Recent developments of dark matter research magnet systems at Oxford Instruments

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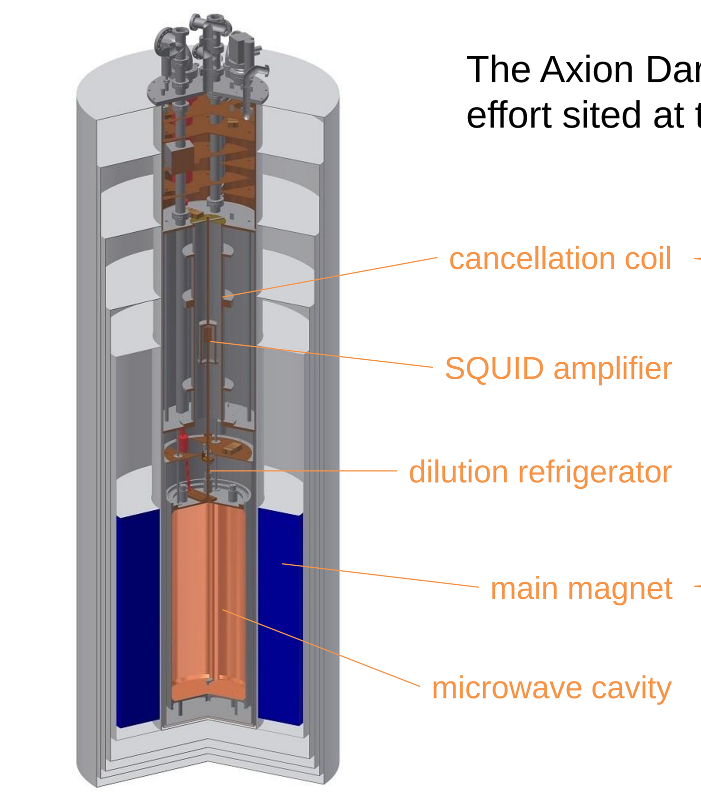
ABSTRACT: Superconducting magnets play a key role in the search for dark matter particles such as axions. This application benefits from a large B^2V factor within the magnet bore. A low B field region in close vicinity of the main magnet and a low temperature environment are also required for the detection. Oxford Instruments has developed a range of large bore superconducting magnet systems for dark matter research. We are presenting the design and performance of recent systems.

The 12 T, 320 mm bore, liquid helium bath cooled magnet system, built for the Center for Axion and Precision Physics Research (CAPP) in South Korea, achieves high magnetic energy stored in the microwave cavity within the magnet bore to maximise signal output power. A cancellation coil located above the main magnet enables field-sensitive measurements close to the magnet. The challenges of making such a system are described.

The Proteox™MX system designed for the Quantum Sensors for the Hidden Sector (QSHS) collaboration in the UK, features a smaller, actively shielded, Cryofree® magnet. This design not only provides a low field region for the readout electronics but also reduces the radial stray field significantly. The integrated dilution refrigerator, which delivers a base temperature below 10 mK, cools down both the electromagnetic resonator and the quantum electronics, greatly improving the signal-to-noise ratio. The advances already made to further developments in dark matter research are described.

Typical magnet requirement for axion dark matter detection



ADMX model (credit: Gray Rybka)

The Axion Dark Matter Experiment (ADMX) is a large collaborative effort sited at the University of Washington, USA.

A local low-field region is essential to enable field-sensitive measurements with SQUID amplifiers.

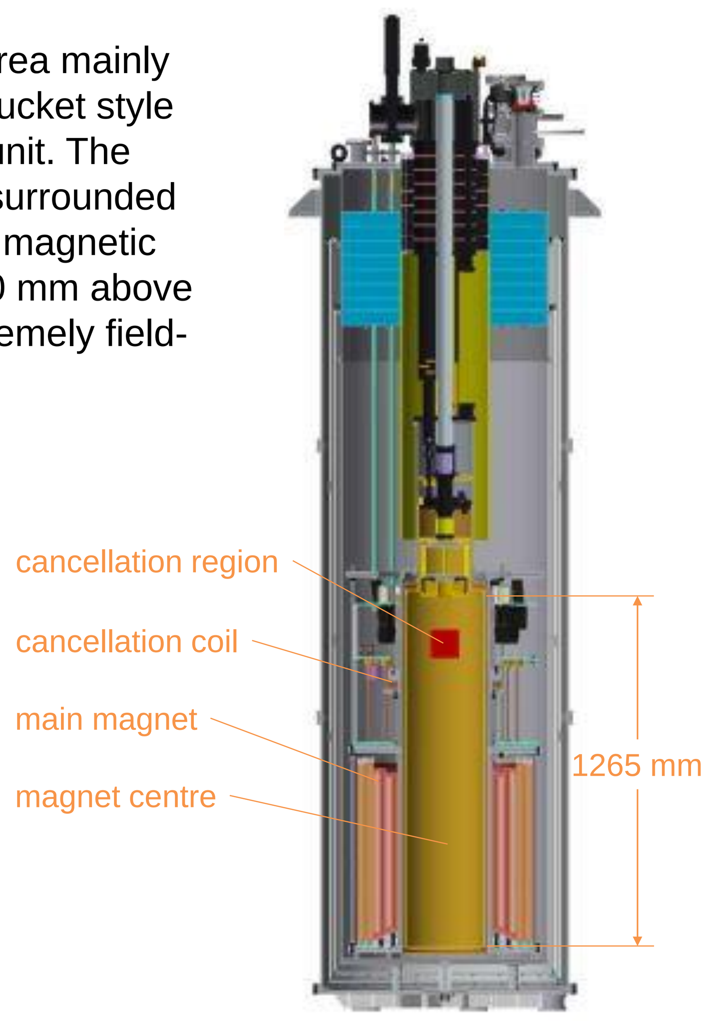
The goal is to maximise the magnetic energy stored in the cavity.
Magnetic energy $\propto B_{avg}^2 V_{cavity}$,
where $B_{avg}^2 V_{cavity} \equiv \int_{V_{cavity}} B^2 \, dV$.
This is why a high-field magnet with large bore volume is required.

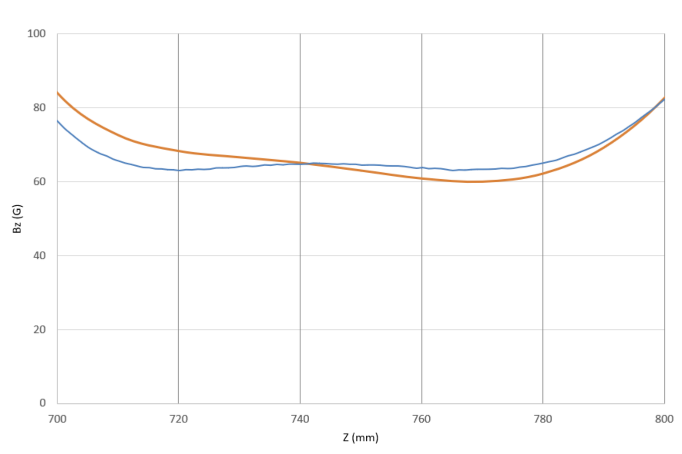
12 T / 320 mm bore wet magnet system

This customer system delivered to CAPP in South Korea mainly consists of a 12 T, 320 mm bore magnet, a low-loss bucket style dewar and a customer-supplied dilution refrigeration unit. The main magnet has two nested concentric Nb_3Sn coils surrounded by two outer NbTi coils. The cancellation coil reduces magnetic field to < 100 G in the cancellation region situated 750 mm above magnet centre, enabling the customer to perform extremely field-sensitive measurements close to the magnet.

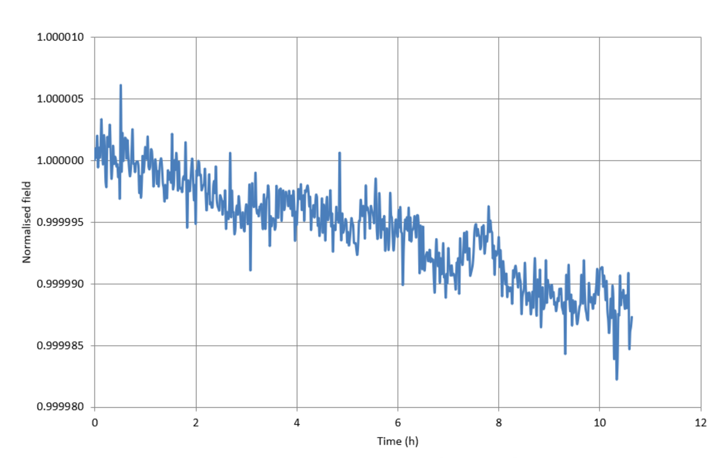
Key requirements achieved & unique features:
- Low-vibration vapour-cooled radiation shield
- Persistent magnet for long-term experiments
- Low-loss magnet current leads
- Fully integrated magnet protection system

Key design challenges overcome:
- Large axial forces between coils
- Stress/strain management
- Quench protection, including cancellation coil





Field on axis in cancellation region (measured vs designed)



Measured temporal stability

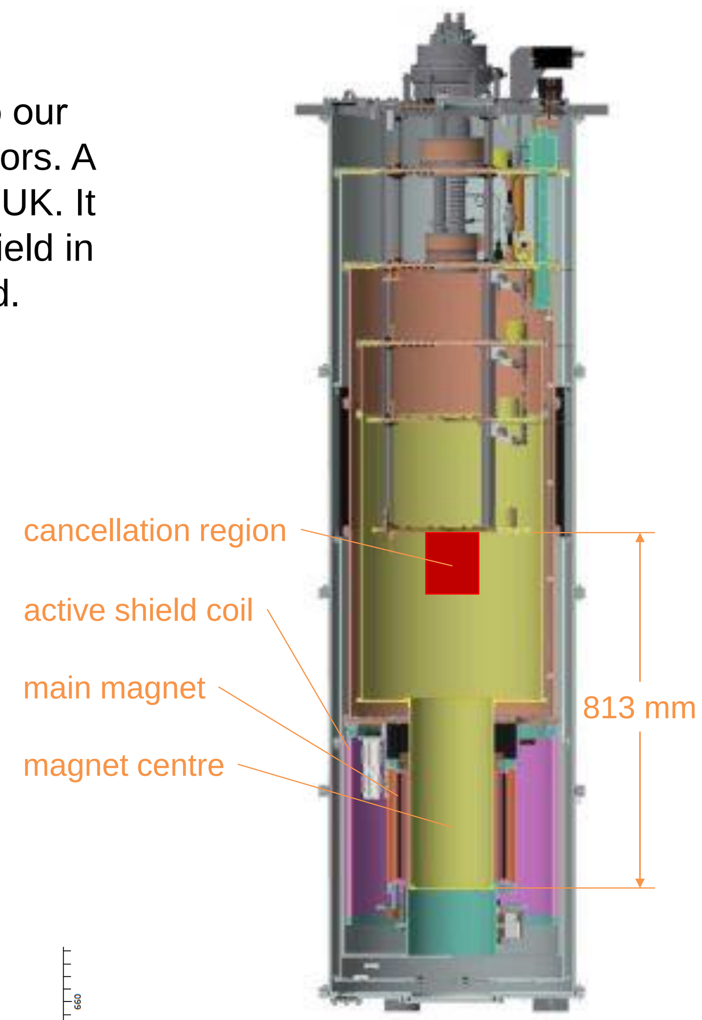
System main parameters	
Main magnet	
Central field	12 T
Magnet bore	320 mm
operating current	266 A
Inductance	161 H
Stored energy	5.68 MJ
Field homogeneity over 10 mm DSV	< 0.1%
Field stability	< 10 ppm/h
Cancellation coil	
Cancellation field	< 100 G
Cancellation region	⌀ 100 mm L 100 mm
Cryostat	
Helium capacity	300 L
Static helium boil-off	< 2 L/h
Outer diameter	0.9 m
Overall height	3.5 m

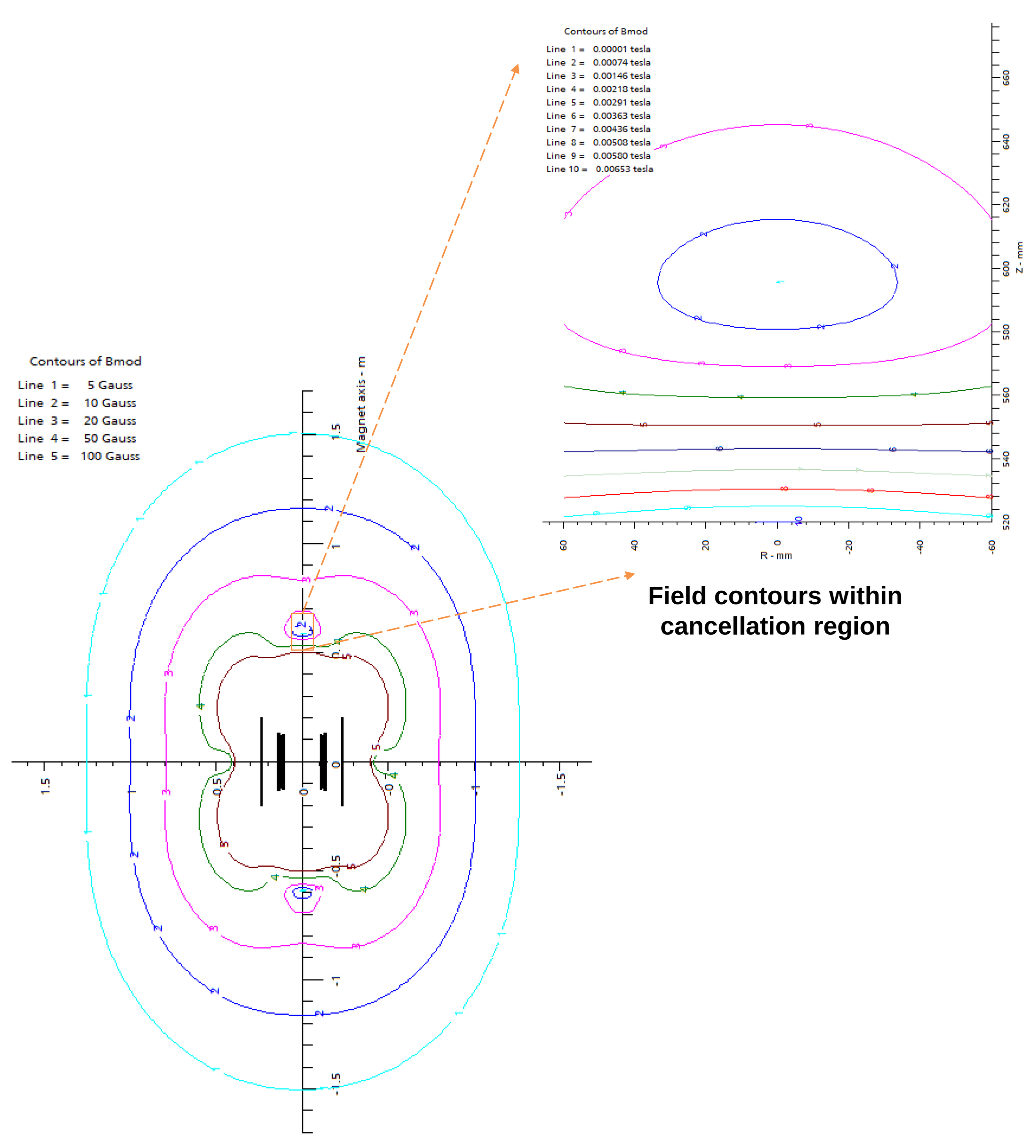
8 T / 200 mm bore Cryofree magnet system

Building beyond existing 'wet' magnet technology, we developed a range of 'dry' magnets for integration into our Cryofree cryostats including Proteox dilution refrigerators. A customer system has been designed for QSHS in the UK. It features an active shield coil, which not only cancels field in the required region, but also reduces overall stray field.

Key requirements achieved & unique features:
- Low-vibration pulse tube dry dilution refrigerator with integrated large-bore magnet
- Persistent magnet for long-term experiments
- Low-current HTS Cryofree current leads to minimise ohmic heating

Key design challenges overcome:
- Stress/strain and thermal budget management
- Quench protection, including shield coil
- Optimised cancellation with shield coil in large vacuum space





Field contours within cancellation region

Stray field plot

System main parameters	
Main magnet	
Central field	8 T
Magnet bore	200 mm
operating current	169 A
Inductance	31 H
Stored energy	0.44 MJ
Field homogeneity over 10 mm DSV	< 0.1%
Field stability	< 100 ppm/h
Cancellation coil	
Cancellation field	< 100 G
Cancellation region	⌀ 120 mm L 150 mm
Cryostat	
Base temperature	< 10 mK
Cooling power at 100 mK	> 450 μW
Outer diameter	0.6 m
Overall height	2.5 m

Conclusions

Very large bore, but compact, liquid helium bath cooled magnet systems can be built. The full performance of LTS superconductors can be utilised at 4.2 K stable temperature. This enables the highest B field with volume to be achieved to date.

Building upon the success of liquid helium bath cooled systems, a new generation of large bore, Cryofree magnets for axion dark matter research are emerging. These systems can be sited in small laboratory spaces, creating new opportunities for detectors and payload experimentation.

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