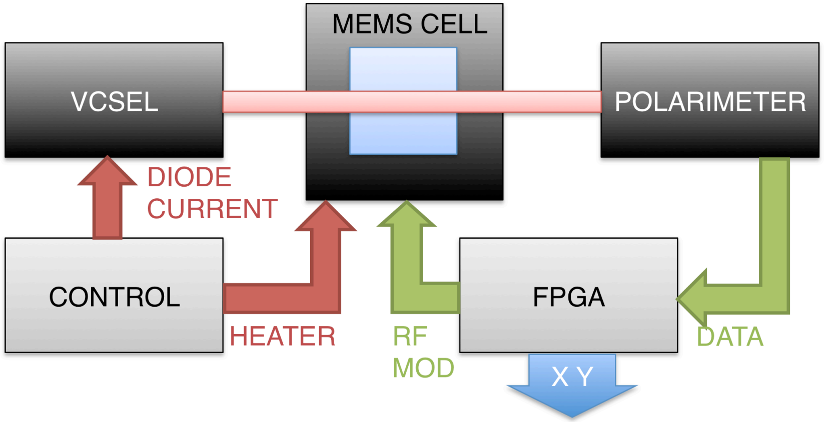
UK National
Quantum Technology Hub
Sensors and Metrology

University of Strathclyde Science

- 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 B_0 orientation - ?
  - Dead-zones
  - Heading errors
- Portability - yes
  - Single frequency pump-probe
  - Firmware signal processing



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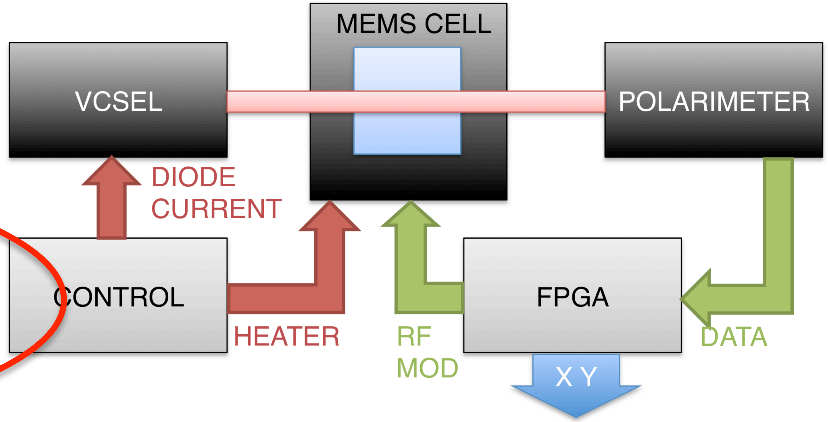
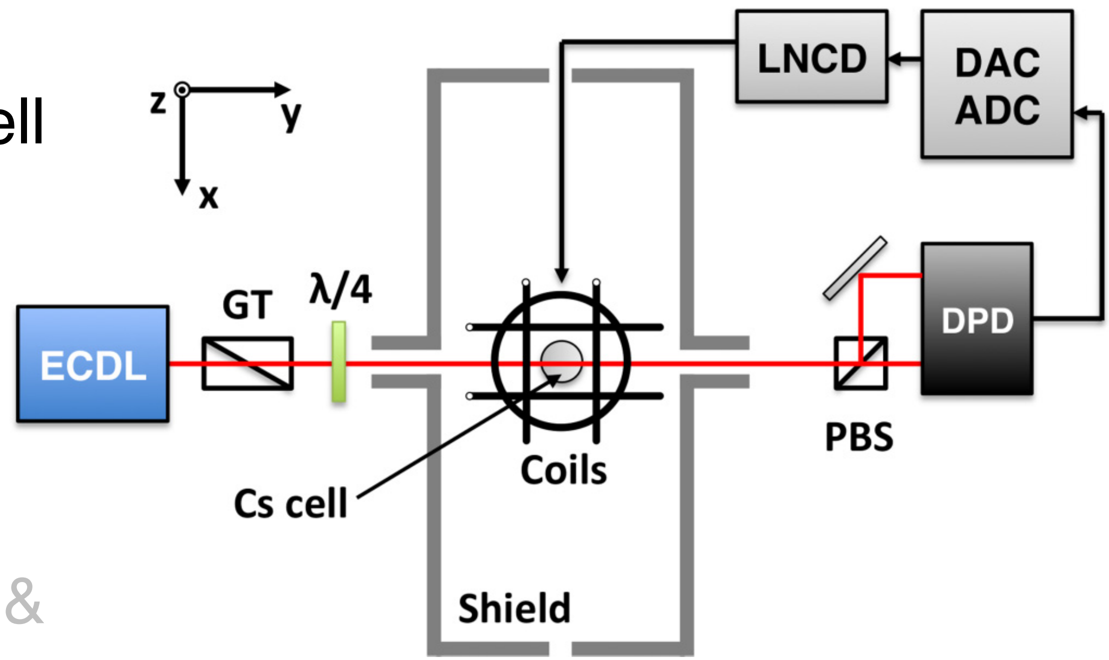


B_0 Orientation: Shielded Test System

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



[1] N. Castagna *et al.* , Appl. Phys. B: Lasers Opt. **96**, 763 (2009)

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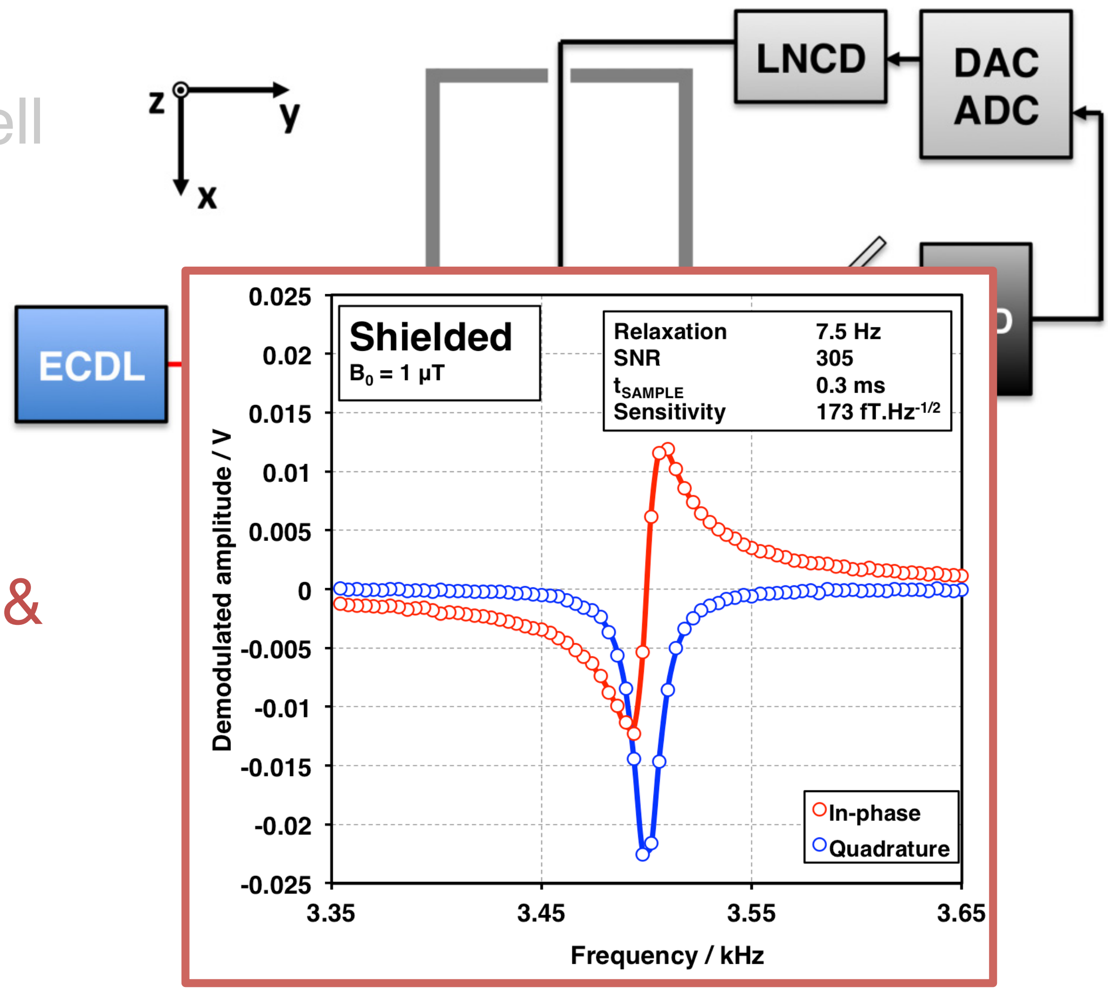
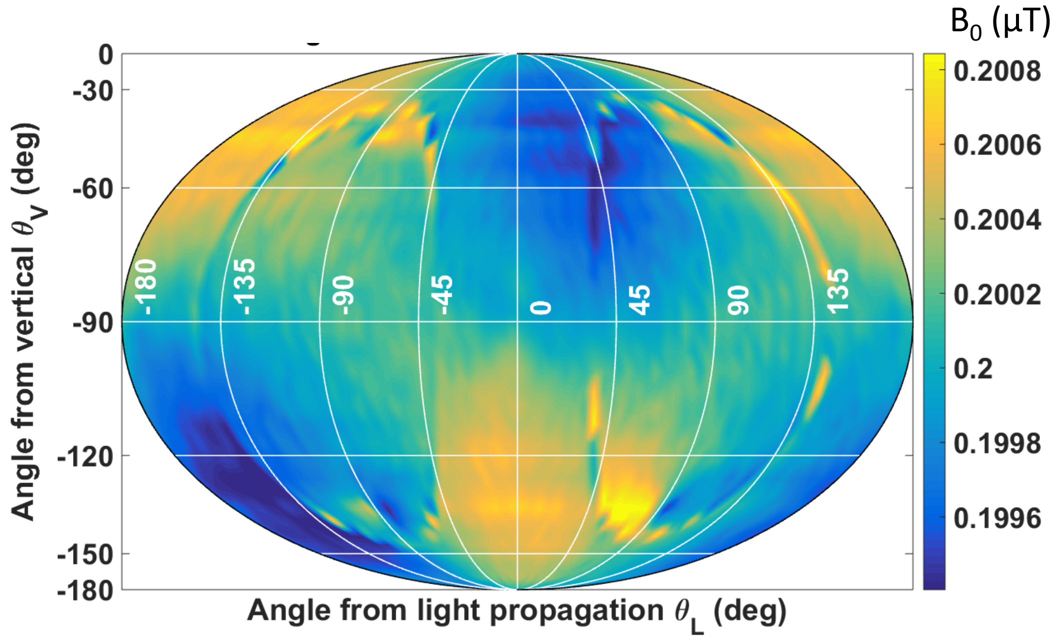


B_0 Orientation: Shielded Test System

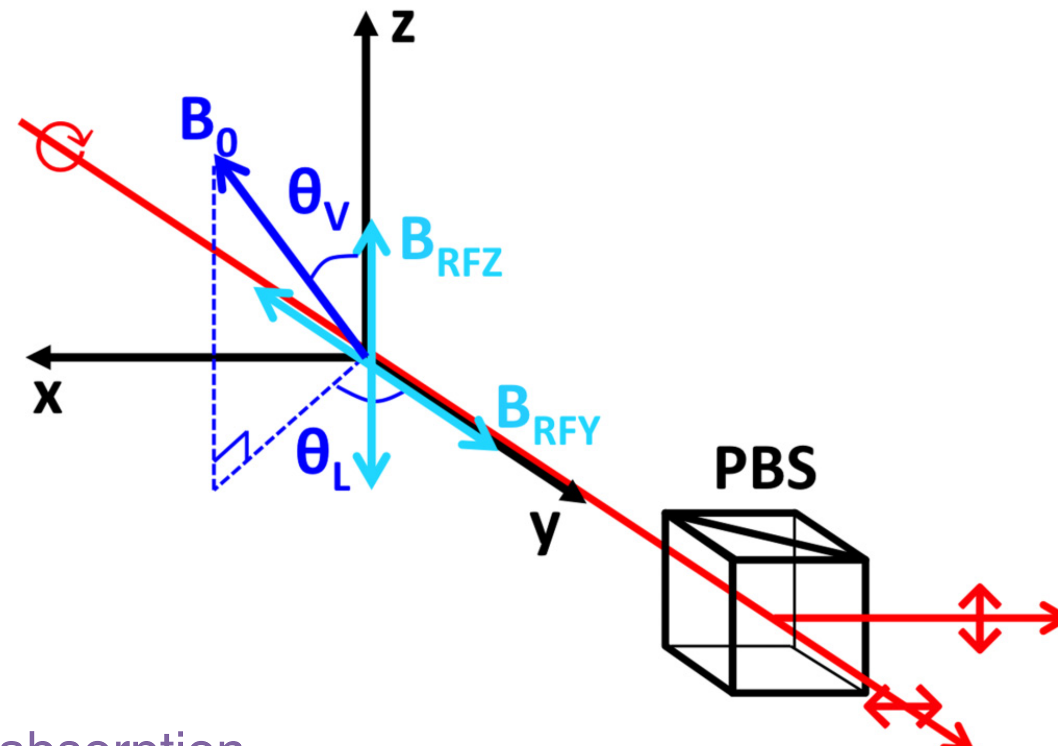
- B_0 control
    - Low-noise current drivers
    - Shield degauss
    - Single-axis calibration [2]
    - 3D calibration
      [C. O'Dwyer poster]
- 200 nT B_0
    - $\delta|B| = 0.24$ nT
    - $\delta\theta = 0.23$ mrad



[2] S. J. Ingleby *et al.* , Rev. Sci. Instrum. **88**, 043109 (2017)

B_0 Orientation: Theory

- Pump
  - Cs D1 4-3
  - σ-polarised
  - 20 μW
    - $\Gamma_{PUMP} << \Gamma$
- Evolution
  - $B_0 >> B_{RF}$
  - $\Omega_{RF} \sim \Gamma$
- Probe
  - Polarimeter signal
    - Linear dichroism
    - Cancellation of ⟳ absorption



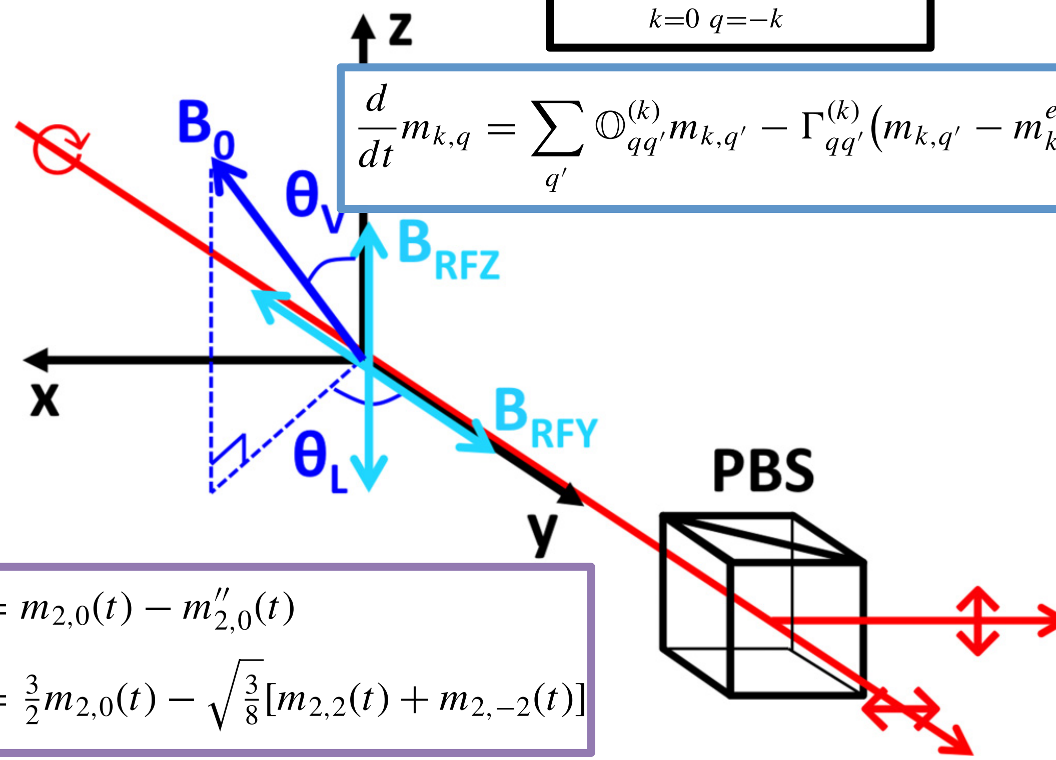
B_0 Orientation: Theory

Multipole moment model [3][4]

- Pump
  - Creation of $k = 1,2\ldots$
  - Equilibrium $q = 0$
    - B_0 frame
- Evolution
  - RW frame
    - B_0 // z
    - $B_{RF}(t=0)$ // -x
  - Obtain $m_{kq}(t)$
- Probe
  - Difference in ↕ and ↔

$$\rho = \sum_{k=0}^{2F} \sum_{q=-k}^{k} m_{k,q} T_q^{(k)}$$

$$\frac{d}{dt} m_{k,q} = \sum_{q'} \mathbb{O}^{(k)}_{qq'} m_{k,q'} - \Gamma^{(k)}_{qq'}\left(m_{k,q'} - m^{eq}_{k,q'}\right)$$

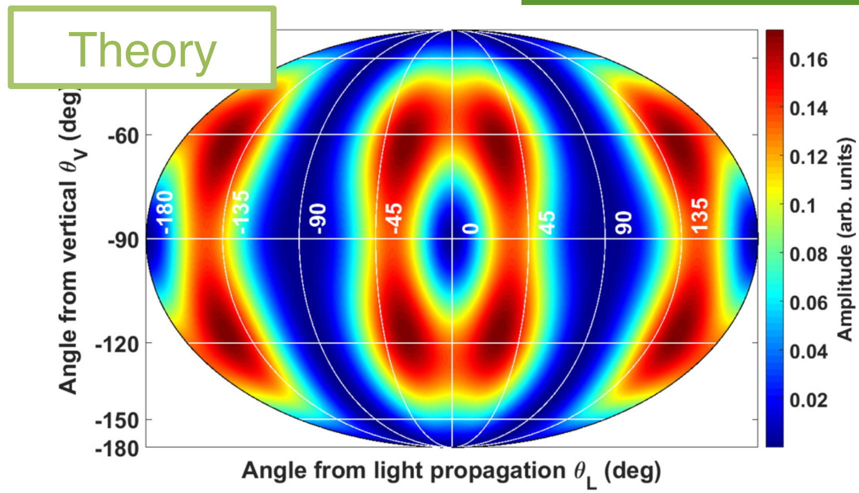


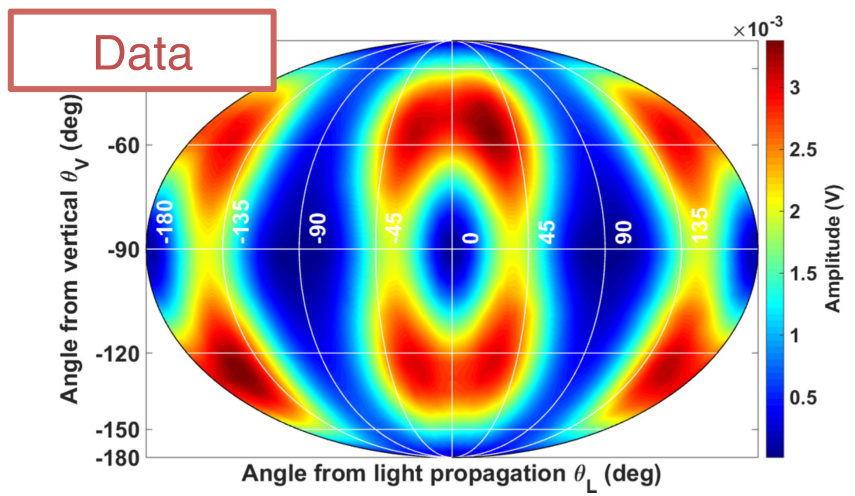
$$\begin{aligned} f(t) &= m_{2,0}(t) - m''_{2,0}(t) \\ &= \tfrac{3}{2} m_{2,0}(t) - \sqrt{\tfrac{3}{8}}\,[m_{2,2}(t) + m_{2,-2}(t)] \end{aligned}$$

[3] A. Weis, G. Bison, A. S. Pazgalev, Phys. Rev. A **74**, 033401 (2006)
[4] M. A. Morrison and G. A. Parker, Aust. J. Phys. **40**, 465 (1987)

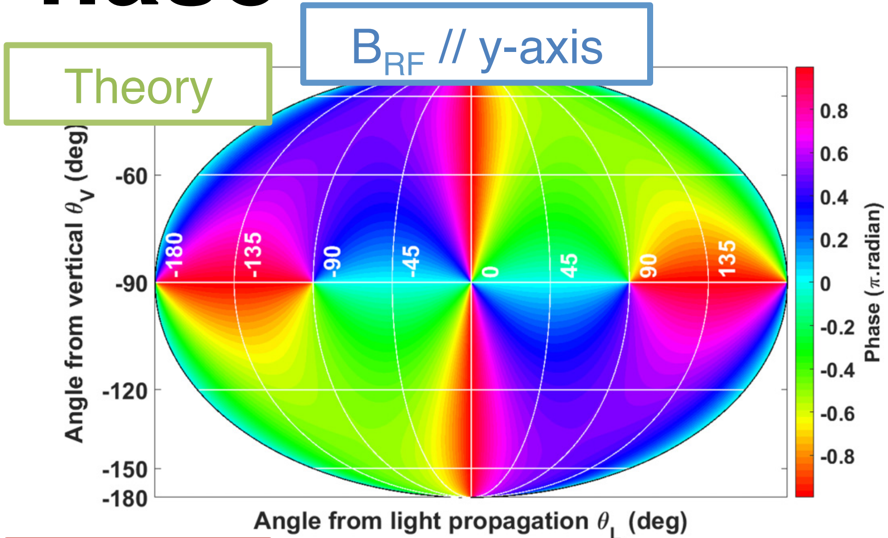
B_0 Orientation: Amplitude

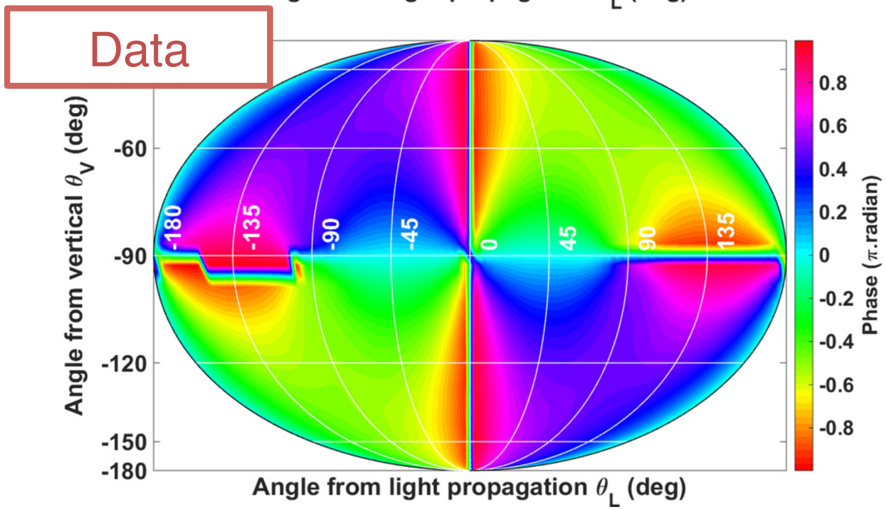
- 4π angular scan
  - 1646 resonance fits
  - 3½ hours
- $R^2 \equiv X^2 + Y^2$
  - Extract *X* and *Y* from *f(t)*
- Dead-zones





B_0 Orientation: Phase





- On-resonance phase

$$\tan\phi \equiv X/Y$$

- Strong dependence
  - B_0 orientation
  - B_{RF} orientation

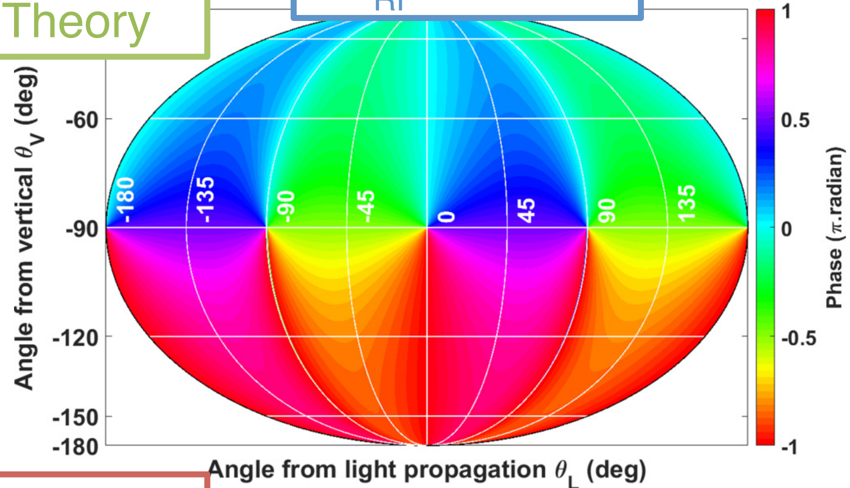
$$\tan\phi_{RFy} = \frac{2\sin\theta_L\tan\theta_V}{(\sin^2\theta_L\tan^2\theta_V - 1)\cos\theta_L\sin\theta_V}$$

$$\tan\phi_{RFz} = \frac{-\sin 2\theta_L\sin\theta_V}{(1+\cos^2\theta_L)\sin 2\theta_V}$$

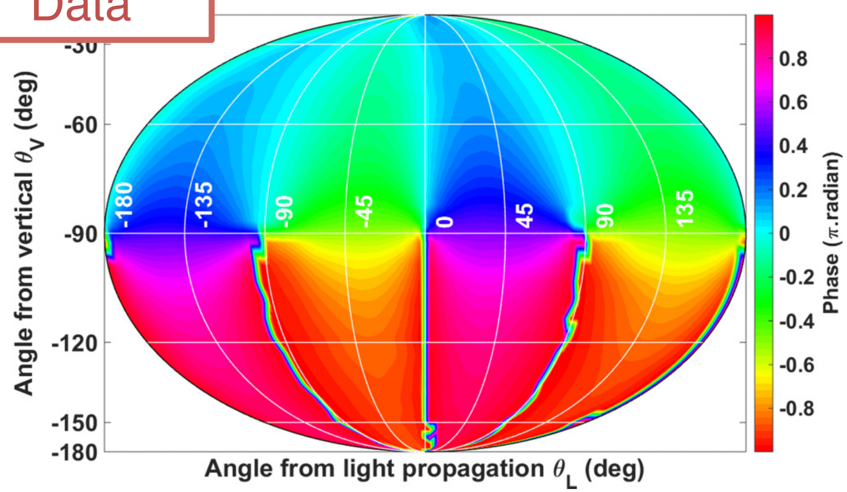
B_0 Orientation: Phase

B_{RF} // z-axis

Theory



Data



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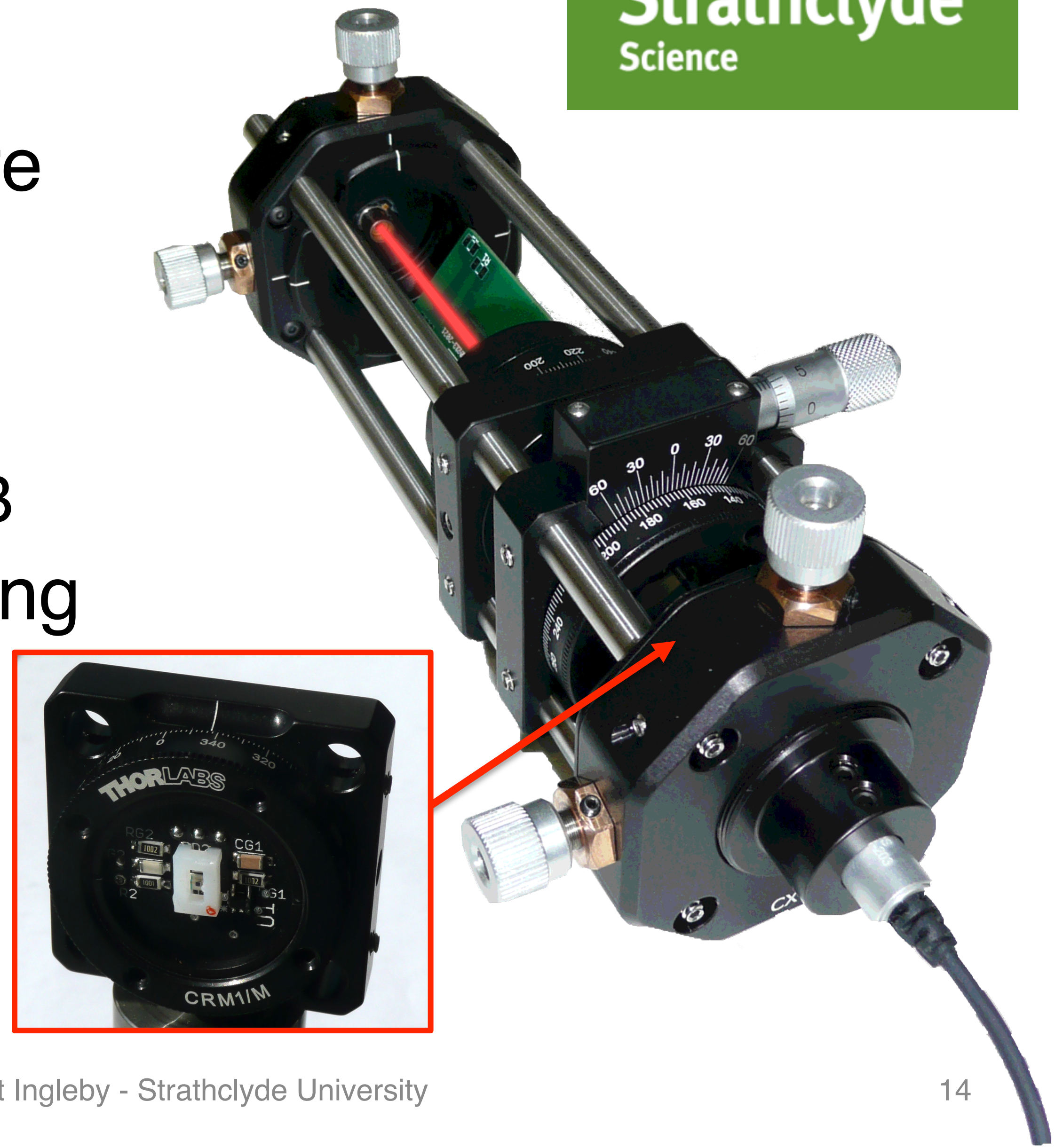
Portable Demonstrator System

- 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