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High temperature superconductors: enabling technology for next generation space systems

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Abstract:

This paper introduces the phenomenon of superconductivity, in particular modern high temperature superconductor or HTS materials, along with some examples. HTS components and in particular HTS electromagnets have significant potential to benefit a wide range of space applications from exploration to active debris removal in Earth orbit. However there are a number of challenges to the required system engineering including meeting thermomechanical requirements, active thermal control to around 77K (-196ºC) or less, electrical interfacing and magnetic field management. No high temperature superconductors have yet flown in space.

Rocket Engineering have been working with Tokamak Energy to evaluate HTS magnets designed for plasma confinement in the fusion energy sector, for space applications. UK Space Agency technology funding has enabled preliminary space environment testing, assessment of high thrust to weight electric propulsion applications in particular the 'Supermagdrive' and systems engineering work.

We have developed a roadmap to commercial applications to show scaling, robustness and suitability of HTS magnet technology for space surveillance & tracking and active debris removal applications. This includes equipment level design, and a concept design of a low cost space experiment to demonstrate the operation of an HTS magnet assembly including critical supporting equipment such as cryocoolers. A combination of grant and private funding are targeting a UK In-Orbit Demonstration platform with a target flight date before 2025.

Keywords: Superconductor Electromagnet Plasma Debris Cryogenic

Acronyms/Abbreviations

ESA	European Space Agency
HTS	High Temperature Superconductor
IoD	In Orbit Demonstration
NSTP	National Space Technology Programme
REBCO	Rare Earth Barium Copper Oxide
SSC	Small Scale Cryocooler
TRL	Technology Readiness Level

1. Superconductivity and its relevance to space

1.1 What is superconductivity?

Superconductivity was discovered in 1911 and is a phenomenon where electrical resistance falls to almost near zero values on cooling below a transition or critical temperature. Most conductive materials show significant decreases in electrical conductivity as temperature falls, due to reduced atomic thermal motion, but there is a sharp transition, only explainable by quantum mechanics in a superconducting material, as shown below:

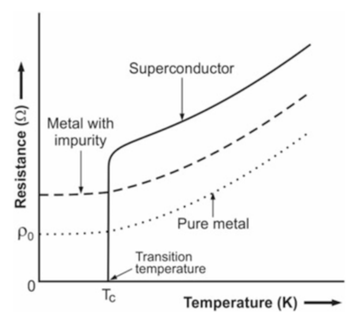

Fig. 1. The superconductivity phenomenon [1]

Although the benefits of a superconductor, with its very low electrical resistance, over a conventional conductor are self evident for electrical systems from microwave components to large scale data centres, superconductivity showed only limited utility for many decades as it only took place at temperatures reachable by liquid helium cooled systems, limiting practical, affordable large scale applications.

Discovery of High Temperature Superconductors or HTS in 1986 lead to a range of engineering applications. HTS have transition temperatures above 90K (-183C), allowing cooling to below this by the inexpensive refrigerants liquid nitrogen or argon (boiling points 77K and 87K respectively), or conduction cooling using a small space-qualified cryocooler. This potentially facilitates many experiments and applications such as high current and hence high magnetic field density electromagnets that are less practical at lower temperatures such as the boiling point of liquid Helium, 4.2K.

However, the second generation of ReBCO high temperature superconducting materials are brittle ceramic compounds which at face value presents challenges for making robust coils for space applications., Engineering applications have been facilitated by deposition of thin layers of active HTS material on more robust materials such as stainless steels.. This has enabled manufacture of very robust magnets by Tokamak Energy, by simple coiling of multiple tapes and potting in solder.

An example tape, representative of a number of supplier products eg from Superpower, SuperOx, Fujikara and THEVA is shown below:

Fig. 2. High Temperature Superconductor tape sample

1.2 Potential benefits of superconductivity to spacecraft

The US Navy was one of the first organisations to recognise the potential uses of superconducting satellite payload components, assembling a payload experiment (HTSSE-I) based on passive microwave devices, which was launched but failed to reach orbit, delivering no useful data in 1996. A follow-on experiment HTSSE-2 was not completed, both are reported on in [2].

A general introduction to the staff at NASA on the potential of bulk high temperature superconductors to enhance space mission capabilities, and their potential for exploration, including but not limited to plasma propulsion, high current transmission lines for nuclear power systems and radiation shielding is made in [3]. This summary also assumed that a future in-space liquid hydrogen infrastructure cooled to 20K would provide the required cryogenic sink needed to permit wide-ranging applications of REBCO superconductors operating at very high current densities.

NASA funded the construction of the AMS-02 Alpha Magnetic Spectrometer particle physics experiment for space station as a successor to AMS-01, first flown on the space shuttle for 10 days in 1998. AMS-02 was designed to use a superfluid helium cooled superconducting magnet built by a UK company Space Cryomagnetics Ltd. The magnet system consisted of a pair of large Helmholtz coils together with two series of six racetrack coils, circumferentially distributed between them to minimise the stray field outside of the magnet [4]. Although the experiment and the Space Cryomagnetics work demonstrated that engineering with superconducting magnets even at the low temperatures of liquid helium was possible, failure during test of the magnet and changes in space station programme requirements meant that AMS-02 flew in 2011 with a much less capable permanent magnet set.

Studies in Europe on propulsion applications have also taken place, for example [5] leading to experimental work on cooled superconductors for Hall effect electric propulsion funded by ESA in 2007/2008 [6]. The next subsection outlines some of the interrelated challenges, followed by an illustrative example in Section 2.

1.3 Challenges for system engineering of superconductors in space missions

High temperature superconductor applications, in particular magnets, present significant interfacing challenges:

- Thermal control both to lower the superconducting magnet to below its critical temperature and then maintain this state once current flows, despite parasitic heat leaks from the spacecraft and interfaces with non-superconducting components. Although passive approaches may assist, active cryogenic cooling is preferable given predicted thermal uplift and the variable thermal environment in low Earth orbits. The power required for thermal control is a major system design driver, since the higher the coil operation temp, the lower the power needed to run the cryocooler, but the less current the coil can carry.
- Low resistance electrical connectivity to non superconducting components must be mastered,
- A need to provide robust physical but also thermally isolating mountings to address magnetic stresses and thermomechanical loads,

- Addressing potential conflicts with magnetically sensitive sensors or actuators on many spacecraft.

Although some of these have been addressed by projects summarised in Section 2.1, these collectively pose a significant system integration challenge, particularly where the budget to TRL (Technology Readiness Level) is constrained. Hence, despite the potential of HTS magnet technology, no western space agency or commercial organisation has successfully operated a modern high temperature superconductor in space.

2. HTS magnets for Space applications

2.1 Plasma confinement for propulsion application

In 2020, Rocket Engineering was funded along with Magdrive, under the UK Space Agency's National Space Technology Programme (NSTP) to explore whether superconducting materials could practicably generate large magnetic fields (>0.5T) to enhance the performance of Magdrive's novel, compact, high thrust to weight propulsion system using metallic propellants. The principle of the Magdrive is explained in a paper IAC IAC-22,C4,5,1,x72726 [7] and in further detail at www.magdrivespace.com. The four-month project generated the following outcomes:

- Market and requirements review for high thrust electric propulsion, targeting the in-orbit servicing market,
- Derived a superconductor specification, and understanding of supply chain option, with the support of the Oxford University Centre for Applied Superconductivity www.cfas.ox.ac.uk ,
- Developed a model to predict performance of plasma confinement system using coils operating at >0.5T magnetic field strength at low temperature; and validated the model with some high current, and low temperature tests using conventional materials,
- Created a system concept design and analysed a preliminary specifications for a cooled superconductive magnetic coil system, to support a future 'SuperMagdrive' propulsion system able to support active debris removal missions. This concept design is shown below, and includes two stacked pancake coils, an external shell, a thermal radiation shield, and four small scale (two shown) cryocoolers on a baseplate:

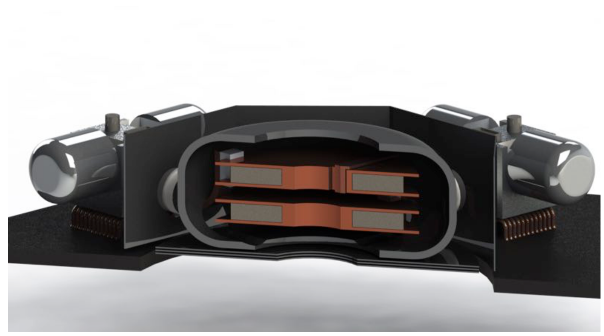

Fig. 3. SuperMagdrive early concept design

2.2 Magnets from fusion energy research

The 2021 culmination of this initial collaborative project served to highlight the challenges of integrating a superconducting magnet assembly with an electric propulsion system. However: a key commercial outcome was the identification of a local developer of HTS magnet technology, Tokamak Energy. This company is developing a prototype fusion power plant based around the spherical tokamak and are also developing HTS magnet technology. Recent advances include demonstrating sustained 100 million degree plasma temperature in their ST40 tokamak, and production of robust high temperature superconducting magnet technology capable of generating magnetic fields well in excess of 22 T with coils operating at 20 K [8].

An early prototype HTS electromagnet, manufactured by Tokamak Energy is show below:

Fig. 4. Small HTS magnet manufactured by Tokamak Energy

The single pancake coil shown in Figure 4 is 12 mm thick, has 44mm and 96mm inner and outer dimensions respectively, and weighs just over 0.5 kg. It can generate a central field of around 0.5 T when energised with an applied current of several hundred amps at 77 K. The coil is solder encapsulated and individual turns are not insulated. It is therefore considered thermomechanically very robust, being designed to resist conditions in a fusion reactor. However the interfacing required to enabling operation in the space environment requires several considerations.

2.3 Space environment requirements

Thermal: the magnet must be thermally isolated from the surrounding environment, to minimise cooling power required to draw it down to cryogenic operating temperature, and to maintain this in the varying thermal environment of an orbit. Additional heat loads from coupling superconducting with non-superconducting elements must be identified and managed. Applications such as plasma propulsion may require further management of extreme thermal gradients arising from close proximity to high temperature plasma sources.

Mechanical: the magnet must be supported against magnetically and thermomechanically generated forces, within the weight constraints common to any space mission, while also meeting the above thermal requirements.

Electrical: a magnet such as that shown is designed to be operated with applied currents up to 500 A. This requires a very low voltage, high current power supply. Joint resistance has been designed to be as low as possible (in the nanoΩ range) for the original fusion energy application, maximising contact area and busbar area with copper connectors. Meeting both of these requirements in a spacecraft environment while also minimising parasitic heat leaks is unusual and requires specialist equipment, for example superconducting current leads are being considered as a design trade-off.

Magnetic: Field design minimising stray field effects on sensitive spacecraft attitude control systems, and potential interaction with the Earth geomagnetic field will be a requirement. Multiple coils if correctly configured can reduce magnitude of stray external fields, reduced torque from interaction with Earth's field while also increasing overall dipole field, but at the expense of complexity which magnifies the previously described mechanical, thermal and electric challenges.

The challenge for the astromagnetic engineer is therefore to meet the above design constraint, while reducing complexity, applying a space platform mass and power constraint, and developing space heritage first through ground based testing and second through an early flight test of the magnet technology and its support subsystems. This is a systems engineering problem which our roadmap detailed in Section 4 is addressing.

3. Testing

The first step to transfer fusion energy sector HTS magnet technology to space for qualification is to understand the performance under typical space environment conditions. Supported by of a further UKSA Space Surveillance & Tracking or SST grant a series of preliminary tests on the magnet shown in Fig4. Were carried out. These were limited by schedule to vibration (not under load) of a magnet in a representative multi coil stack, and thermal cycling in ambient conditions. Before, and after each test the magnet properties, in particular its resistance and the generated field for a given current, were measured at the Tokamak Energy facility in Didcot. The general test setup including electric connections and magnetic sensor equipment including a liquid nitrogen bath is shown below:

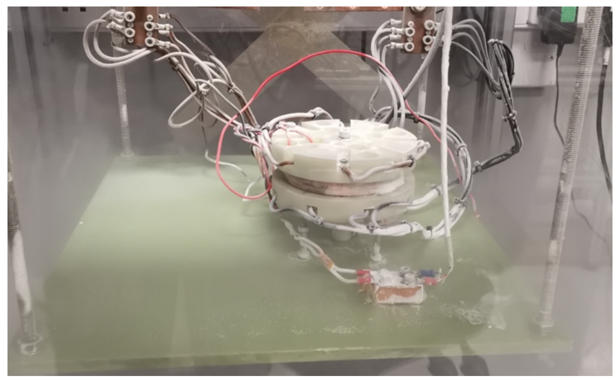

Fig. 5. HTS magnet plus electrical interfaces prior to cooling to operating temperature. *Credit Tokamak Energy*

Following measurement of electric and magnetic characteristics, the coil was integrated into a stack of 3 including spacers, representative of a potential plasma chamber application suggested by Magdrive. Sinusoidal vibration testing at 20g RMS for 180s in each of 3 axes took place, using the Space Catapult's vibration test facility at Harwell, using slip table RT 600 Mg.

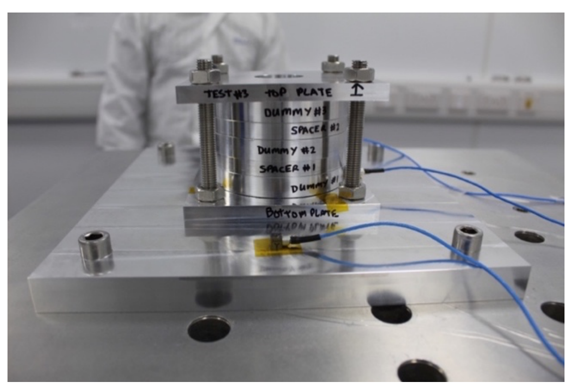

Fig. 6. Representative HTS magnet stack including stainless steel spacers

Thermal cycling in a new oven also at the Harwell Space Catapult was carried out between -30 and +80ºC For 110, ninety-minute cycles.

Testing was successful in that the magnet showed no changes in its electrical characteristics, when a step current was applied and resulting voltage measured across the coil terminals, as shown in Figure 7: no significant changes were apparent in the coil's electrical and magnetic properties after both vibration and thermal testing.

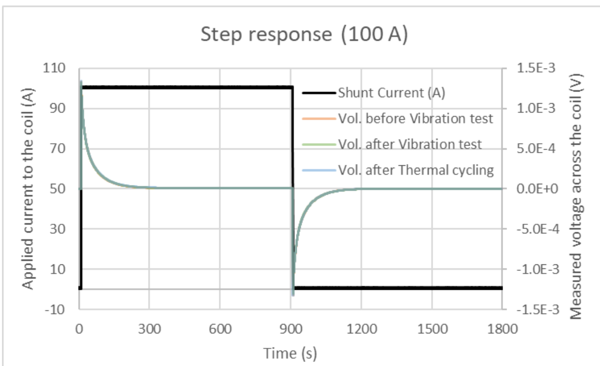

Fig. 7. Step current v. voltage across the coil showing no coil resistance changes following all tests

A change in coil resistance would be an indication of potential degradation from space environment effects. No such effects were anticipated, nor measured, although observations highlighted the importance of maintaining a controlled , vacuum environment during all future testing.

A thermal vacuum test, of a fully connected and operating magnet is planned next, although this will require a significant increase in experimental complexity.

4. System integration of HTS magnets for space

4.1 Roadmap

A technology development roadmap leading to commercial applications for active debris removal within 5 years has been draw up, critical technology steps are shown below in Figure 8:

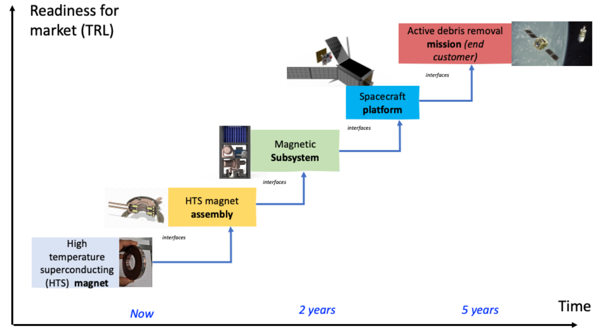

Fig. 8. Astromagnetic systems roadmap for commercial HTS applications.

4.2 Equipment design

Irrespective of application, the first step is to design, model, build and test an HTS magnet assembly designed specifically for space applications. Our prototype design using low thermal conductivity mounts to separate a 'cold block '(magnet units) from a 'warm hub' (cylindrical mount). Initial thermal modelling , assuming a physical connection to a cooling unit such as the RALSpace Small Scale Cryocooler, SSC [8] able to provide thermal uplift from a 77K heat sink, indicates a promising initial design which is being developed further. The main components are shown in the diagram below, arranged to suit a future 'SuperMagdrive' propulsion system [7]. These include a high current low voltage power supply (red box) which is also common to the Magdrive, cryocooler control electronics (blue), and two cylindrical cryocoolers shown top right.

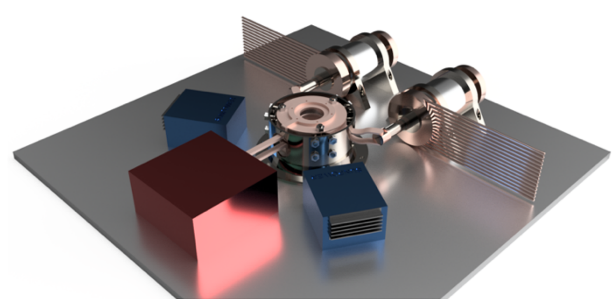

Fig. 9. HTS magnet assembly & supporting equipment

4.3 Space Experiment design

Rocket Engineering supported by In-Space Missions limited, studied how to reliably, repeatably operate an HTS magnet system in space, using all UK technologies. In-Space demonstration on a small scale to reduce technical risk and life cycle costs of any new technologies is a tried and tested approach in the UK.

Any operational heritage gained is also likely to help convince customers of the merits of early adoption.

Requirements and constraints of small spacecraft platforms were gathered and used as direct inputs in the design of the HTS experiment payload.

A formal system design study identified key system elements required to support operation of an HTS magnet in low Earth orbit, and their interfaces with a small spacecraft platform. Thermal control options, superconductor electrical interfaces and a payload system power budget were drawn up.

The experiment design comprising superconducting magnet and its supporting cryogenics and control avionics aimed to establish cost and schedule of an early demonstration at minimum viable scale. platform for an early in-orbit demonstration. A concept design showing key components is show in Figure 9. Simulation and discussion with equipment providers has allowed mass, volume and cost budgets to be elaborated. A cubesat architecture and platform for technology demonstration represents a cost-effective methods of demonstrating many undemanding technologies but is only one option among many for rapid in -orbit demonstration.

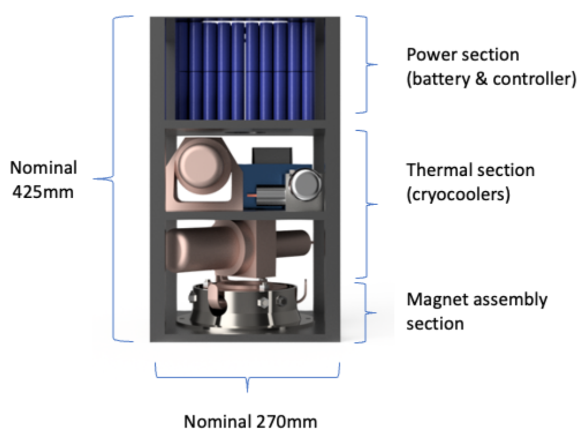

Fig. 10. Concept design for high temperature superconducting space experiment

At present we have elaborated high level mass, power, volume and data budgets which are compatible with a UK IoD, In Orbit Demonstration platform provider. We are working to design, procure assembly and test breadboard parts capable of energising an HTS magnet in a simulated space environment to retire key risks in
- HTS magnet assembly design
- Thermal control: cryocooler & passive insulation
- Power supply unit
- Electric interfaces
- Operational approaches to HTS magnets in space.

5. Conclusions

This paper has introduced the phenomenon of superconductivity, in particular modern high temperature superconductor or HTS materials, along with some examples. HTS components and in particular HTS electromagnets have significant potential to benefit a wide range of space applications from exploration to active debris removal in Earth orbit. However there are a number of challenges to the required system engineering including meeting thermomechanical requirements, active thermal control to around 77K (-196ºC) or less, electrical interfacing and magnetic field management. No high temperature superconductors have yet flown in space.

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We have developed a roadmap to commercial applications to show scaling, robustness and suitability of HTS magnet technology for space surveillance & tracking and active debris removal applications. This commercial application is discussed in the linked paper IAC-22-A6.6.10 [10].

Our roadmap includes equipment level design, and a concept design of a low cost space experiment to demonstrate the operation of an HTS magnet assembly including critical supporting equipment such as cryocoolers. A combination of grant and private funding are targeting a UK In-Orbit Demonstration platform with a target flight date this decade.

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