IAC-22-C4.5.1

High temperature superconducting magnet enabled electric propulsion from fusion energy technology

Dr. Adam M. Baker[a]*, Lolan Naicker[a], Philip Dembo[a], Dr. Thomas Clayson[b]

[a] *Astromagnetic Systems Limited,* 24 Courtfield Gardens London, W13 0EZ, UK. adam@astromagnetics.space
[b] Technology Director, Magdrive Limited, Unit 7, Zephyr Building, Eight Street, Harwell Campus, OX11 0RL, UK

An enabling benefit of superconducting magnets is their ability to confine and focus high plasma densities. Pulsed power electric propulsion concepts for example the Magdrive, can benefit from high field strength superconducting electromagnets, although a number of practical challenges need to be resolved before space based demonstrations.

Two system design studies on fusion energy derived superconducting magnet technology have been conducted to (a) raise the TRL of a Magdrive compact superconducting electric propulsion system for low Earth orbit active debris removal applications, and (b) explore feasibility and estimate and the cost of magnet-only in-space demonstration mission on a small satellite platform. High thrust and high Isp requirements have been identified by a potential client and can uniquely be met by a single, superconducting magnet enabled propulsion system.

The paper discusses system engineering efforts addressing the thermal management and power supply challenges faced when integrating superconducting electromagnet, power supply and coolers into a spacecraft. Work is ongoing under UK government space technology development funding to combine propulsion systems evaluation with superconducting magnet qualification and system breadboarding work to define a high temperature superconductor space demonstration. This aims to be the first step of a roadmap leading to a flight demonstration of the technology this decade.

Keywords: High Temperature Superconductor Electric Propulsion Magnet

Acronyms/Abbreviations

ADR Active Debris Removal
MAS Alpha Magnetic Spectrometer
BSCCO Bi-Sr-Ca-Cu-Oxide (superconductor)
CfAS Centre for Applied Superconductivity
HTS High Temperature Superconductor
HTSSE High Temperature Superconducting Space Experiment
MPD MagnetPlasmaDynamic
NSTP National Space Technology Programme
TE Tokamak Energy

1. Introduction

High temperature superconductors enable compact, ultra-high magnetic field strength electromagnets with reduced cooling requirements. These high performance electromagnets have the potential to enhance many different space applications, in particular propellantless and plasma propulsion of various forms.

5.1 *Superconductivity*

Superconductivity was discovered in 1911 and is a phenomenon where electrical resistance falls to unmeasurable values on cooling below a transition or 'critical' low 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 temperature, only explainable by quantum mechanics in a superconducting material, illustrated below:

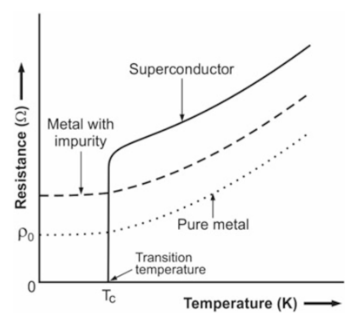

Fig. 1. The superconductivity phenomenon [1]

Superconductivity showed limited utility for many decades as it only manifested itself at temperatures reachable by liquid helium cooled systems, limiting practical, affordable and 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 (-183°C), allowing operation when cooled by inexpensive refrigerants such as liquid nitrogen or argon (boiling points 77K and 87K respectively). 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 around the liquid Helium boiling point of 4.2K.

Engineering applications have further been facilitated by deposition of thin layers of active but ordinarily brittle, ceramic like HTS material on more robust materials such as stainless steels. HTS tapes include interlayer materials to manage thermal expansion mismatches, and provide environmental protection. Although HTS tape is costly, at several thousand euro per kilogram, availability from a number of manufacturers including Superpower, SuperOx, Fujikara and in Europe THEVA has enabled manufacture of extremely robust magnets, for example by coiling tape and potting in solder. An example tape, representative of supplier products is shown below:

Fig. 2. High Temperature Superconductor tape

Three critical parameters characterise a superconductor: critical temperature (Tc), the critical field (Bc) and the engineering critical current (Je) which considers the entire cross section of the engineered material. All the three parameters are interdependent, and are often shown in a phase space plot [1]. A superconductor remains superconducting within the confines of its material dependent phase space, but returns to a normal conducting state the moment any of critical parameters is exceeded. Engineering a superconducting device to operate within this phase space is the principle driver behind commercially cost-effective applications of the technology.

5.2 *Potential benefits of superconductivity to spacecraft*

A general introduction, aimed at the staff at NASA, on the potential of bulk superconductors to enhance space mission capabilities, and their potential for exploration, was made in [2], exploring *inter alia* plasma propulsion, high current transmission lines for space nuclear power systems and radiation shielding. The US also recognised potential uses of superconducting satellite payload components, assembling a payload experiment (HTSSE-I) to explore operation and utility of high temperature superconducting passive microwave devices. HTSSE-1 was launched in 1996 but failed to reach orbit, delivering no useful data on operational characteristics of HTS. A follow-on experiment HTSSE-2 was not completed; both are reported on in [3].

Superconducting magnets have also been proposed for space science usage, notably the Alpha Magnetic Spectrometer particle physics experiment to search for evidence of dark matter, first flown on the space shuttle for 10 days in 1998. This example illustrates some of the challenges of engineering with superconducting magnets in space. The requirements for AMS-02 to be hosted on international space station from 2010, but delivered by space shuttle, included a 6-fold field increase in magnetic field to 0.865T, increasing the instrument resolution for antinuclei detection, plus a wider acceptance aperture. The required configuration able to meet aperture requirements and minimise stray field disturbances on other payloads, lead to design of a set of superconducting Helmholtz coils arranged in a racetrack configuration, see Fig. 3. The magnet bore of 1.1m required a concentric liquid helium vessel and vacuum tank containing 2500 litres of liquid helium and cooling the low temperature superconducting magnet to its operating temperature of 1.7K.The vacuum vessel had a diameter of 2.7m, a height of 1.5m and a mass of just under 2.4tonnes [4].

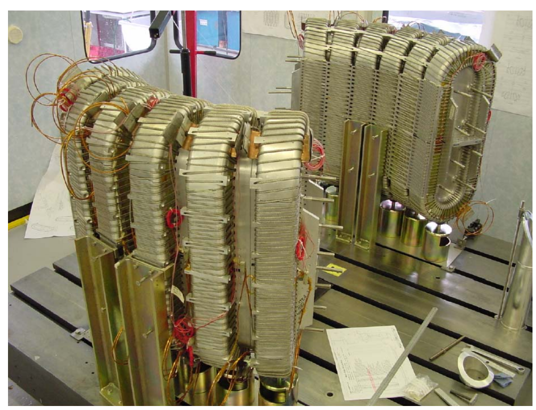

Fig. 3. AMS-02 low temperature superconducting magnet coil assembly, *excluding vacuum cryostat* [4]

A combination of (a) changes in mission requirements including an extended mission made possible with space station life extension and an inability to service or return large components, and. (b) engineering challenges including a critical failure during test at CERN lead to the superconducting magnet being replaced with the AMS01 permanent magnet before delivery to the space station. Although absence of a Helium cryostat meant a longer operational life, the instrument performance was greatly reduced, owing to the permanent magnetic field being only around 20% that of the superconducting magnet [5].

2. Plasma Propulsion

2.1 Magnetism and plasma (electric) propulsion

Plasma or electric rockets are a class of low thrust, high specific impulse alternatives to chemical rockets. Propulsive force can be provided by the J×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 (force) thrust definition 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

…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.

2.2 Benefits of superconductors for EP

Generating high magnetic fields can be efficiently achieved (in terms of volume and mass) using high current density coils or electromagnets 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 between 80-100K are now a commercially available product. Offsetting this potential is the need for onboard spacecraft cooling to maintain the magnet in the superconducting operating regime, 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.

[2] reported on MagnetoPlasmaDynamic (MPD) thruster work 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.

More recent study work [6] 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).

In 2021 Neutron Star Systems, working with Stuttgart University and Theva Dünnschichttechnik explored the potential benefits of HTS magnets for MPD thrusters [7]. 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.

The European Space Agency ESA through its telecommunications and integrated applications (ARTES) programme funded experimental work on high temperature superconductive materials as magnetic field generators for Hall Effect Thruster electric propulsion systems [8]. Proof of concept work using liquid nitrogen breadboard magnet assemblies based on BSSCO material in the laboratory, operating without a heat source (plasma discharge) was carried out, and theoretical thermal management feasibility was simulated. A mass assessment of the cryocooler needed to lower the magnet to its operating temperature, plus a cryostat and high current low temperature terminals showed a mass estimate of at least 15kg for the coil system. The conclusion from the work completed in 2008 were that use of superconducting instead of resistive coil materials resulted a thruster system mass benefit where operation above 10kWpower was required. Magnetic field measurements also confirmed simulations, but the engineering feasibility of a system level solution was not demonstrated.

3. Engineering challenges to enable HTS EP

3.1 State of the art fusion energy HTS magnets

Rocket Engineering have been working with Tokamak Energy (TE), a UK based fusion power company since 2019. TE are developing a prototype fusion power plant based around spherical tokamaks in conjunction with HTS magnet technology. The company have already achieved over 100Million degree plasma temperature in their ST40 design, enabled largely from their use of high temperature superconducting magnet technology, to generate the large magnetic fields needed for plasma confinement. An HTS test magnet, manufactured by Tokamak Energy is show below:

Fig. 4. Small HTS magnet manufactured by Tokamak Energy

The magnet shown in Fig. 4 is 10mm thick, has 44mm and 96mm inner and outer dimensions respectively, appropriately dimensioned to support plasma confinement in a small thruster, and weighs just over 0.5kg. While simple in appearance, if correctly connected, cooled and energised with an applied current of several hundred Amps, the magnet can generate a field strength at the bore of around 0.5Tesla. TE are confident that their proprietary manufacturing technology is thermomechanically very robust, designed to resist conditions close to the heart of a fusion reactor. Considerably larger magnets can be manufactured and are being used in TE's ST40 prototype reactor. However the interfacing required to enabling operation in the space environment requires several considerations including meeting a different set of design requirements, as discussed below:

3.2 Space environment requirements

Thermal: the magnet must be thermally isolated from the surrounding environment, to minimise cooling power to draw it down to cryogenic operating temperature, and it. 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 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 in Fig 4 is designed to operated with applied currents up to 500Amps. 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 constraints, while reducing complexity, applying a mass 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. The first in-orbit demonstration of a superconducting magnet must also be affordable within the context of UK space missions, indicating a small (<100kg) satellite platform where. mission costs tend to be <£10M. This is a systems engineering problem which must be addressed if superconducting electric propulsion is to become a practical reality.

4. Magdrive electric propulsion & applications

4.1 Magdrive and Supermagdrive research

In 2020, Rocket Engineering received funding under the UK Space Agency's National Space Technology Programme (NSTP) to work in partnership with Magdrive, supported by Oxford University's Department of Materials, to explore whether superconducting materials could practicably sufficiently large magnetic fields (>0.5T) to enhance the performance of electric propulsion. The specific applied was superconducting magnetic confinement of plasma to enhance the performance of Magdrive's novel, compact, high thrust-to-weight electric propulsion system. The study examined the potential space market uses, enabling technology and preliminary budgets and feasibility for a Supermagdrive.

The Magdrive is a novel, compact propulsion system able to offer a combination of high thrust, near impulsive transfer at an Isp exceeding that of chemical propulsion ('sport' mode) or low thrust orbit maintenance at an Isp comparable with the best electric propulsion ('eco' mode), delivering unrivalled propulsive mission flexibility. Magdrive also addresses the fundamental shortcoming of electric propulsion which is the power limitation constraining operation to either high Isp or high thrust, but not both simultaneously; by operating in a stored energy mode using pulsed power. Magdrive's energy storage and pulsed power systems are currently optimised to the power and volume constraints of cubesats and nanosatellites, but could provide large, rapid deltaV increments to larger spacecraft through scale up and the use of higher strength magnetic fields to improve confinement and collimation of the plasma exhaust, ref. Equations (1) and (2).

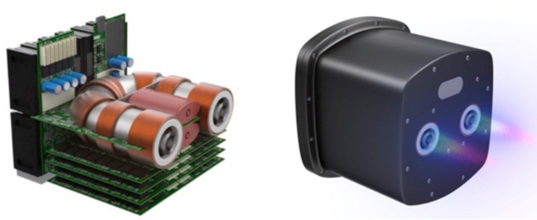

Fig. 5. Magdrive thruster design

4.2 Propulsion system design study

Initial work concluded in 2021 resulted in the following outcomes:

- A market and requirements review for high thrust electric propulsion, indicating an attractive space surveillance, tracking, debris removal and in-orbit servicing market,
- Derivation of a superconductor specification, preliminary modelling, and understanding of supply chain options, with the support of the Oxford University Centre for Applied Superconductivity, CfAS www.cfas.ox.ac.uk . An initial requirement from Magdrive allow CfAS to model defining the scale of magnet needed using commercial HTS tape operating at its maximum current density, as shown in Fig. 6.

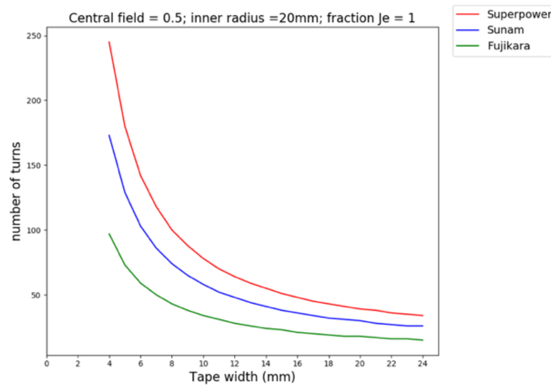

Fig. 6. HTS modelling for Magdrive application

- Magdrive also modelled conventional conducting coils and built a low temperature test rig to explore the effect of lowered temperature on their coil magnetic topology and to validate their models.
- A significant output was a system concept design and preliminary specifications for a cooled superconductive magnetic coil system, able to support a future 'SuperMagdrive' propulsion system, aimed at the market for active debris removal and on-orbit servicing missions.

4.3 Further work & key findings

The 2020/2021 work was continued through a further grant from the UK Space Agency's National Space Technology Programme, in collaboration with the Space Surveillance & Tracking programme. This allowed Tokamak Energy to be brought in as a partner to the consortium, providing the magnet shown in Fig. 4 for partial space environment testing. This is reported on in Section 5. This follow on project 'Supermagdrive ADR (Active Debris Removal)' further confirmed the potential operational conflicts of cooling, energising, and powering a superconducting propulsion system while thrusting.

Although a well-insulated, passively cooled superconducting magnet housing 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 raised the required system complexity volume and mass.

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

This concept design for the magnet element of a SuperMagdrive shown in Fig. 7 includes two co-axial magnetic coils, an external shell, a radiation shield, and two small scale cryocoolers to the right. Power electronics to provide the high current, low voltage energisation of the magnet, and cryocooler drive electronics are shown in red and blue, respectively.

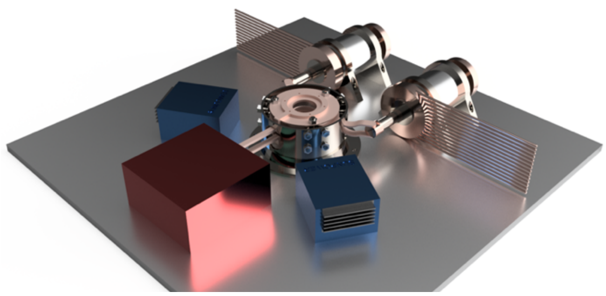

Fig. 7. SuperMagdrive HTS magnet equipment

5. Magnet testing programme

The first step to qualify fusion energy sector HTS magnet technology for space usage is to understand its performance under typical space environment conditions. In 2022 the consortium ran vibration of an HTS magnet in a representative multi coil stack, without current load, and carried out thermal cycling tests in ambient conditions. Before, and after each test the magnet properties in particular resistance and the generated field were measured at 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. 8.

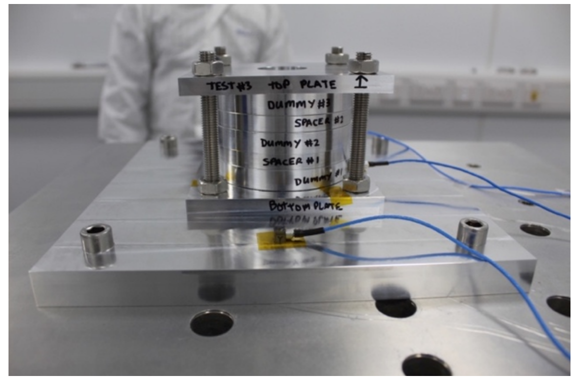

Fig. 8. Representative HTS magnet stack including stainless steel spacers

Thermal cycling in a new oven also at the Harwell Space Catapult was carried out between -30 and +80ºC for 110, ninety-minute cycles over a total of 168 hours.

Testing was successful in that the magnet showed no changes in its electrical characteristics (typified by radial resistance), as measured from applied step current and measured voltage across the coils, and no significant changes in its magnetic properties after both vibration and thermal testing.

A whole system approach has been taken to electrical system design, designing a power system that would not only power the HTS magnet, but the other components of the SuperMagdrive driving circuit, and energy storage to provide the high power requirements of both the plasma generation and initial energizing of the HTS coils. Breadboard hardware has been tested at Magdrive.

6. Roadmap and further work

Rocket Engineering under a small grant for exploratory ideas, from the UKSA worked with In-Space Missions studied to understand how to integrate an HTS magnet system onto a UK built In-Orbit demonstration platform. Raising the TRL through spaceflight of an HTS magnet system, never flown in space to-date, is a core activity regardless of the specific application.

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 payload system power and data budgets 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. Although a cubesat architecture and platform for technology demonstration represents a cost-effective methods of demonstrating many undemanding technologies it is only one option among many for rapid in -orbit demonstration, we identified the In-Space Missions Ada microsatellite platform as well suited to demonstrating this unique technology in space.

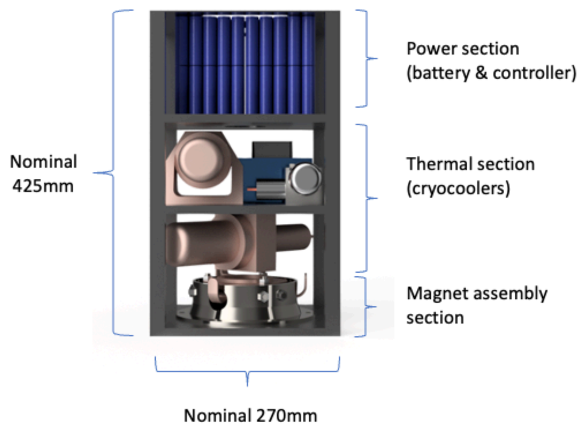

Fig. 9. Concept design for high temperature superconducting space experiment

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.

Further space environment tests followed by in-space demonstration of the magnet operability, catalyses the following roadmap to commercial applications in active debris removal within 5 years:

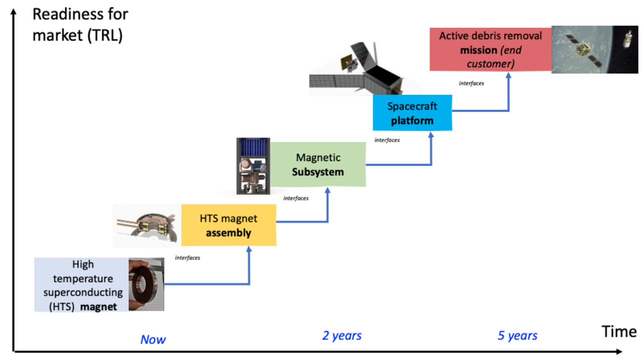

Fig. 10. Astromagnetic systems roadmap for commercial HTS applications.

A spacecraft concept design (see below) and operations concept have also been used to determine constraints on orbits and manoeuvres, and to better understand the operational constraints and system engineering requirements on an operational high temperature superconducting system in orbit.

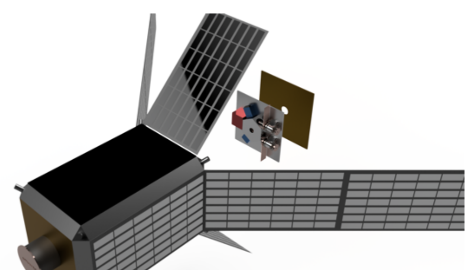

Fig. 11. Debris removal mission concept *(propulsion system shown upper right)*

7. Conclusions

The phenomenon of superconductivity, and how the discovery of high temperature superconductors in the late 20th century has allowed practical materials and applications, in particular high field electromagnets able to operate at temperatures around the boiling point of liquid nitrogen, 77K. Robust high temperature superconducting electromagnets are being manufactured for plasma confinement in nuclear fusion, and the technology transfer into the space sector is being explored. The thrust and I_{sp} of electric propulsion systems can be considerably improved with access to the magnetic fields in the Tesla range that superconducting magnets can support. However no high temperature superconductor has flown in space.

The paper has covered the considerable thermal, mechanical, electrical and magnetic requirements, and the overall system integration challenge which must be mastered to engineer a high temperature superconducting plasma confinement chamber. Using the Magdrive as an example, with active debris removal missions as the target customer, modelling of size mass and power for a concept design and identification of key components has been carried out under UKSA funding. Preliminary testing under space environment vibration spectra, and thermal cycling has been performed, confirming the robustness of the coild technology and manufacturing approach from Tokamak Energy. The design of a in-orbit demonstration experiment aimed at qualifying the technology, determining engineering interfacing issues, and quantifying the commercial impacts of using superconducting magnets in space propulsion and other applications has been made. Although superconducting coils suited to propulsion applications are small, potentially <1kg mass, the system mass required to support their sustained operation in space is much more significant and a realistic platform required to demonstrate ther technology at equipment level is around 100kg.

A key trade-off under evaluation is the most efficient means of cooling a superconducting plasma confinement system: laboratory tests can use immersion in, or cooling loops of liquid nitrogen to assess performance of engineering equipment. This is not practical on the scale of many space missions and instead cryocoolers using solid state conduction are being considered, however their efficiency falls at low temperatures and the electrical power demand to enable superconducting operation and its benefits becomes a key design driver and may determine commercial feasibility when compared to alternative approaches.

Acknowledgements

The authors of this paper would like to thank:

The UK Space Agency's National Space Technology Programme in particular grant funding agreements PF3-008 (2020) and GEI-013 (2021) and project officers Karen Pembridge and Claire Willetts.

Professors Chris Grovenor and Susie Speller at Oxford University and the Centre for Applied Superconductivity for their initial help in assessing superconducting supply options and modelling.

The HTS magnet and Alternative Technology Applications teams at Tokamak Energy (Chris Morris, Sriharsha Venturumilli and Robert Slade).

Stephen Wokes, Chief engineer and Daniele Frollani, Senior engineer at Astroscale.

References

[1] R. G. Sharma, Superconductivity: Basics and applications to magnets. Springer Series in Materials Science, vol 214. Springer, 2021 https://doi.org/10.1007/978-3-030-75672-7.

[2] D. J. Connolly, R. R. Romanovksy, P. Aron, M. Stan, Opportunities for Superconductivity in future space exploration programmes. App. Superconductivity 1 No's 7-9 (1993), 1231-1249.

[3] C. L. Lichtenberg, G. E. Price, M. Nisenoff, High temperature superconductivity space experiment: communications and satellite payload applications, AIAA Paper 96-1058, IAA International Communications Satellite Systems Conference, Washington, USA, 1996, 25-29 February.

[4] R. Battiston, The Anti Matter Spectrometer (AMS-02): a particle physics detector in space. Proc. 29th International Cosmic Ray Conference Pune (2005) 10, pp. 151-172.

[5] A. Kounine, Status of the AMS experiment, Proc. XVI International Symposium on Very High Energy Cosmic Ray Interactions ISVHECRI, Batavia, USA (2010).

[6] C. Bruno, D. Casali. Superconducting materials applied to electric propulsion systems. J Spacecraft & Rockets 41 (2004), 671-676.

[7] M. Collier-Wright, *et*, High-temperature superconductor based power and propulsion system architectures as enablers for high power missions. Proc. ASCEND 2021 conference. AIAA 2021-4105. (2020) doi: 10.2514/6.2021-4105

[8] INASMET-Tecnalia. Superconductive Materials for Electric Propulsion Systems. Final Report, Document N° SCEP-TN7-4854-INAS. (2008). Public summary available at https://artes.esa.int/projects/superconductive-materials-electric-propulsion-systems-scep [page accessed 10/04/2022, last updated 13/03/2013].