HIGH TEMPERATURE SUPERCONDUCTING MAGNETS: ENABLING TECHNOLOGY FOR ENHANCED SPACECRAFT ELECTRIC PROPULSION SYSTEMS

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ABSTRACT:

High Temperature Superconductors enable technology for ultra high strength, compact and low power electromagnets, currently used in a wide range of industries. Such electromagnets are also enablers for a wide range of plasma propulsion applications where performance strongly depends on magnetic field strength. Despite disruptive potential, no high temperature superconducting magnet has ever been operated in space.

Three pieces of collaborative, UK government funded work were carried out between 2020-2022. A technology study supported by Oxford University, established the feasibility of using modern high temperature superconducting materials in plasma propulsion. Operation of a propulsion system tailored for a future low Earth orbit active debris removal mission, and qualification activities on critical equipment were carried out in parallel to a system study of a magnet-only in-space demonstration mission on a small satellite platform.

The systems engineering challenge of integrating nuclear fusion derived superconducting magnet technology, with novel plasma propulsion technology, is significant. A clear roadmap has been identified leading to a UK-first high temperature superconducting space demonstration.

1. INTRODUCTION

This paper will cover the following key points

- Requirements for enhanced plasma propulsion spacecraft
- Other nearer term applications for HTS magnets exist which will drive the commercial case
- Availability of commercial high quality robust High Temperature Superconducting (HTS) magnets which could fly in space
- Ongoing development of a suitable EP system in the UK which requires high strength magnets – the Magdrive.
- Recent UKSA funded work under NSTP Space Surveillance & Tracking programme (SST), to be reported on.
- The numerous system engineering challenges

2. MAGNETISM AND PLASMA PROPULSION

Plasma rockets are a class of low thrust, high specific impulse alternatives to chemical rockets. Propulsive force can be provided by the $J \times B$ (Lorentz) force associated with an electric current passing through an ionised propellant flow within a magnetic field. The high specific impulse (Isp) offers the potential for one or more orders of magnitude savings in propellant mass for any given mission. The trade off is that an increasingly large power plant is needed to obtain acceptable thrust and hence time of flight for many mission scenarios. This energy demand is also strongly influenced by the conversion efficiency between electric power input to the propulsion system and its conversion into jet, or motive power.

The Lorentz thrust equation above implies that for a specific mission and thrust profile, a reduction in powerplant power and mass scales with an increase in B, magnetic field strength. More specifically, it can be shown that

$$Thrust \sim \propto B^2 R^3 \quad \text{Equation 1}$$

And

$$I_{sp} \sim \propto B R \quad \text{Equation 2}$$

where R is the coil radius, with further dependencies on plasma generation and power system. Modeling by organisations in the US and Europe, and within this consortium has demonstrated that increased electromagnet field strengths will support thrust levels considerably in excess of 1N, with further benefits to component lifetime and electric-to-jet conversion efficiency, depending on the type of

thruster.
Generating high magnetic fields is most efficiently achieved (in terms of volume and mass) using high current density coils made of superconducting material. The absence of measurable resistivity below the superconducting material's critical temperature minimises ohmic heating losses. Practical magnets able to support current densities of hundreds of Amps / mm^2, and actual currents in the hundreds of Amps, while cooled to temperatures of the order of liquid nitrogen's boiling point (80-100K are now a commercially available product. Balancing this potential is a need for onboard spacecraft cooling and specialised switching and power conditioning design to deal with very high currents. These challenges tend to translate into additional electric power system and thermal control costs.

Superconducting magnets can therefore enable a range of plasma propulsion, and other applications. Although not a low-cost item, a technology which offers high efficiency, compactness, and reliability may often be forgiven high costs. An example of currently available magnet technology is seen in Figure 1. This magnet is round 10mm in axial thickness, has 44mm and 96mm inner and outer dimensions respectively, and weighs just over 0.5kg. it is capable of generating a central field of around 0.5T with an applied current of several hundred Amps.

Figure 1: Compact electromagnet manufactured from high temperature superconducting material

3. PREVIOUS WORK

Superconductors have been studied extensively for their potential to enhance the performance of propulsion and other space systems. A general introduction from the staff at NASA to the potential of bulk superconductors to enhance space mission capabilities is given in [1]. One of those authors carried out the original work on magneto-plasmadynamic (MPD) thrusters at NASA in the early 1970s that showed the potential increases in efficiency from high strength magnetic field confinement. Work to explore the benefits of higher field benefits up to, and above 1T was reportedly abandoned due to the impracticality of cooling the thruster superconducting magnet technology available at the time [1].

More recent work [2] in Europe explored the potential for superconducting materials in plasma propulsion, quantifying the potential mass and volume savings achievable through using superconducting materials, in this case the low temperature material NbTi. An estimate of mass of a magnet, and cryostat capable of producing 5T of magnetic field strength enabling an MPD thruster to deliver a thrust of 10-20N was 11kg (total excluding power supply).

The European Space Agency ESA through its telecommunications and integrated applications (ARTES) programme has in the last decade funded work on superconductive materials for electric propulsion systems [3]. Proof of concept work using breadboard magnet assemblies in the laboratory without a heat source (plasma discharge) was carried out, although theoretical thermal management feasibility was simulated. Conclusions from the work completed in 2008 were that use of superconducting instead of resistive coil materials resulted in a lower thruster system mass, with increased mass savings towards higher powers Hall Effect plasma thrusters operating at powers above 10kW.

In 2021 Neutron Star Systems, working with Stuttgart University and Theva Dünnschichttechnik explored the potential benefits of HTS magnets for MPD thrusters [4]. The need for cryogenic cooling, overall thermal control of the electrical architecture to minimise resistive heating, and the use of flux pump to energise superconducting magnets without physical contact was reported on, as well as other applications of HTS materials such as energy storage and power transmission. Although the research largely focused on the potential benefits of superconducting MPD thrusters for future space exploration missions, a mechanical cryocooler design able to provide several 10s of watts of cooling power to an HTS magnet was estimated to weigh no more than 20kg.

In 2020 the UK Space Agency's National Space Technology Programme funded a small study into the feasibility of whether high temperature superconductors could be used to make extremely high field strength (>0.5T) electromagnets to support high thrust plasma propulsion. The study had several findings

1) Superconducting magnet plasma confinement can increase the thrust of a novel high Isp electric energy propulsion system. The power constraint on high Isp and high thrust plasma

propulsion can be avoided by use of pulsed thrusting, although this shifts the technical challenge to one of energy storage and imposes a mission constraint on energy collection if the host spacecraft is limited to classical solar battery power systems.

2) Two class of HTS, High Temperature Superconducting materials were recommended by Oxford University's Centre for Applications of Superconductors, CfAS. MgB2 with a critical temperature of 40K is readily available in inexpensive wire form from companies such as Epoch wires in the UK. REBCO or Rare Earth Barium Copper Oxide materials, with critical temperatures above 77K, are available as more expensive tape from a range of suppliers including Superpower, Sunam, Fujikara and Theva.

3) Working with CfAS highlighted the many technical risks of developing a practical magnetic confinement device suitable for spaceflight. This steered the collaboration towards manufacturers of magnets made from superconducting material, as way to circumvent manufacturing development of a bespoke magnet product. This allowed Rocket Engineering to focus on an efficient system level integration of equipment addressing the challenges highlighted in Section 4 below.

The study also served to illustrate the non-trivial challenges of cooling and then operating a superconducting magnet below its critical temperature. Although an open cycle liquid coolant system using a suitable refrigerant such as cryogenic nitrogen allowed for relatively low-cost lab experiments, a closed cycle cryocooler is a far more practical option for the majority of modern space missions.

A preliminary concept design for a SuperMagdrive thruster was produced (Fig. 1) to show a potential thermomechanical configuration, based on a nominal plasma confinement requirement. This excludes propellant storage, vapourisation and any plasma beam shaping requirements:

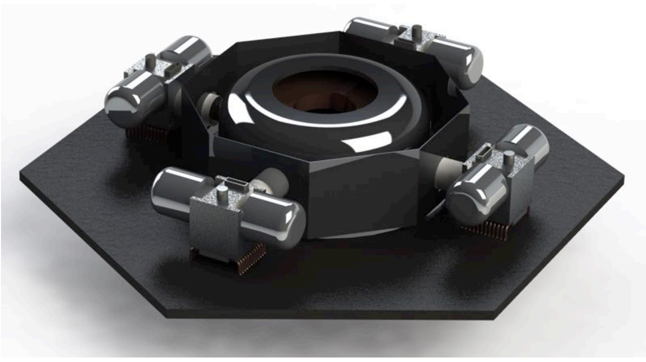

Figure 2: SuperMagdrive early design concept

Fig. 1 shows an arrangement using four STFC small scale Stirling cycle cryocoolers, thermo-mechanically joined to a magnet coil arrangement through an (octagonal) radiative heat shield.

Two further system design studies have been conducted to raise the TRL, Technology Readiness level of HTS magnet technology applicable to plasma propulsion and other in-space applications.

4. CHALLENGES OF HTS IN SPACE

Superconducting magnets have been proposed for a variety of uses in space, notably the particle physics experiment Alpha (particle) Magnetic Spectrometer AMS-02, installed on the international space station form the space shuttle in 2011. This device searches for evidence of dark matter, and is the successor to the AMS01 flown on the space shuttle for 10 days in 1998. The requirements for AMS-02 included a 6-fold field increase in magnetic field to 0.865T, increasing the resolution for antinuclei detection, plus a wide acceptance aperture; and volume mass and power constraints dictated by launch on the space shuttle and operation on the space station [5].

To deliver the required Helmholtz coil configuration able to meet the large aperture scientific requirements and minimise stray field disturbances on the space station, a set of racetrack coils giving a magnet bore of 1.1m were contained in a concentric liquid helium vessel and vacuum tank containing 2500 litres of liquid helium to cool the magnet to its operating temperature of 1.7K. The magnets were made from NbTi based superconducting wire. High temperature superconductors were not considered technically mature enough to meet programme requirements at the time. The superconducting magnet assembly was the greatest technical challenge of the experiment, storing over 5Megajoule of energy when operating, requiring the spacecraft platform to deliver a current of nearly 500 Amps, and support a vacuum chamber of diameter 2.7m and height 1.5m, with a mass of just under 2.4tonnes.

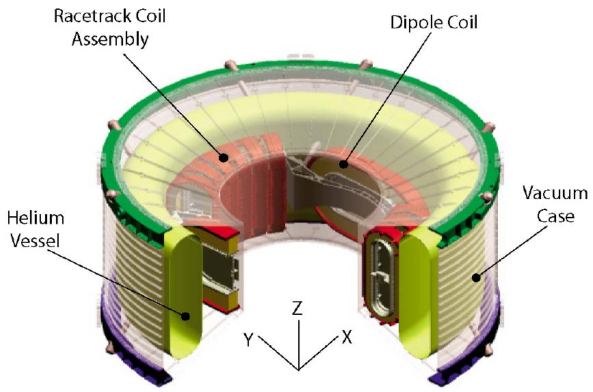

Figure 3: AMS-02 magnet system design [6]

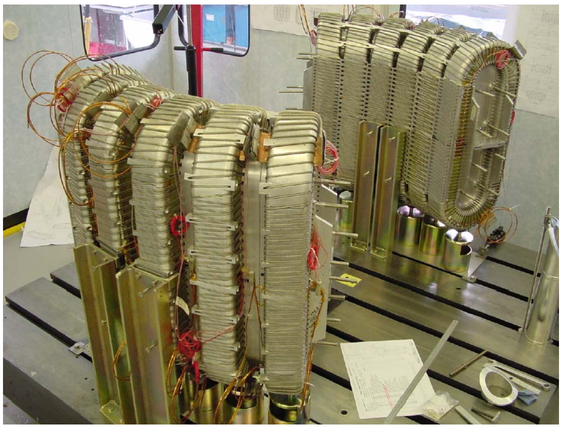

Figure 4: AMS-02 Magnet coil assembly [6]

In order to meet programme requirements the superconducting magnet assembly was replaced before launch with a conventional permanent magnet similar to the earlier AMS-01.

The AMS-02 programme :serves to emphasise the extreme challenges of engineering solutions to enable bulk superconducting devices in the space environment. In brief these challenges can be summarised as

- **Thermal**: cooling to and maintaining at cryogenic temperatures in the demanding thermal environment of space, coupled with managing extreme thermal gradients from close proximity to high temperature plasma sources,
- **Mechanical**: managing magnetically and thermomechanically generated forces within the weight constraints common to any space mission,
- **Electrical**: handling extremely large electric currents and managing parasitic resistances and their consequent heat loads,
- **Magnetic**: Field design minimising stray field effects on sensitive spacecraft attitude control systems, constrained by plasma containment requirements for propulsion.

Considered individually, all of the above are addressable with standard engineering design approaches.

When defined as requirements for cooling, energising, thrusting and powering a superconducting propulsion system in the context of an operational Earth orbiting spacecraft, the problem magnifies. In concert, mapping a solution space requires extensive space systems engineering knowledge skills and experience.

No organisation including NASA has solved this expceptionally difficult problem, and no high temperature superconducting magnets have ever flown in space.

5. DESIGN STUDY 1: HTS MAGNET SPACE EXPERIMENT

Rocket Engineering supported by Magdrive and In-Space Missions studied how to reliably, repeatably operate of an high temperature superconducting (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.

Particular focus has been to establish the minimum viable scale of an experiment comprising superconducting magnet and its supporting cryogenics, to validate others' work e.g. [2] and [4] and also to explore whether a 3U cubesat platform as proposed in [7] is a viable platform for an early in-orbit demonstration. A concept design showing key components (top to base: energy storage to maximise operational flexibility, cooling system and control electronics, HTS magnet assembly, plus passive thermal control elements). Simulation and discussion with equipment providers has allowed mass, volume and cost budgets to be elaborated. The cubesat architecture and platforms for technology demonstration represents cost effective methods of demonstrating many undemanding technologies although the life cycle cost of any space experiment or mission should always be considered in its entirety to maximise chances of success, reference [5] and [6] discussed earlier.

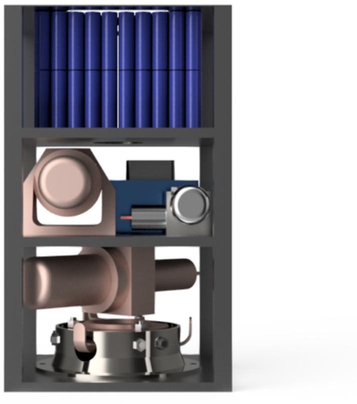

Figure 5: Concept design for high temperature superconducting space experiment

6. DESIGN STUDY 2: PROPULSION SYSTEM FOR ACTIVE DEBRIS REMOVAL MISSIONS

Rocket Engineering are working with a leading space mission integrator who are developing commercial active debris removal missions. A study funded by by the UK Space Agency's Space Surveillance & Tracking programme has conduct a detailed study into a scaled up plasma propulsion system targeted at future debris mitigation mission. The study aimed to raise the TRL of key plasma propulsion technology using HTS magnetic confinement to 4, 'Component and/or breadboard validation in laboratory environment'

The main required manoeuvres are:

- Rendezvous and Docking: requirement for high thrust and precise impulse bits.
- Orbit transfer with captured client satellite / debris: requirement for high Isp and low / moderate thrust.

We have explored replacement of the current combined and high mass / volume / power chemical and plasma (electric) propulsion systems for agile missions in low Earth orbits, with a superconducting Magdrive or 'SuperMagdrive' to meet the UKSA programme objectives of active debris removal and space surveillance and tracking more competitively. A spacecraft concept design (see Figure 6 below) and operations concept have been constructed to determine constraints on orbits and manoeuvres, and a customer driven development is proceeding.

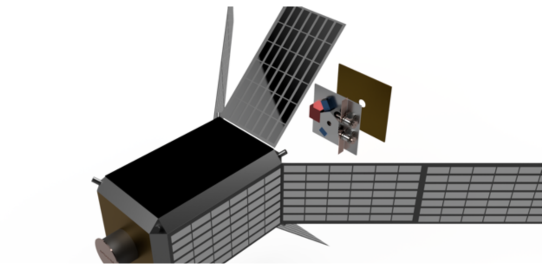

Figure 6: Debris removal mission concept (propulsion system shown upper right)

Our work reports two major findings:

1) Dry mass threshold at which the simplest SuperMagdrive plasma propulsion system is expected to be viable approaching 100kg including all required equipment and applying reasonable margins. However this propulsion system can offer a thrust in excess of 5N, with a Isp exceeding that of any commercial plasma thruster.

2) The operational requirements of cooling, energising, thrusting and powering a superconducting propulsion system can potentially pose a significant operational conflict. Although a purely passively cooled design may be feasible for some orbit and spacecraft orientations, maximising mission flexibility and therefore the commercial benefit of a SuperMagdrive will require an actively cooled design. This significantly raises the required system complexity volume and mass. The problem, as also recognised in [4] is primarily a thermal control one and finding a a viable solution is principally one of adept systems design and engineering, coupled with a comprphensive knowledge of the space sector supply chain.

Preliminary tests to establish suitability of HTS magnet technology for operation in a space environment have been carried out with the support of a leading provider of HTS magnet technology.

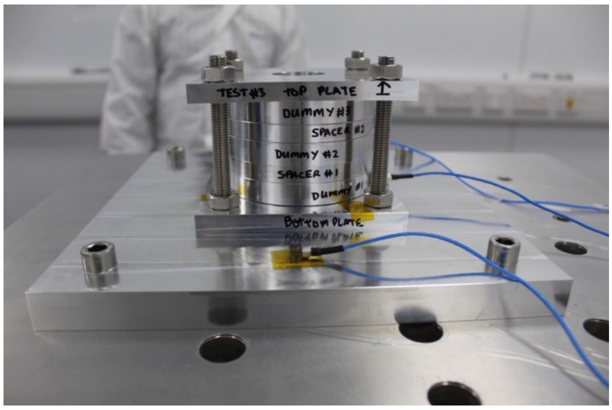

Figure 7: Vibration test setup for HTS magnet stack

Work to develop suitable power system architectures suitable for controlling a high power plasma propulsion system and energising its HTS magnets has also been carried out at Magdrive.

A detailed propulsion system design (see Figure 8 below) and a clear roadmap to meet commercial targets set at propulsion system and space mission level have also been derived.

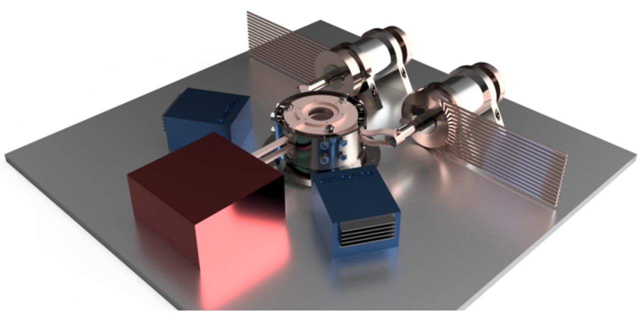

Figure 8: SuperMagdrive design, TRL4

7. DEVELOPMENT ROADMAP & GOALS

For superconducting materials to realise their potential for space plasma propulsion systems and other applications, a demonstration of operability and reliability in the space environment is required. This can be preceded by reasonable testing to raise the TRL of magnet, assembly, and (propulsion) subsystem to give confidence that it can be integrated without significantly compromising platform operation, this enabling or enhancing mission performance as shown below.

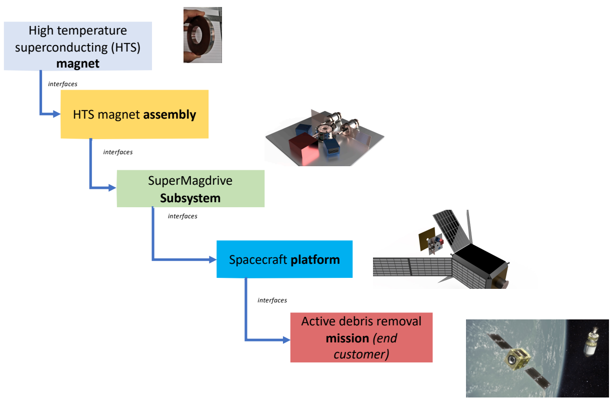

Figure 9: Roadmap to enhancing active debris removal mission performance

SuperMagdrive will enable highly competitive commercial active debris removal missions, allowing the UK to play a leading role in sustainable space development, within a decade.

The next two steps are a space demonstration of high temperature superconducting magnet technology in the early years of this decade. In parallel, progress on high power plasma propulsion, demonstrating critical Magdrive plasma technologies in orbit parallel will occur. Upscaling high plasma propulsion technology to match high temperature superconducting magnet technology will allow a step change in the competitiveness of space propulsion. When high thrust high efficiency plasma propulsion is further coupled with advanced high energy power sources (and these are further facilitated by high bulk superconductor technology as discussed in [1]) the potential exists for commercially viable cislunar infrastructure, and to open the door for large scale exploration of the planets & asteroids, and ultimately unconstrained access to the vast resources of our solar system.

8. SUMMARY CONCLUSION

Rocket Engineering are a systems design organisation with many decades of collective experience in finding solutions for difficult and extreme environment engineering problems. The extraordinary potential that high temperature bulk superconductor materials, in particular electromagnets offer to many space mission applications has yet to be realised even by capable organisations such as NASA.

We have brought together a uniquely experienced and all UK consortium, including commercial and academic viewpoints, and experience across the value chain from fundamental science through to mission level end customer. Working closely with a UK based team of development partners, we have developed our understanding of:

1. The availability and potential of modern, commercial high temperature superconducting materials, and the technology transfer potential of electromagnets developed using these materials for commercial non-space applications.
2. Studies, and previous design and development work aimed at operating superconductors in support of space missions.
3. Engineering challenges in cost-effectively implementing high temperature super-conductors: A plasma propulsion system using HTS magnets to confine and accelerate the working fluid has the potential to deliver more competitive performance than any commercial system, and be a major enabler for our sustainable use of space. However, realising this potential requires some exceptional systems engineering expertise and knowledge of the space sector supply chain.
4. The logical next step, is to qualify and demonstrate magnet technology on a low cost space mission platform, to reduce risk and perceived risk in the eyes of potential users.
5. A space HTS magnet demonstration will stimulate development of ultra-high performance plasma propulsion systems such as the SuperMagdrive, aiding near term commercial active debris removal capabilities and in the longer term space exploration missions that are not yet commercially viable.
6. The world's first In-Space Mission demonstration of this game changing technology will leverage ongoing support from public grant funding, with longer term private capital. The commercial case for investment is being prepared.

7. ACKNOWLEDGEMENTS

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