Design, Manufacture and Test of an Adiabatic Demagnetization Refrigerator Magnet for use in Space

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***Abstract*—The proposed European Space Agency (ESA) XEUS mission will use an adiabatic demagnetization refrigeration (ADR) system to cool X-ray detectors to a temperature of less than 0.1 K. The superconducting magnet for the flight standard prototype is currently under construction by Space Cryomagnetics Ltd of Culham, England. The magnet is subject to tight constraints on its mass, stray field, and power consumption. This paper describes the design, manufacture and test of the magnet.**

***Index Terms*—Cooling, Cryogenics, Superconducting magnets, Space technology**

I. INTRODUCTION

XEUS or X-Ray Evolving Universe Spectrometer is being studied by ESA as a possible permanent space-borne X-ray observatory [1]. Grazing incidence X-ray mirrors, with 50 m focal length, and the focal plane instruments will be housed in separate spacecraft and maintained in relative station to high accuracy.

To achieve state of the art X-ray spectroscopic sensitivity, the detectors in the focal plane must be cooled to less than 50 mK [2, 3]. Two techniques are available to achieve this: the ^{3}He dilution refrigerator, and adiabatic demagnetization refrigeration (ADR). ADRs offer the advantage that they are less complex and more robust than ^{3}He systems but are limited in the duration of cooling for simple ADR configurations. Sufficient cooling time can be achieved by controlling field decay according to the temperature. ESA is therefore funding the development of a prototype ADR system for XEUS with Astrium as prime contractor and the Mullard Space Science Laboratory as principal investigators. Space Cryomagnetics Ltd has been chosen to design, manufacture and test the superconducting magnets for the ADR.

The prototype ADR will be tested in the laboratory under conditions representative of all phases of the XEUS mission.

II. MAGNET DESIGN

A. ADR Configuration

To achieve the goal of 50 mK for the focal plane of the instrument the target ultimate temperature is 30 mK. This temperature has to be reached from a reservoir temperature of approximately 4 K, provided by a thermo-mechanical cooler with a thermal budget of just 5 mW for the ADR including the magnet.

The temperature of the thermal reservoir dictates that the ADR is a two stage device (Fig. 1) using salt pills of Dysprosium Gallium Garnet (DGG) for the first stage above 1 K and Chromic Potassium Alum (CPA) below 1 K. Each section has its own superconducting magnet independent of its neighbour generating fields at the pill centres of 3.0 T.

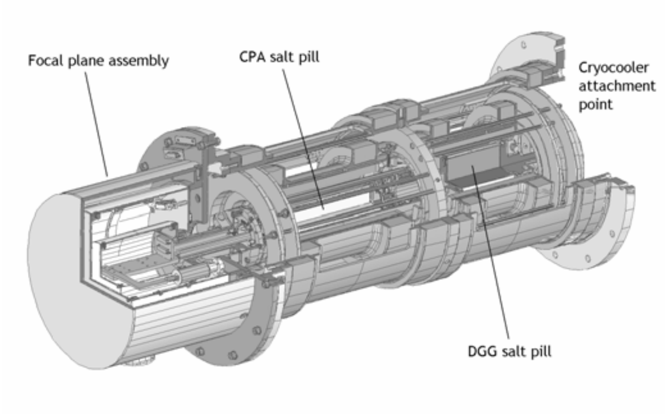

Fig. 1. Cut-away view of the ADR assembly.

B. Magnet Design

From the ADR design, a full design requirement for the superconducting coils was established (Table I).

Fig. 2 shows the optimized coil configuration devised to meet the requirements. The design comprises short solenoids with end compensation coils and bucking coils for the DGG and CPA sections, and the Helmholtz coils in the focal plane assembly (FPA). There are five coils in the DGG and CPA sections respectively plus the Helmholtz pair.

In addition to the coils shown, extra magnetic shielding is provided around the FPA using high magnetic permeability

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materials to bring the field at the centre below 5 μT. The Helmholtz coils, used to null the field further, are inside this passive shield.

TABLE I
ADR MAGNET COILS DESIGN REQUIREMENTS

Requirement	Value
DGG and CPA magnets will operate independently	
CPA pill length	148 mm
DGG pill length	97 mm
Minimum field at the centre of each pill	3.0 T
Minimum field at the pill ends	2.4 T
Operating current	less than 2.5 A
Pill centre on-axis separation	222.5 mm
Minimum free bore diameter of the coil formers	62.25 mm
CPA coil to focal plane assembly (FPA) separation	167 mm
Maximum field at FPA	5 μT
Maximum field at DGG centre from CPA coils	20 mT
FPA Helmholtz pair	30 mT at 15 mT/A
Homogeneity of FPA Helmholtz pair	1 in 1000 in a 2 mm DSV[a]
Maximum stray field at a radial and axial distance of 500 mm from the coils	50 μT

[a] Diameter Spherical Volume.

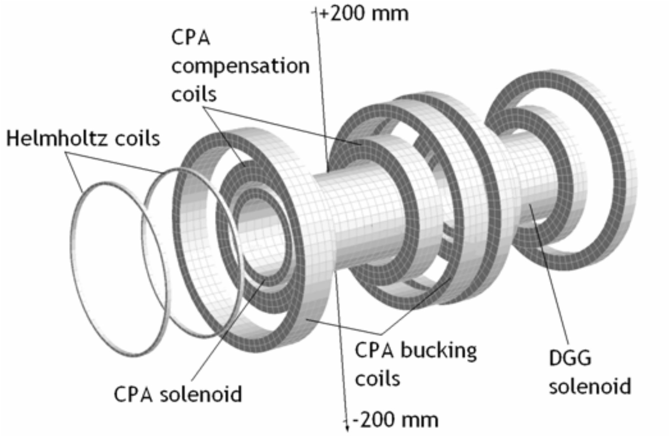

Fig. 2. ADR coils configuration.

More passive shielding is used around the whole ADR assembly to reduce the stray field to the specification value at large distances. To save weight this takes the form of a low carbon steel vacuum vessel.

Use of high strength aluminium alloy and metal matrix composite (MMC) in the coil formers has allowed the total weight of the magnet assembly (excluding the cryostat and ADR components) to be kept to 24 kg, with just over 11 kg contributed by the coils. MMC also minimises thermal stresses on the coils as its rate of thermal contraction can be tailored, at least to some extent, to match that of the coils.

With all coils energized inside the iron shields, the total stored energy is approximately 10 kJ giving an inductance of nearly 4 kH at 2.3 A operating current.

Quench protection is by simple circuit sub-division [4] using silicon diodes and resistors to allow current to by-pass a quenching coil. Space qualified components were selected and the protection circuit fabricated as a complete assembly. This was tested in liquid helium to ensure the components withstood thermal cycling and that the diode conduction threshold voltage was acceptable. Fig. 3 shows the diode protection assembly under test with the Helmholtz coils.

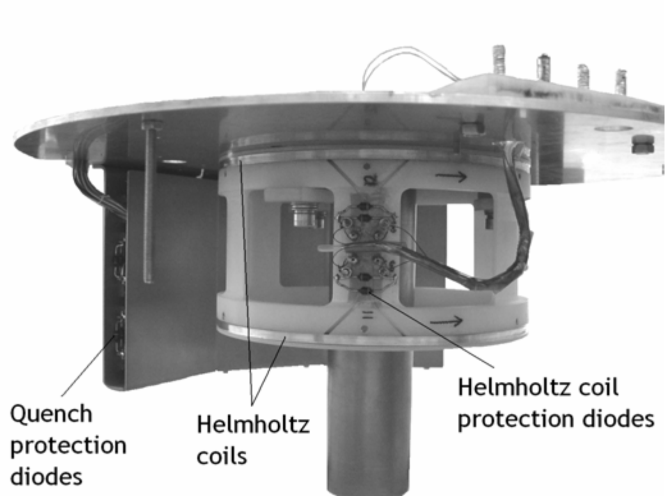

Fig. 3. Diode quench protection assembly mounted with the Helmholtz coils for test at 4 K in liquid helium.

III. COIL MANUFACTURE

To keep the magnet operating current within the severe limit imposed by the thermal budget, the coils must be wound from extremely fine conductor. With a bare diameter of 76 μm and an insulated diameter of 100 μm, the 54 filament wire used has a Cu:Nb-Ti ratio of 1.3:1 and a breaking tension of just 300 grams. Winding tension was closely controlled to avoid wire breakage and build-up of excessive hoop stress in the coil formers. A total of 235 km of conductor is required to complete the coil winding.

Epoxy resin is included in the winding to give mechanical stability and to promote load sharing through the coil section. Connections for thermally anchoring the coils to the cooler are fitted to the bore of the solenoids and to the outside of the smaller coils.

IV. COIL TESTING

To minimise manufacturing risk, coil subassemblies were tested individually during manufacture. For example, the DGG solenoid and compensation coils were tested as an assembly, and then retested with the outer bucking coils fitted. The CPA coils underwent a similar process before, finally, all the coils were tested as a complete magnet assembly. The Helmholtz coils, as they operate within an iron enclosure at very low background field from the rest of the magnet, have been tested separately.

When tested in a subassembly rather than in the final magnet configuration, the coils had a different peak field and peak stress. To ensure that sub-assembly tests were meaningful, the current was adjusted so that the coils being

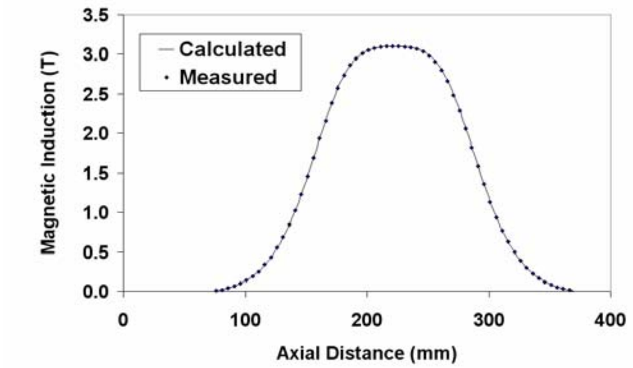

Fig. 4. Axial field plot through the DGG magnet section at 2.37 A.

tested performed to the maximum stress they will experience in the complete assembly. For example for the DGG solenoid and compensation coils tested without the bucking coils, this meant operating the coils at slightly below design current and a little above design field. To minimise delays, subassembly tests were performed in liquid helium rather than using a mechanical cooler. This allowed the coils to be run to field more quickly that in a dry configuration, and also enabled a faster recovery after a quench. The coils were mounted from the bottom plate of a simple bucket cryostat insert so that a room temperature bore tube could be passed through the bore of the coils. A hall probe was used to measure the field as a function of position along the coil axis for comparison with the calculated field for the configuration tested. Fig. 4 shows a plot of field along the axis of the complete DGG magnet section.

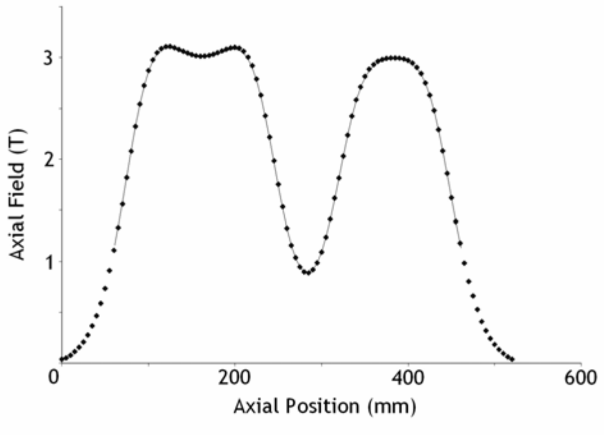

Fig. 5. Axial field plot of the complete magnet assembly at 2.37 A. The solid squares indicate field measurements: the line represents the field predicted using a magnetic finite element calculation. The correlation between the measurement and the prediction is extremely good.

The measurement in Fig. 4 was repeated at slightly above normal operating current to verify that the magnet has operating margin in excess of the requirement given in Table I. Only one quench was experienced while testing all the DGG coils together.

On completion of the subassembly testing, the CPA and DGG sections of the magnet were integrated and tested as a finished assembly. With a charging voltage of approximately 1.5 V, the magnet was run to full field in 2 hours: the central magnetic field requirement of 3.0 T was achieved with a current of just 2.37 A. Fig. 5 shows a field plot through the completed magnet system, including both CPA and DGG sections, at full field.

Fig. 6. The completed ADR magnet system, after testing.

V. SUMMARY

Space Cryomagnetics Ltd has designed, assembled and tested an ADR magnet (Fig. 6) for the Mullard Space Science Laboratory as part of the ESA XEUS programme. The magnet has met all specifications. In particular it has achieved the required field of 3 T in both sections with a current of 2.37 A: 5% lower than the maximum allowable.

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