

# 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  $^3\text{He}$  dilution refrigerator, and adiabatic demagnetization refrigeration (ADR). ADRs offer the advantage that they are less complex and more robust than  $^3\text{He}$  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.

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## 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. 3) 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.

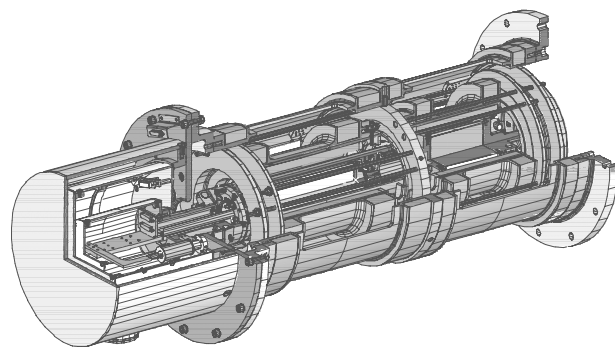


Fig. 1. Cut-away view of the ADR assembly.

### 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 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

materials to bring the field at the centre below 20 mT. The Helmholtz coils, used to null the field further, are inside this passive shield.

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.

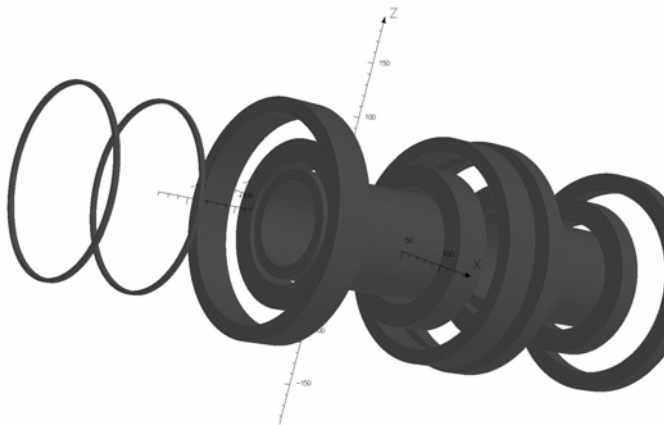


Fig. 2. ADR coils configuration.

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.

### 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  $\mu\text{m}$  and an insulated diameter of 100  $\mu\text{m}$ , 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, and connections for thermally anchoring the coils to the cooler

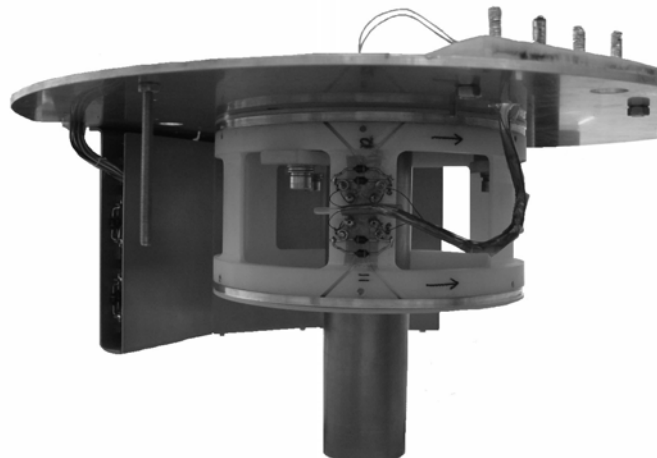


Fig. 3. Diode quench protection assembly mounted with the Helmholtz coils for test at 4 K in liquid helium.

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 are tested as manufacturing proceeds. For example, the DGG solenoid and compensation coils have been tested as an assembly, and then retested with the outer bucking coils fitted. Similarly, the CPA solenoid and compensation coils have been tested and will be retested with the bucking coils and in the 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 as a separate assembly.

When tested in a subassembly rather than in the final magnet configuration, a coil will have a different peak field and peak stress. To ensure that sub-assembly tests are meaningful, the current is adjusted so that the coils being tested perform 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 means operating the coils at slightly below design current and a little above design field. To minimise delays, subassembly tests are performed in liquid helium rather than using a mechanical cooler. This allows coils to be run to field more quickly than in a dry configuration and enables a faster recovery after a quench. The coils are mounted from the bottom plate of a simple bucket cryostat insert so that a room temperature bore tube passes through the bore of the coils. A hall probe is 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.

The measurement in Fig. 4 was made 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 and this was at 2.37 A, i.e. higher than

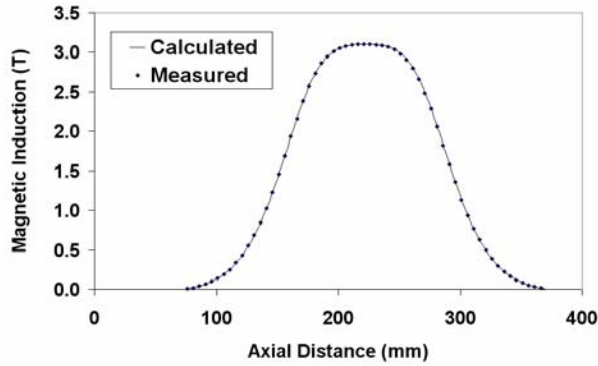


Fig. 4. Axial field plot through the DGG magnet section at 2.37 A.

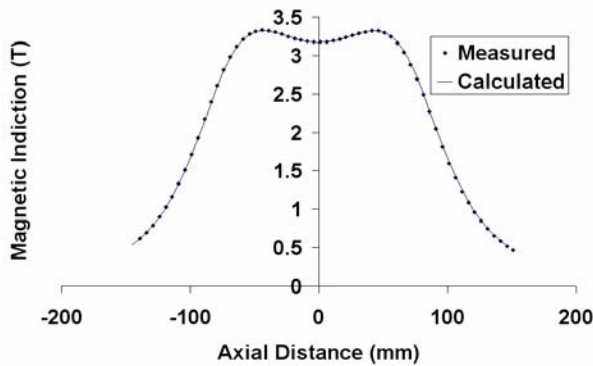


Fig. 5. Axial field plot of the CPA without bucking coils at 2.1 A.

normal current.

Fig. 5 shows a field plot through the CPA section incorporating the solenoid and compensation coils only.

## V. SUMMARY

Space Cryomagnetics Ltd has designed an ADR magnet for the Mullard Space Science Laboratory as part of the ESA XEUS programme. Manufacture of the coils is almost complete and successful testing of one complete section of the magnet verifies the design and manufacturing process. It is expected that the remaining coils will be complete in October 2004.

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