Precision Magnetometry for Neutron Electric Dipole Moment Experiments

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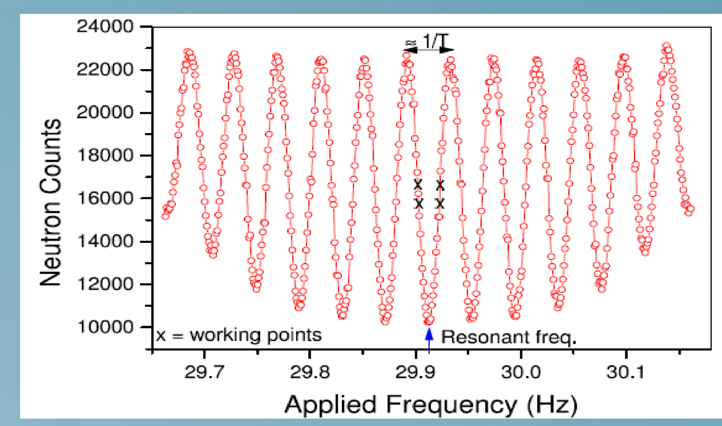
Measuring a Neutron Electric Dipole Moment

Neutron electric dipole moment (nEDM) measurements use a technique similar to NMR known as the Ramsey Method of Separated Oscillatory Fields. The difference in Larmor precession frequencies in the cases of parallel and antiparallel E and B fields is sensitive to the nEDM:

$$d_n = \frac{h(\nu_{\uparrow\downarrow}-\nu_{\uparrow\uparrow})}{4E}$$

This expression is valid if the static B field, B_0, is constant. Fluctuations in B_0 produce frequency shifts and hence false EDM signals. These can also magnify the impact of systematic errors, such as the geometric phase effect [1] . Precision magnetometry is therefore important to monitor and correct for any perturbations in B_0.



The Ramsey resonance curve showing the neutron count as a function of the RF frequency of the applied, oscillating B field. Working points are chosen where the slope is greatest.

The ^{204}Hg "reading light" traversing the neutron volume, the Ramsey cell, in the nEDM measurement. The ^{199}Hg atoms can absorb the light, leading to a varying intensity

The nEDM Experiment

The room temperature experiment, which ran from 1998-2002, holds the current limit of $|d_n| = 2.9 \times 10^{-26}$ ecm (90% C.L.) [2]. A ^{199}Hg comagnetometer was developed for this measurement: the free mercury atoms occupy the same volume as the neutrons and thus sense the same fields to a first degree of approximation*. Under this assumption, the precession frequencies of the two species are related by:

$$\frac{\nu_n}{\nu_{Hg}} = \left|\frac{\gamma_n}{\gamma_{Hg}}\right| + \frac{(d_n + |\gamma_n/\gamma_{Hg}| d_{Hg})}{\nu_{Hg}} E$$

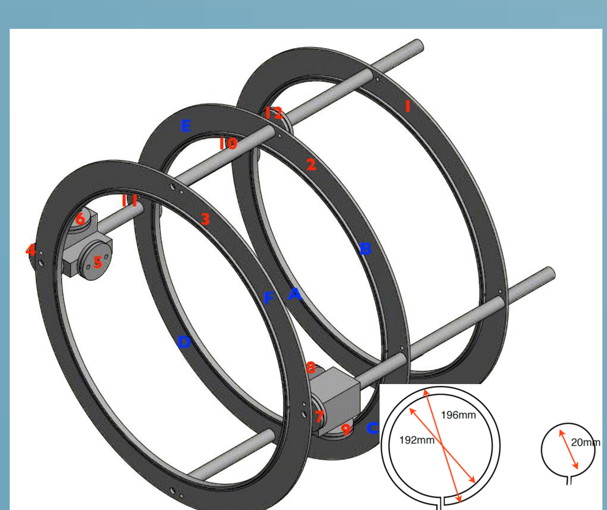
where γ is the gyromagnetic ratio. Note that the EDM of ^{199}Hg is small enough ($|d(^{199}Hg)| < 3.1 \times 10^{-31}$ecm (95% C.L.) [3]) that its precession frequency is unaffected by the applied E field. To measure ν_{Hg}, polarised light from an isotopically-pure ^{204}Hg source was directed across the neutron volume and its intensity measured by a PMT. With the ^{199}Hg spins oriented perpendicular to the plane of polarisation of the beam, their absorption cross section and hence the transmitted light intensity was seen to vary sinusoidally as the ^{199}Hg atoms precessed, modulated by an exponential decay due to spin relaxation. Even with systematic effects derived from e.g. the spin relaxation of the ^{199}Hg atoms, the comagnetometer was able to measure volume and time-averaged magnetic fields of a few mG with sub-nG precision, reducing the impact of these systematic errors by a factor of ~20 compared to previous experiments [4].

* The centres of mass of the neutrons and the ^{199}Hg atoms differ by a few mm

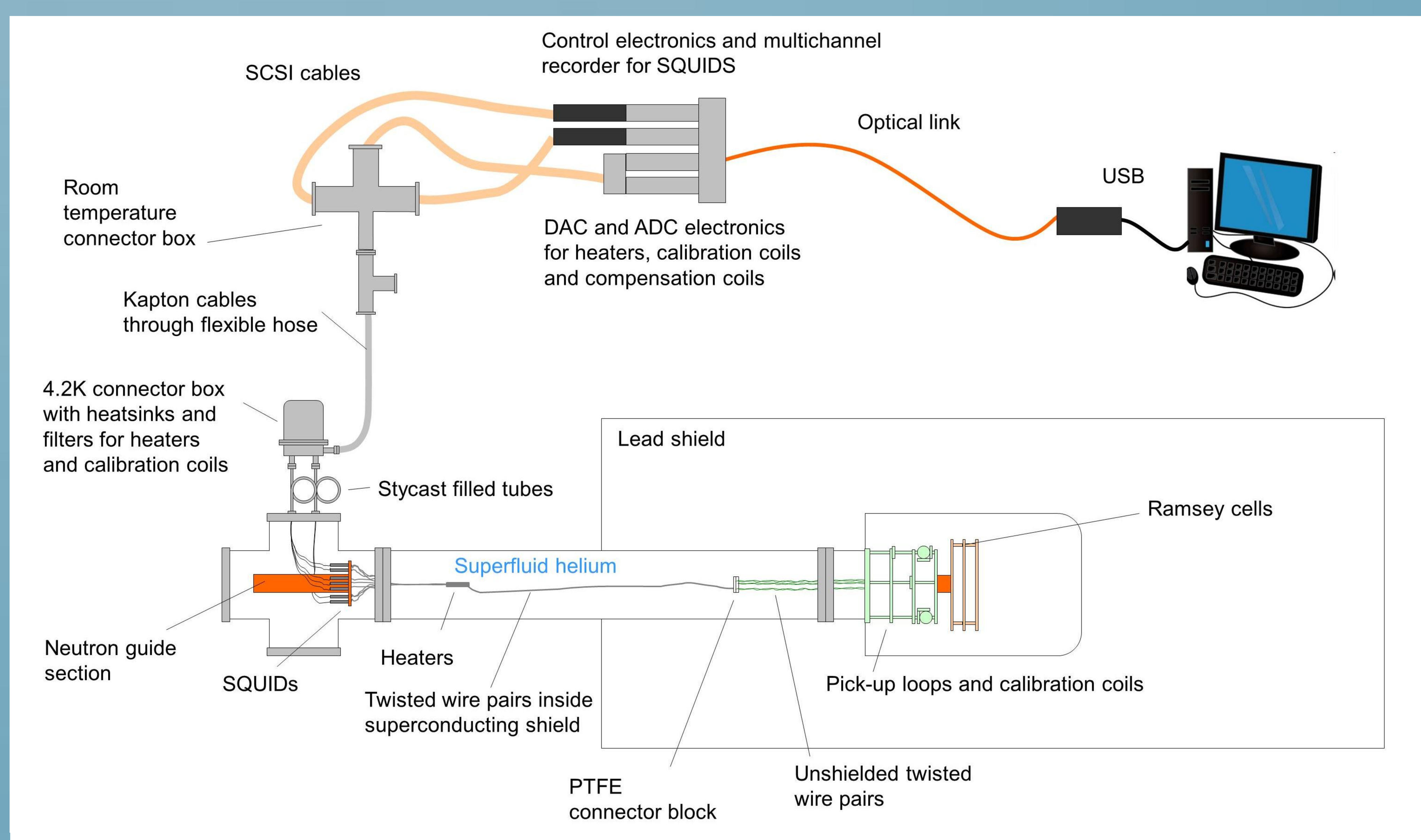
SQUID Magnetometry for CryoEDM

Many current experiments operate in a cryogenic environment to maximise the ultra-cold neutron flux so as not to be limited by neutron statistics. A ^{199}Hg comagnetometer cannot work at low temperatures, and so other magnetometry options must be explored. One possibility is a ^{3}He comagnetometer, which will be used in the SNS experiment [5]. This, however, faces complications due to the interactions between the neutrons and the ^{3}He atoms. CryoEDM has therefore opted for more conventional SQUID magnetometry: since sensitivity to the volume-averaged field is lost, this comes with the challenge of extrapolating the magnetic field from the SQUID pick-up loops to the Ramsey cells.

DC-SQUIDs have been shown to have resolutions on the order of fTHz$^{-1/2}$: integrated over the neutron storage time, this yields a sensitivity greater than ~0.1pT . To achieve adequate spatial resolution, a system involving 12 SQUIDs has been developed for CryoEDM: a schematic of the apparatus is provided below. These SQUIDs are easily damaged by high voltages across their inputs, and so are mounted on the neutron guide away from the Ramsey cells. The pick-up loops are placed as close to the neutron chamber as possible, so ~2m long twisted wire pair (TWP) connections are required to the SQUID inputs. A section of the TWPs emerge out of the magnetic shield: these are encased in superconducting solder capillaries to reduce their susceptibility to magnetic fluctuations. Stycast filled tubes are custom-made cold feedthroughs to allow the 48 TWPs to pass through a 5mm diameter stainless steel hose from the superfluid helium at 0.5K to the 4.2K connector box. Kapton cables, which are manufactured in-house, are chosen to make the connections to the room temperature connector box because of their durability and low heatload. Readout is performed by a compact, USB-based data acquisition system developed in Oxford.

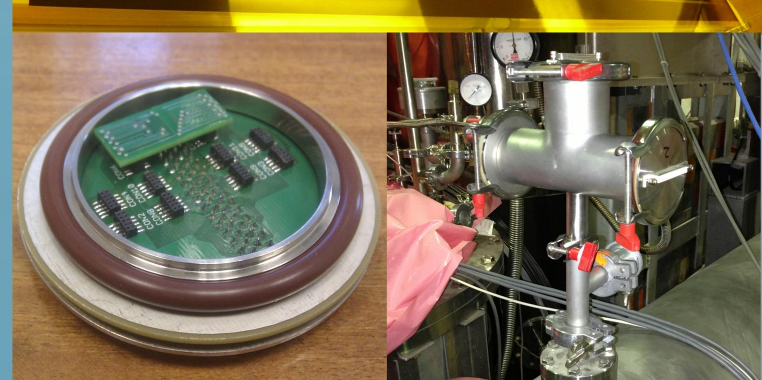


The design of the pick-up loop formers. Shown are the positions of the pick-up loops (1-12) and the coils (A-F) used to generate magnetic fields to calibrate the SQUIDs. The pick-up loops are mostly oriented along the axis of the lead shield, since magnetic perturbations should be largest in this direction. A double loop formation is used to allow a pick-up loop centred on the axis of the Ramsey cell, whilst maintaining a small sensing area.

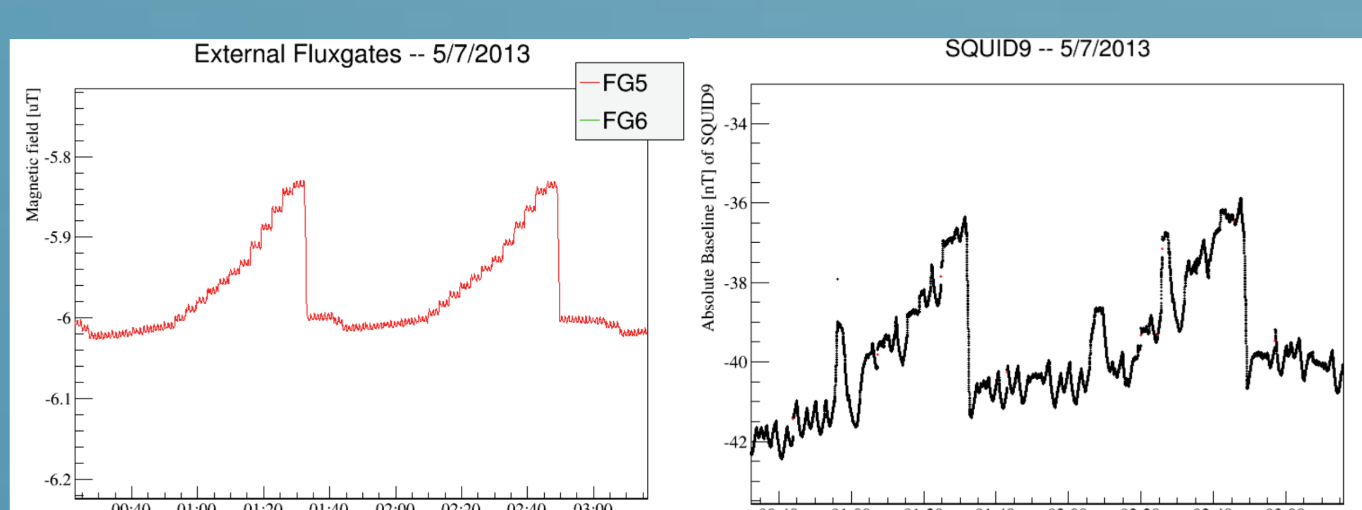


Schematic of the CryoEDM SQUID Magnetometry System

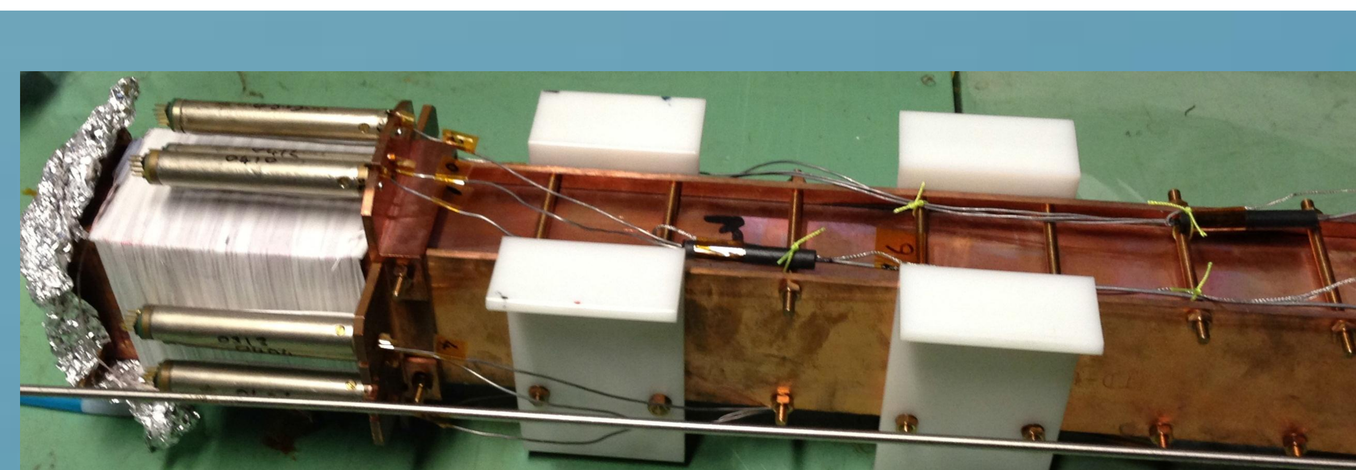
The phototool for the Kapton cables. A photolithographic process is used to etch the stainless steel tracks, which are copper-plated at both ends for soldering of Samtec connectors



The custom-built room temperature connector box, mounted at the top of the six-way section, with associated PCBs used to connect the Kapton cables



Sample data from a fluxgate mounted outside the shields (left) and a SQUID (right) prior to the superconducting transition of the lead shield. The magnetic signal produced by a nearby experiment, IN15, is clearly picked up on both. The SQUID signal, having been attenuating by the mu metal shielding, is smaller in magnitude, though more dominated by magnetic fluctuations.



The SQUIDs mounted on the neutron guide, with solder capillaries surrounding the inputs. These have heaters that can heat the solder into the normal state to release trapped flux. Shown also is the SQUID compensation coil (SQCC) wound around the guide. The cryoperm used to shield the SQUIDs is a high permeability material which distorts the magnetic field inside the guide. This can cause the depolarisation of the neutrons. The SQCC generates a field to compensate for this effect.

References

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[2] C.A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006)
[3] K. Green et al., Nucl. Meth. Inst. A 404, 381 (1998)
[4] W. C. Griffith et al., Phys. Rev. Lett. 102, 1103 (2009)
[5] Y. J. Kim and S. M. Clayton, arXiv:1210.4599v1 (2012)