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A Magnetohydrodynamic enhanced entry system for space transportation: MEESST

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ABSTRACT

This paper outlines the initial development of a novel magnetohydrodynamic (MHD) plasma control system which aims at mitigating shock-induced heating and the radio-frequency communication blackout typically encountered during (re-)entry into planetary atmospheres. An international consortium comprising universities, SMEs, research institutions, and industry has been formed in order to develop this technology within the MEESST project. The latter is funded by the Future and Emerging Technologies (FET) program of the European Commission's Horizon 2020 scheme (grant no. 899298). Atmospheric entry imposes one of the harshest environments which a spacecraft can experience. The combination of hypersonic velocities and the rapid compression of atmospheric particles by the spacecraft leads to high-enthalpy, partially ionised gases forming around the vehicle. This inhibits radio communications and induces high thermal loads on the spacecraft surface. For the former problem, spacecraft can sometimes rely on satellite constellations for communicating through the plasma wake and therefore preventing the blackout. On the other hand, expensive, heavy, and non-reusable thermal protection systems (TPS) are needed to dissipate the severe thermal loads. Such TPS can represent up to 30% of an entry vehicles weight, and especially for manned missions they can reduce the cost- efficiency by sacrificing payload mass. Such systems are also prone to failure, putting the lives of astronauts at risk. The use of electromagnetic fields to exploit MHD principles has long been considered as an attractive solution for tackling the problems described above. By pushing the boundary layer of the ionized gas layer away from the spacecraft, the thermal loads can be reduced, while also opening a magnetic window for radio communications and mitigating the blackout phenomenon. The application of this MHD-enabled system has previously not been demonstrated in realistic conditions due to the required large magnetic fields (on the order of Tesla or more), which for conventional technologies would demand exceptionally heavy and

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power-hungry electromagnets. High-temperature superconductors (HTS) have reached a level of industrial maturity sufficient for them to act as a key enabling technology for this application. Thanks to superior current densities, HTS coils can offer the necessary low weight and compactness required for space applications, with the ability to generate the strong magnetic fields needed for entry purposes. This paper provides an overview of the MEESST project, including its goals, methodology and some preliminary design considerations.

1. Introduction

1.1. The (re-)entry problem

When a spacecraft enters the atmosphere at high velocities on Earth or elsewhere, the surrounding gas is heavily compressed into a high-temperature, partially ionised state, illustrated in Fig. 1. The temperature in this environment exceeds the operational temperatures of materials commonly used in spacecraft structures like Aluminium or fibre-reinforced plastics. Therefore, in order to protect the spacecraft and its structure, a TPS is necessary. Historically such TPS were and still are implemented through either ceramic or composite tiles as used on the Space Shuttle design, or through ablative heat shields as recently used on SpaceX's Dragon capsule programme.

Both approaches come with very significant drawbacks in the form of design time and cost. Purely physical TPS designs lead to very heavy heat-shield structures due to the necessity of using large amounts of material to absorb or carry away thermal energy from the vehicle during entry. Especially for interplanetary missions, the launch mass of the spacecraft greatly impacts launcher requirements and therefore launch cost. Conventional TPS is not fully reusable and, therefore, must be tailored to each individual mission, bringing significant design, testing and manufacturing overhead in terms of time and cost with them. Especially tiled TPS often require a very high number of unique custom parts, further driving design and manufacturing costs up. Furthermore, currently used TPS technology does not address the issue of radio blackouts during entry phases. The plasma environment during hypersonic entry into a planetary atmosphere inhibits incoming or outgoing radio signals and prevents direct communication with ground stations. This problem is commonly circumvented through the use of separate satellite constellations. The materials used for heat shields is often extremely brittle resulting from use of very porous materials or ceramic composites, leading directly to low resistance to impact or other mechanical damage and leaving the entire spacecraft vulnerable to even slight damage. This was demonstrated in the events of the STS-107 mission as a foam piece shattered a part of the Carbon-Carbon composite heat shield components and claimed the lives of all 7 astronauts on board [2]. The aforementioned TPS of the Space Shuttle orbiters are often referred to as reusable, however even with such tile-based, reusable TPS, a significant part of the heat shield must be replaced after each flight, resulting in higher maintenance cost and long maintenance downtime between flights in case of a fully reusable vehicle [3].

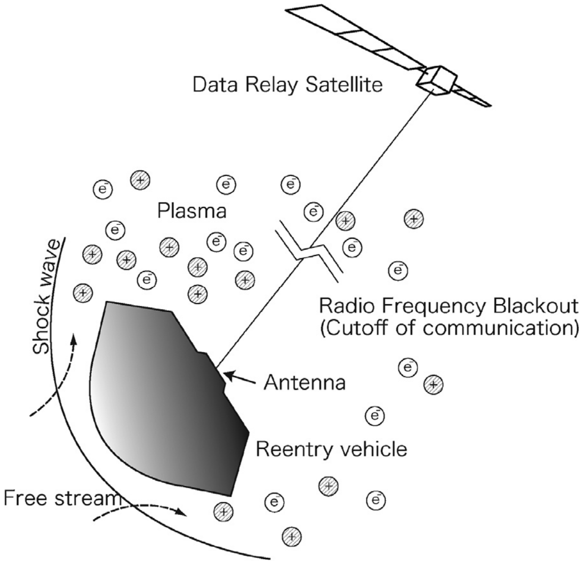

Fig. 1. Illustration of atmospheric entry conditions [1].

2. The MEESST project and consortium: A solution

The MHD Enhanced Entry System for Space Transportation (MEESST) project aims at providing a solution to the previously mentioned problems by applying MHD principles in order to influence the dynamics of the plasma surrounding the spacecraft and reduce thermal contact between the harsh entry environment and the surface materials of the vehicle. As part of the EU Horizon 2020 FET-OPEN programme, the MEESST consortium was formed in order to develop and demonstrate an entry shielding system which is based on MHD principles using HTS technology. This project will first harmonize existing numerical codes for entry simulations and corresponding plasma physics modeling, and then produce a magnet using HTS technology and test it in ground facilities which simulate both Earth's and Martian atmosphere. The project is carried out by a consortium of several institutions and entities in academia and industry, spanning many different fields of expertise.

The von Karman Institute (VKI) of Fluid Dynamics is the consortium's leading entity for experimental studies related to MEESST, especially for topics concerning radio blackout mitigation. The driving force behind the validation of numerical modelling tools, experimental studies of heat flux and radiation characterization in the MEESST project is the Institute of Space Systems (IRS) of the University of Stuttgart, an institution with a great heritage and research output in the field of hypersonic entry systems and electric propulsion technology such as magnetoplasmadynamic thrusters (MPDT) which are based on similar mechanisms as leveraged by MEESST [4]. VKI and IRS bring the capability of replicating the Earth's and the Martian atmosphere, both primary targets for entry systems to operate in, in their plasma wind tunnels. The VKI offers plasma facilities with Inductively Coupled Plasma (ICP) generators delivering powers up to 1.2 MW, whereas the IRS runs several tunnels with plasma generator powers ranging from several hundred KW up to 6 MW. These facilities are capable of operating with air or CO_2, enabling the reproduction of entry conditions similar in composition to Earth's or Martian atmospheres [5,6]. The Plasmatron facility of VKI, which will be used for the radio communication blackout experiments in MEESST, is shown in Fig. 2.

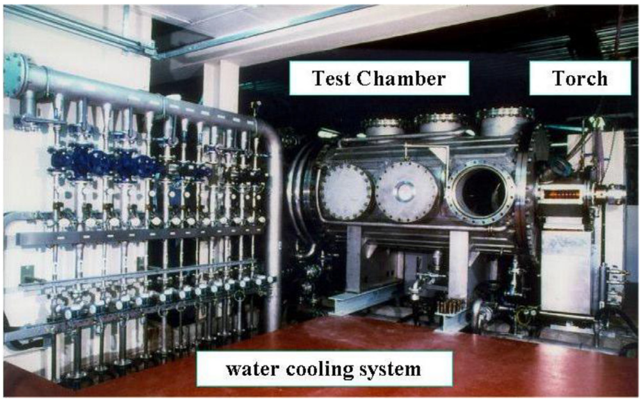

Fig. 2. The VKI 1.2 MW plasmatron facility [7].

The University of Southampton has strong expertise in numerical simulation tools and is the main entity responsible for the development, extension, verification, and harmonisation of numerical tools. The University of Luxembourg and AEDS SARL of Switzerland have strong expertise in modelling and simulating radio blackouts and radiation, respectively, around the spacecraft during entry conditions. The University of Luxembourg is further developing an existing ray-tracing algorithm for simulating radio communications blackouts [8] and validates the consortium's numerical results against experimental measurements of radio blackouts. The HTS-based magnet hardware and the cryogenic system are designed and manufactured by the Karlsruhe Institute of Technology and Absolut System SAS, respectively. THEVA Dünnschichttechnik GmbH provides state-of-the-art HTS Rare Earth Barium Copper Oxide (REBCO) tapes for the project's magnet and contributes to the design of the magnet by performing numerical simulations. The project is coordinated by the Katholieke Universiteit Leuven (KU Leuven) while also heavily contributing to all plasma numerical simulation and validation activities both for the heat flux and radio blackout characterisation. Neutron Star Systems (NSS) UG is responsible for the dissemination and exploitation of the MEESST project outcomes.

3. Principles of operation

The entry environment produces extremely high thermal loads on the order of MW/m^2 on the spacecraft surface. At the highest speeds, the surrounding gas ionizes forming a plasma sheath which prevents radio signals to pass through, leading to a communication blackout which can typically last for minutes. MEESST aims at reducing the thermal loads on the spacecraft structure significantly by applying a strong magnetic field that interacts with the plasma generated by aerodynamic heating during atmospheric entry. The configuration of the magnetic field used is shown in Fig. 3.

The magnetic field influences the dynamics of the plasma around the spacecraft in such a way that the Lorentz force acting on the charged particles of the plasma is directed approximately opposite to the flow direction. Due to the applied force, the distance between bow shock and spacecraft surface is increased and the shock structure is modified [11–13]. In particular, the bow shock is displaced, keeping hot particles of the plasma further away from the spacecraft surface as illustrated in Fig. 4 which shows an experiment with argon as test gas [10]. This can lead to significantly lower surface thermal loads, therefore drastically reducing the TPS requirements. The minimal magnetic field strength which is needed in order to create sufficient impact is on the order of $10^{-}1$ to 1 Tesla. For instance, a value of 1.2 Tesla is used in [11].

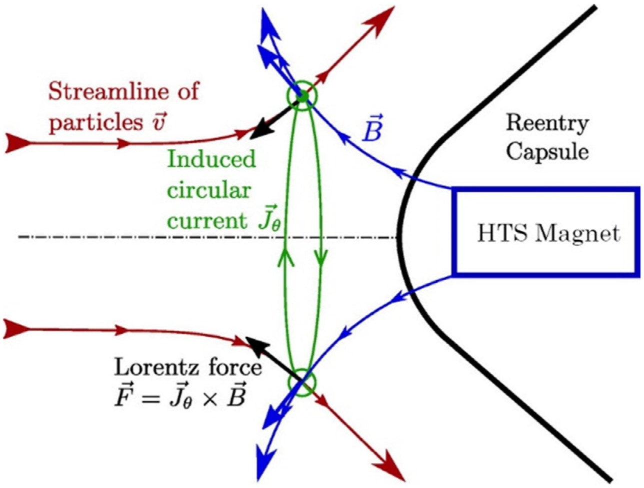

Fig. 3. Magnetic field configuration introduced by the MEESST device [9].

Looking at the history, the first to suggest the MHD heat shield and MHD aerobrake concept was Kantrowitz in [14]. Ziemer and Bush first published an experimental and computational study of the bow shock standoff increase in [15]. Wilkinson [16] and Romig [17] were the first to experimentally demonstrate the decrease in heat transfer with an applied magnetic field. Porter and Cambel [18] showed that the Hall effect strongly diminishes the effectiveness of control. Modern computations were first carried out by Palmer [19] and by Poggie and Gaitonde [20]. More recent heat transfer measurements of heat transfer were published in [21] and [22], where the effect of the B-field shape on MHD heatshield investigated. Numerical simulations of MHD heatshield are also presented in [11,23–25]. More recently, Li et al. n [26] have investigated the effect of Hall parameters on MHD heatshield, showing that such an effect is an important factor limiting the applied magnetic induction strengths for the implementation of the concept. In particular, a strong Hall effect (that would exist for high altitudes and strong magnetic fields) can actually diminish the increase in shock standoff distance. As the Hall parameter is related to the magnitude of the magnetic field, this challenge can be technically solved by seeding conductive particles thus increasing conductiv-

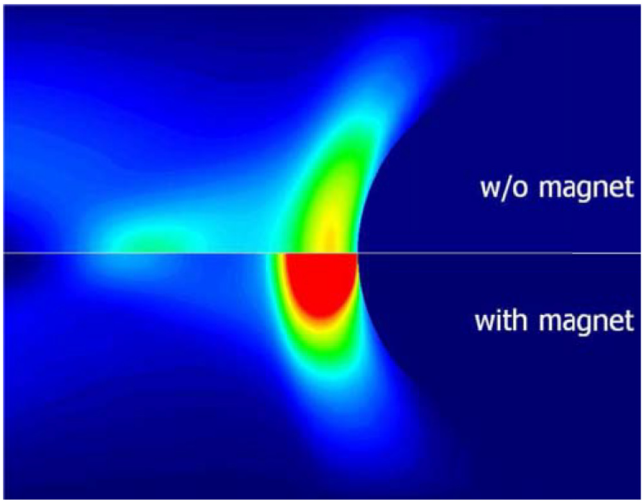

Fig. 4. Effect of an applied magnetic field on the bow shock location on a 50 mm diameter hemispherical probe in Argon plasma at M = 2.1, p = 240±5 Pa, T_e = 17377±2604 K and $n_e = 7{,}38 \pm 0{,}1 \cdot 10^{19}$ m^{-3}. The magnetic field strength immediately in front of the probe was measured to be 0.265 T [10].

ity, so that the system can be operated at weaker magnetic field. An additional point of complexity for high-altitude simulations is due to the high-Knudsen number which limits the applicability of MHD-based approaches, relying on the continuum flow assumption. However, the application of Hybrid Particle In Cell (PIC) or even fully kinetic codes for simulating such flows, even if desirable, is out of the scope of the present project. Within MEESST, the focus is on manufacturing and testing a magnetic shielding device under experimental conditions in the consortium's plasma facilities (IRS PWK1 and VKI Plasmatron) for which the effect of the Hall parameter is expected to be negligeable. The prototype magnet will be tested across a wider range of B-field strengths and plasma flow conditions (in terms of specific enthalpy and Mach number) than any similar experimental campaign performed to date for air and CO_2. The further extension and development of this technology for actual flight conditions will be part of future projects and will require significantly more efforts. In particular, it has yet to be proven that the cost, in terms of weight of superconducting magnets, cooling systems, and power conditioning equipment, is worth the benefit obtained from the MHD system and this project won't provide an answer to that since the prototype that will be manufactured and tested in the consortium's plasma wind tunnels won't be resembling a realistic device for flight. It is too early for MEESST to face this discussion which needs to be tailored to a specific mission scenario and vehicle characteristics. Nevertheless, the testing of our prototype magnet in conditions resembling (re-)entry in Earth and Mars atmosphere's will provide new and unique data to validate the numerical models to be used, at later phases, to study the effects of this kind of technology for actual flight conditions and provide inputs to design a device for which an optimal trade-off of weight, mass and power will be sought/F.

The plasma enveloping the vehicle during entries causes interference with radio waves, leading to a disrupted or temporarily disabled communication with any mission control facilities. The plasma varies strongly in its electron number density over the plasma sheath around the spacecraft and, as a result, radio waves for the purpose of communication are refracted and attenuated when their frequency is close to or lower than the local plasma frequency, causing radio brownout or blackout. Thus far, this critical phenomenon which can in principle jeopardize a whole mission, is hard to predict. MEESST aims at developing reliable numerical simulation tools to predict brownout and blackout conditions and their mitigation for both experimental and flight conditions. To analyze the propagation of EM waves in plasma, the modeling strategies are generally divided in full wave methods and ray tracing methods. Full wave methods, i.e. FDTD, FEM [27], solve the full set of Maxwell equations without approximations, with the drawback of large computational cost. This makes their use particularly disadvantageous for large propagation problems, such as in space entry applications, where plasma is generated in the front part the spacecraft but also largely affects the flow in the wake region downstream, the main region of propagation of communication signal. For this reason, the use of ray tracing methods is particularly indicated to analyze large propagation problems since they are based on approximate solutions of Maxwell equations, reducing the complexity of the corresponding numerical simulation. This is possible considering the cold-plasma approximation that is valid in the wake region of a spacecraft [28]. The first example of application of ray tracing theory to atmospheric entry problems is the work of Vecchi et al. [29]. A preliminary application of ray tracing methods to analyse blackout in Martian atmosphere is the work of Ramjatan et al [30], in which a simplified hybrid CFD/Lagrangian approach has been coupled to a rather basic ray tracing algorithm in order to asses the validity of the proposed analysis model. This approach has been further developed in Giangaspero et al [8] by the use of an extended version of the same CFD solver, for neutral and ionized flows, capable of computing ionization levels in the whole computational domain, with a particular focus on the extended wake region. The numerical strategy for the communication blackout analysis of this project consists of:

1. hypersonic *CFD simulations* at different free stream conditions in order to reproduce atmospheric entry trajectories,
2. computing the *optical properties* of plasma by solving the Appleton-Hartree equation for the specific plasma model;
3. application of *ray tracing* for propagating the EM waves through plasma.

This methodology is implemented in the BORAT code. The latter can be easily interfaced to arbitrary hypersonic/entry flow solvers, from which the CFD solutions are used as an input for the ray tracing analysis. An example of a ray-tracing analysis can be found in Fig. 5, where this type of technique was applied to the "Schiapar-

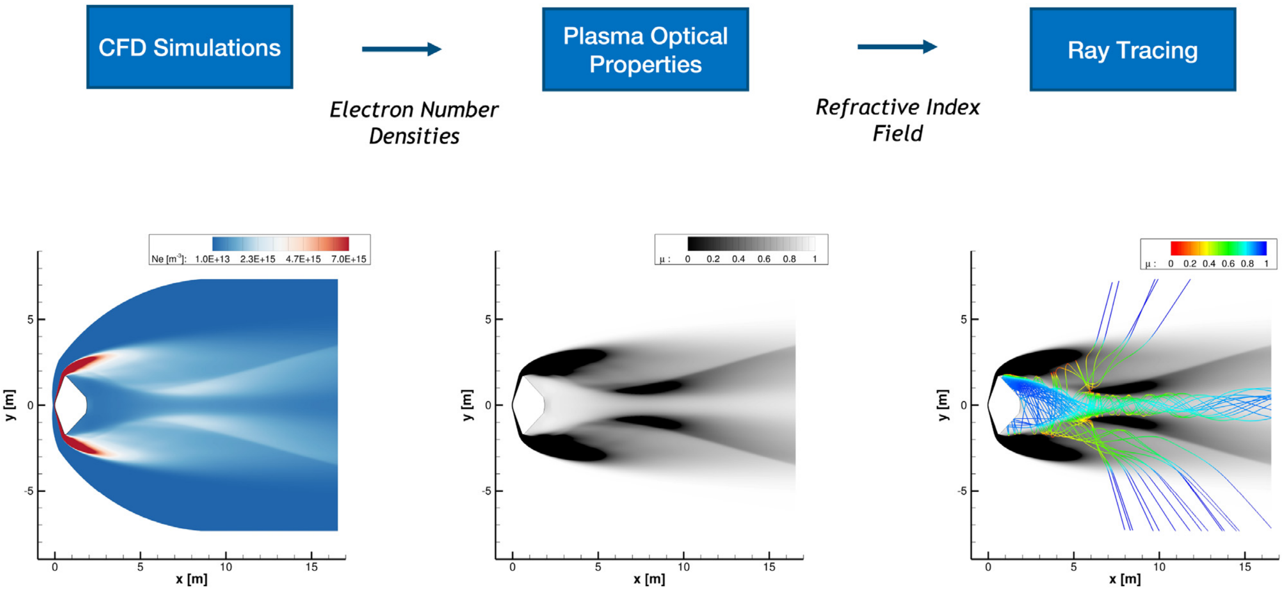

Fig. 5. An example of a radio communication analysis using a ray-tracing-based method on the case of the ExoMars Lander capsule. Note the contrast of different refractive indices μ within the plasma, guiding the radio waves (curved rays) and leading to a brownout [8].

elli EDM" Mars landing craft which was deployed by the Trace Gas Orbiter [8]. This example shows a brownout case where only a few rays escape the plasma cloud. Applying a magnetic field displaces the bow shock in front of the vehicle and opens up a "magnetic window" with a reduced electron number density, allowing radio signals to locally penetrate the plasma surrounding the spacecraft and enabling communication during this critical phase. The improved ray-tracing-based techniques promise to model accurately the wave propagation in magnetized plasmas allowing predictions of designs and take advantage of the magnetically modified plasma flow to enable radio communication with ground stations or relay satellites. The ray-tracing algorithm will also include the prediction of the signal quality and the far field radiation for brownout cases.

4. HTS as an enabling technology

The construction of a magnet able to provide a magnetic field strength on the order of several Tesla, as required for the effective operation within an MHD-enhanced entry system, is only possible with exceedingly heavy designs that take up large volumes and draw extremely high power with conventional conductor technology and would reduce the benefit of any MHD-based entry system. Instead, HTS offer the key to access all benefits without requiring excessive mass and volume and to reduce also launch and development cost penalties. Superconductors provide very high current densities that allow for developing compact and light electromagnets that can be operated onboard spacecraft and generate the necessary magnetic field strength. HTS also enable operation at higher temperatures for similar field strength compared to LTS. This allows for significant simplification and compaction of the cooling system, which would be overly sized otherwise. However, even with the use of HTS, the cooling system necessary is not negligible.

4.1. A brief history of superconductors

In 1911 the Dutch physicist Heike Kamerlingh Onnes discovered superconductivity by cooling mercury metal to extremely low temperature with the help of liquefied Helium and observing that the metal exhibited zero resistance to electric current. In the following years, many other metals and metal alloys were found to be superconductors at temperatures below 23 K and subsequently became known as Low-Temperature Superconductor (LTS) materials. Since the 1960s a Niobium-Titanium (NbTi) alloy has been the material of choice for commercial superconducting magnets. More recently, a brittle Niobium-Tin intermetallic material (Nb_3Sn) emerged and is now primarily used for magnets whose field strength exceed the upper critical field strength of NbTi. An overview of superconductors available in sufficiently long lengths for magnet applications, including NbTi and Nb_3Sn, can be found in Fig. 6. Later, the discovery of oxide based ceramic materials that demonstrated superconducting properties as high as 35 K was followed by the announcement by C. W. Chu on a Cuprate-based REBCO superconductor, $YBa_2Cu_3O_{7-\delta}$ (YBCO), remaining superconducting above 77 K, the boiling point of liquid nitrogen (LN_2). This discovery made superconductors far more suitable for wider use in industry since they could now be operated by using liquid Nitrogen as cooling medium, a readily available fluid that is already widespread in several industries. However, while REBCO superconductors may be op-

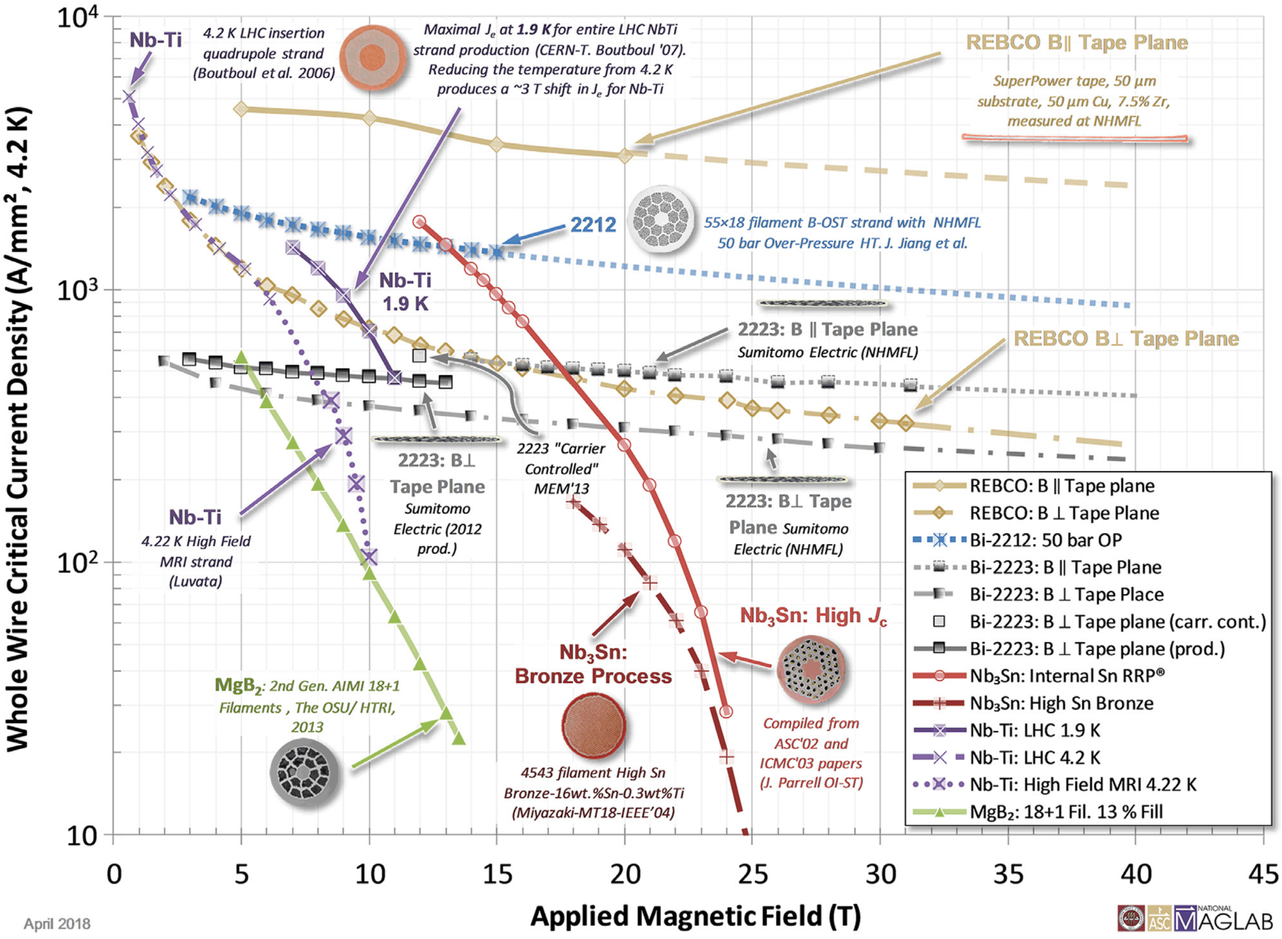

Fig. 6. Overview of various superconductors available in long lengths for different current densities and applied magnetic field strengths [33].

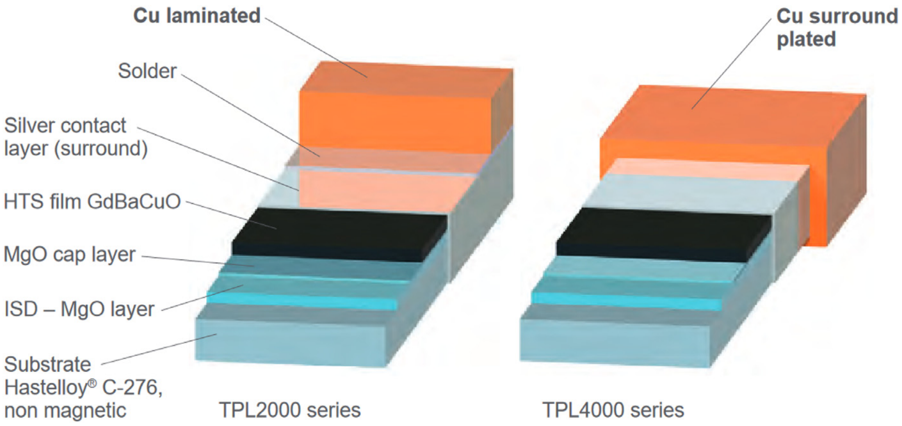

Fig. 7. Coated Conductor architecture as developed and used by THEVA [37].

Fig. 8. A Mars Transfer Vehicle of the Mars Design Reference Mission 5.0 concept study of NASA [40].

erated using LN_2 in various applications like power lines, magnet applications typically require operating temperatures lower than 30 K which cannot be achieved with LN_2-based cooling systems. In the case of the necessary high field strength and current density magnet application for the MEESST device, more sophisticated cryogenic cooling systems are necessary [31,32].

Since the discovery of HTS materials in the 80s, extensive research worldwide has uncovered many more oxide-based superconductors with potential manufacturability benefits and critical temperatures as high as 135 K. A superconducting material with a critical temperature above 77 K today is known as a HTS, despite the continuing need for cryogenic refrigeration for any application [34]. Since the development of YBCO in 1987, the development of long flexible tapes with thin layers of Cuprate-based superconductors called coated conductors (CC) has been a success story of sophisticated processing and scale-up efforts. These CCs are promising for superconducting magnet applications because of their high critical current density with a low dependency on the external magnetic field, good mechanical properties, and reasonable cost, which offer opportunities to develop ultra-high-field magnets [35,36]. Today, CCs are produced by means of a technologically advanced processes. THEVA Dünnschichttechnik GmbH, for example, exploits a scalable technique known as Electron Beam Physical Vapour Deposition to produce a multi-layer tape described in Fig. 7.

4.2. Industrial maturity of 2G high-Temperature superconductors

REBCO coated conductors are known as second generation, or “2G” HTS wires, as they offer improved mechanical properties and improved performances in magnetic fields compared to their predecessors, the first-generation Bismuth-Strontium-Calcium-Cupper-Oxide compounds. The most common REBCO compounds are Yttrium-, Gadolinium- or Samarium-based.The HTS industry has leveraged these advances in production techniques to achieve economies of scale, with a worldwide production capacity of 1,000km/year of HTS tape. THEVA Dünnschichttechnik GmbH has developed production capacity of type 2G superconductor tape of 120 km/year. With companies already achieving high throughput, relatively low material costs, and a high yield, type 2G superconductors have reached industrial maturity. A continuing increase in HTS demand is expected and with it a continuing decrease in production costs, enabling access in more markets including the aerospace field, as targeted by MEESST technology [38].

5. Conclusion

The MEESST project could solve many of the downfalls of currently used ablative and semi-reusable entry systems. The MHD-based technology which is being developed within the project can significantly decrease weight and volume requirements of current TPS through influencing the plasma formed around the spacecraft during atmospheric entry. Compared to conventional TPS that comprises up to around 30% of the total spacecraft mass as in the case of the NASA InSight Lander [39], MEESST can provide a much lighter, more compact, and more cost-effective method of protecting the spacecraft, while also being easier and faster to design. Especially on interplanetary missions where increased vehicle mass leads to steep increases in launch vehicle requirements and launch costs, this could be a great benefit. Lower mission costs in turn would allow for a greater mission throughput with any agency or commercial entity exploiting the benefits of MEESST technology.

Due to less reliance on physical TPS on the spacecraft, the risk associated with mechanical impacts or other mechanical damage to the outside of the TPS is also decreased, a very important consideration especially for human-rated spaceflight applications as they are planned for the next decades by several space agencies and even commercial entities. MEESST can achieve this by leveraging MHD to reduce heat flux by a considerable margin, with up 30% lower heat flux being experimentally achieved previously in a test using an Argon atmosphere at IRS [10]. This is set to be further experimentally examined with more accurate representations of the conditions in the atmospheres of both Earth and Mars within the MEESST project through experimental capabilities of the VKI and the IRS.

Furthermore, MEESST technology addresses the issues of radio communication blackouts both experimentally, with tests to be conducted at VKI, and numerically, by greatly improving capabilities in numerical prediction and mitigation of the blackout phenomenon via novel ray-tracing methods and enhanced plasma models including the effects of magnets. The modelling and testing efforts for predicting and mitigating radio blackout will potentially also be beneficial to applications such as radar imaging, surveillance, and GPS navigation, all requiring accurate knowledge of EM signal propagation characteristics through plasmas in the ionosphere. MEESST aims at making the shift towards more reusable and far more cost-efficient entry systems. The project is currently far into the preliminary research and design phase and will conclude in March of 2024. This interdisciplinary project will set a first step to establish a new technology involving plasma, chemistry, electromagnetics, radiation, superconducting materials, cryogenic systems and will therefore potentially impact several academic communities in science and engineering. MEESST's disruptiveness lies in developing new generation lightweight magnets for space applications and in the overall interdisciplinary research approach. With it, MEESST signifies a multiplicator as space systems other than entry-related systems will positively benefit from its outcomes, including radiation protection for manned space flight (fundamental for future Mars missions and spacecraft such as Mars Transfer Vehicle concepts as shown in Fig. 8), advanced MHD-based propulsion systems like M2P2 [41], electric propulsion with MPD thrusters and any other device making use of applied magnetic fields. In the field of electric propulsion specifically, the SUPREME project aims to integrate HTS electromagnet technology with existing applied-field magnetoplasmadynamic thruster (AF-MPDT) technology such as the SX3 thruster of the IRS as pictured in Fig. 9. La Rosa Betancourt et al. [42] MEESST represents the development of new impactful technology that is applicable not only to entry systems, but to many fields and systems in spaceflight and beyond.

Fig. 9. The SX3 AF-MPDT thruster of the IRS within its large applied-field coil [43].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Andrea Lani: Conceptualization, Funding acquisition, Methodology, Project administration, Software, Supervision, Writing – original draft, Writing – review & editing. **Vatsalya Sharma:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Vincent F. Giangaspero:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Stefaan Poedts:** Funding acquisition, Project administration. **Alan Viladegut:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision. **Olivier Chazot:** Funding acquisition, Project administration, Resources. **Jasmine Giacomelli:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Johannes Oswald:** Data curation, Formal analysis, Investigation, Methodology, Visualization. **Alexander Behnke:** Data curation, Formal analysis, Investigation, Methodology, Visualization. **Adam S. Pagan:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization. **Georg Herdrich:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation. **Minkwan Kim:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Writing – original draft, Writing – review & editing. **Neil D. Sandham:** Data curation, Formal analysis. **Nathan L. Donaldson:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Jan Thoemel:** Conceptualization, Methodology, Software, Supervision, Validation. **Juan C.M. Duncan:** Project administration. **Johannes S. Laur:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Sonja I. Schlachter:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Rainer Gehring:** Resources, Project administration. **Matthieu Dalban-Canassy:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Julien**

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