STATUS OF DEVELOPMENT OF A DEORBIT DEVICE BASED ON ELECTRODYNAMIC TETHER TECHNOLOGY IN THE E.T.PACK PROJECT

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ABSTRACT

The Electrodynamic Tether technology for PAssive Consumable-less deorbit Kit (E.T.PACK) is a FET-OPEN project running from March 2019 to November 2022. Its main goal is developing up to technology readiness level equal to 4 an ElectroDynamic Tether Device (EDT-D) for deorbit applications. E.T.PACK's consortium has recently finished the design phase of an EDT-D that is able to carry out autonomously the detumbling, pointing, tether deployment, and deorbit phases. It also includes autonomous navigation and collision avoidance capabilities. The critical scientific and technological activities carried out in E.T.PACK include the development of a deployer mechanism for tape-like tethers, minituarized avionics system, three types of active electron emitters, a low-work-function coating for passive electron emission by the tether itself (the so-called low-work-function tether), a hollow cathode thruster, and a photon-enhanced thermionic emission device. These last two space devices are unrelated to the EDT-D but maintain strong synergies with the main stream of the project. Simulation software on EDT mission analysis have been upgraded to incorporate latest results on tether technology and modelling. The software was used to support the design of the EDT-D and define requirements of critical elements for the avionic system and the tether in-line damper among others. The E.T.PACK consortium's roadmap considers a follow-up 2-year project to increase the maturity of the device and make a demonstration flight by the end of 2024 from an initial orbit of altitude equal to 600 km at medium inclination. Its main goals are testing critical EDT technologies and show that they can reduce the natural deorbit time two order of magnitudes from that orbit. The EDT-D may be the precursor of a full-scale commercial deorbiting device to be used for end of life disposal.

Keywords: Space Tethers, Deorbit Technologies, Electron Emitters.

1. INTRODUCTION

Electrodynamic tethers (EDTs), considered since a long time ago a promising technology for deorbiting space debris from Low Earth Orbit (LEO) [4, 2, 30, 15], recently passed some important milestones. Firstly, several missions have been carried out within the last few years like the Tether Electrodynamics Propulsion CubeSat Experiment (TEPCE, 2019)[3], the demonstration of the Terminator Tape Module (2019)[25], the DEorbiting SpaceCraft using ElectrodyNamic Tethers (DESCENT, 2020) [31], and the Miniature Tether Electrodynamics Experiment (MiTEE, 2021)[1], led by the Naval Research Laboratory, Tether Unlimited, York University, and University of Michigan, respectively. These experiments are different to the ones carried out in the 1990s in the sense that set the actual trend towards miniaturization and compactness in EDT technology. Secondly, after a hiatus of 21 years since the fourth International Conference on Tethers in Space (TiS) in 1995, tether community organized again the TiS conferences in 2016 (Michigan) and 2019 (Madrid), and scheduled the next one in 2022 (Toronto). Thirdly, and after the disruption produced by the bare tether concept in 1993 [19], the robustness, simplicity, and performances of EDT were improved by substituting old wires and multi-strand tether designs by tape-like tethers [8] and introducing new concepts like the Low-Work-Function Tether (LWT) [27, 16] and the bare-photovoltaic tether [22].

Unquestionably, the raising of the international awareness about the space debris problem is also contributing to the development of EDT technology. The sustainable use of the LEO environment requires, in addition to active debris removal mission to clean actual congested orbits, the deorbiting of the satellites at the end of mission [21]. Conventional propulsion technologies, like chemical and electric thrusters, can deorbit satellites with a high reliability, but their need for propellant, or propellant and power, are major drawbacks. In principle, EDTs are excellent candidates for S/C deorbiting because they fulfill all critical requirements [15]: (i) be a small fraction of the S/C mass, (ii) deorbit fast (typically well below 1 year), (iii) be passive, (iv) prevent collisions, (v) decrease the area-time product, (v) allow scalable design, and (vi) be effective in the LEO congested orbits. Furthermore, several missions demonstrated the basic principles of EDTs, including the generation of drag and thrust in the Plasma Motor Generator mission in 1993 [6]. However, it is necessary to raise their Technology Readiness Level (TRL), and prove that tethers can be used routinely in space missions with a high reliability and in a safe manner.

The European Commission took a step towards increasing the TRL of EDTs and funded with 3M€ the FET-OPEN project entitled *Electrodynamic Tether technology for PAssive Consumable-less deorbit Kit* (E.T.PACK). Running from March 2019 to Novemeber 2022, its main objective is to develop a deorbit device and related software based on EDT technology with TRL 4 by the end of 2022. Its status and main achievements are explained in Sec. 3. However, since many recent progresses are not well-known outside the specialized tether community, we first discuss briefly in Sec. 2 the state-of-the-art of EDT technology. The conclusions and roadmap of the consortium are summarized in Sec. 4.

2. STATE-OF-THE ART OF ELECTRODYNAMIC TETHERS

Understanding the potential impact on space debris mitigation and remediation of EDTs requires updated information on tether capabilities. An example is our current knowledge on the vulnerability of EDTs against impacts by small debris, an important issue pointed out for cylindrical tethers and multi-strand tethers in 2006 [12]. Nowadays, we known that an EDT with a tape-like cross sections offers better performance (for instance lower deorbit times) due to its larger perimeter and has a survival probability of about one and a half orders of magnitude higher than a round tether of equal mass and length[8]. Consequently, typical lengths, widths and thicknesses of state-of-the-art EDTs are in the order of a few kilometers, a few centimeters and several tens of microns. This is very different from the 20 km-long and round (a few mm of diameter) tethers used in the Tethered Satellite System 1 and 1R, and Small Expendable Deployer System 1 and 2 flown in the 1990s. Therefore, it is recommended to incorporate such an important progress on EDT technology to international guidelines, that still defined EDTs as objects with several *thousand meters in length and a few millimeters in diameter* in 2019 [7].

Regarding the electric contact with the ambient plasma, state-of-the-art EDTs reach a steady current by capturing electrons passively (bare tether concept [19]) and emit them back to the plasma by using active electron emitters. However, it has been recently proposed to coat a tether segment with a low work-function (low-W) material that emits the electrons passively by using the thermionic [27] and the photoelectric effects [16]. Similarly to a drag augmentation device, a LWT would deorbit spacecraft in a totally passive manner and without using any consumable. Instead of the aerodynamic drag, which is inefficient at LEO orbits congested with space debris (above 800 km of altitude), the LWT takes advantage of the magnetic drag and reduces drastically the area-time product. Although it is unclear whether a coating with a low enough work function (W) is feasible with actual ceramic materials (see Sec. 3), the historical evolution of low-W materials suggest that such achievement may not be far (see Fig. 2 in Ref. [17]).

Interestingly, EDTs can also benefit from photovoltaic technologies. From several decades ago, it has been proposed to use a power supply to reverse the natural direction of the electric current and produce thrust instead of drag in LEO (see for instance Ref. [19] and references therein). Another example is the ElectroDynamic Debris Eliminator (EDDE) [10, 13] that involves two satellite end bodies connected by multiple 1-km long tether segments and thin-film solar arrays distributed along the length. In LEO, such a power supply allows to drive a higher current during the deorbiting maneuver or even to produce re-boost. Recently, the combination of bare EDT and photovoltaic technology was revisited by proposing a bare-photovoltaic tether. Instead of solar arrays intercalated along the tether length or a power supply onboard the satellite, a segment of the tether itself is manufactured with thin film solar cells and current and voltage profiles were computed self-consistently throughout the full tether length [22]. The detailed analysis along such a bare-pv tether showed that the tether-to-plasma bias induced by the pv-segment makes possible to have simultaneously a compact and autonomous deorbit device based on a consumable-less active electron emitter, like a thermionic emitter (TE) or an electron field emitter (EFE), while reaching moderate current levels. Therefore, there are good perspectives for the next development of a free of consumables and fully autonomous EDT-based system.

3. STATUS OF THE E.T.PACK PROJECT

Since the development of an EDT-D represents an important technological challenge, the E.T.PACK project has diversified its activities to mitigate the risk. As shown in Table 1, E.T.PACK's team is working on three different types of electron emitters to be combined with a bare electrodynamic tether (BET). In parallel, a scalable coating based on the $C12A7 : e^-$ electride [24] for an LWT is in progress. Functionalities and performance of the EDT-D have been analyzed through simulations, which

Table 1. E.T.PACK activities on electron emission. Acronyms: Bare Electrodynamic Tether (BET), Low-W tether (LWT), Hollow Cathode Emitter (HCE), Electron Field Emitter (EFE), Thermionic Emitter (TE), Design (D), Manufacturing (M), and Testing (T)..

Tether Type	Cathodic Contact	Expellant	Power	E.T.PACK Activity
	HCE	Yes	Low	D,M,T
BET	EFE	No	High	D,M,T
	TE	No	High	T
LWT	Coating	No	No	D,M,T

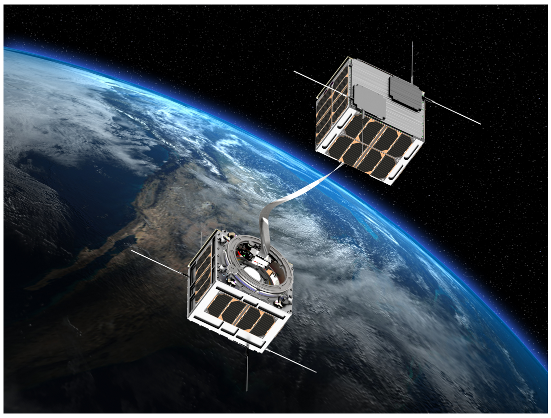

Figure 1. Sketch of E.T.PACK's deorbit device.

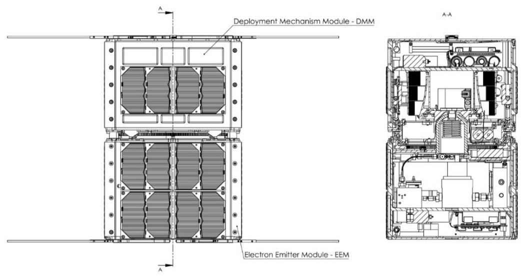

Figure 2. Detail of E.T.PACK's deorbit device.

required an important effort on software development. Dedicated software was also produced to study the current exchange (electron collection and emission) between cylindrical and tape-like EDTs and the ambient plasma. Synergies among partners and cross-fertilization of ideas have been also promoted by including two activities that are not related to the EDT-D but with the $C12A7 : e^-$ electride: the development of an electrothermal thruster and a Photon-Enhanced Thermionic Emission (PETE) device. The next sections summarize the status of these activities and the most important results achieved since March 2019.

3.1. The deorbit device

The flagship result of E.T.PACK is the EDT-D, a deorbit device with TRL 4 for a future demonstration mission. As shown in Figs. 1 and 2 the EDT-D has two modules. The *electron emitter module* host a hollow cathode emitter (HCE) and related expellant system (see Sec. 3.3), whereas the *deployment mechanism module* includes all the elements that are necessary to extract the tether during the deployment phase. The team has completed recently the design phase [23], the detailed model of the system has been generated, and the functionalities and performances have been validated via simulations. The manufacturing plans have been generated and the mechanical parts are currently under production. The main avionics components have been procured and the electrical integration have started. The basic software has been implemented in the on-board computer and the team is currently developing the unit drivers. First version of the breadboard is foreseen by mid summer 2021.

The designed EDT-DD is fully representative of a future commercial product. It includes all the elements that are needed for detumbling the S/C, deploy the tape-tether along the local vertical, and complete the deorbit maneuver by using the Lorentz drag. Key elements of the EDT-DD are a tape-tether with a total length of 500 m, the HCE and its expellant system, the avionics system that includes the on-board computer, torque rods, coarse Sun sensors, and GNSS receivers, and the deployer mechanism. The EDT-DD operates autonomously and can send telemetry and receive telecommands from the ground. The lateral faces of the two modules incorporate small solar panels that provide power to the electronics. Another important feature is that both modules incorporate GNSS receivers and IMUs. Such a design solution, together with the known length of the tether that acts as a geometric constraint, will provide very valuable information on the position of the two modules and the tether during the deorbit maneuver. In case a collision warning is triggered, a collision avoidance maneuver will be possible by switching on/off the tether current. On the other hand, the total volume and mass of the EDT-D are 12 U and 24 kg, respectively. Although the tether length of a future commercial product will be larger (a few km), we expect that the mass and volume of the deorbit device will be similar because most of the elements will remain the same. Tether mass and volume represent a 5% and 3% of the total mass and volume of the EDT-D.

Some critical elements of the EDT-D has been already investigated in more detail by developing breadboards. An example is an in-line damper that helps to keep bounded the amplitudes of the tether oscillations around the local vertical. With size around $50mm \times 35mm \times 10mm$, it works passively and in similar fashion to a dog leash. Breadboards of key elements of the deployer mechanism has been also manufactured and tested (see Sec. 3.2). Regarding the attitude control equipment, simulation software were developed to verify through Monte Carlo analysis that the selected components of the EDT-D accomplish the requirements of the mission. Due to its importance, the attitude dynamics of the EDT-D before the deployment (detumbling and pointing phases), the deployment, and the deorbit maneuver, has been investigated deeply through simulations. These phases have different time scales covering from seconds (pointing before deployment) and minutes (tether deployment) to several days (detumbling) and around a month (deorbit maneuver). The applied forces for each phase have also disparate magnitudes because they include the typical perturbation forces at LEO, the thrust provided by a cold gas during the tether extraction, and the Lorentz drag during the deorbit. It was found that besides magnetic actuators, additional elements should be added to the EDT-D to guarantee the robust and reliable operation of the device during its full mission.

3.2. Deployment mechanism

Two different architectures of the deployer mechanism (DM), here named #1 and #2[1], were designed and analyzed. Breadboards were also constructed to test the ability of the mechanical system to extract the tape-like EDT and handle different thicknesses of the tape. The 500-m long tether of the 12U EDT-D is indeed made of different segments that serve various functions: a few-meters of insulated tape is followed by a 400m x 40µm bare Aluminum tape and by a $\sim$90m x 50μm non-conductive tape. After carrying out trade-off analyses, configuration #2 was selected for the EDT-D because the tether spool is stationary and it yields a cubic-like shape for the EDT-D that is more suitable for potential customers.

A key element of the DM is the motorized drive pulleys assembly that extracts the tape from its spool and force it to follow a prescribed deployment profile, i.e. tether length versus time (see Fig. 3). In fact, an important simulation effort was carried out to find optimal deployment maneuver in terms of initial pointing direction of the EDT-D and tether length profile determination. One of the target was to leave the tether aligned with the local vertical at the end of the deployment. Regarding experimental activity, it has focused thus far on constructing two different configurations of spring-loaded, motorized drive pulleys assembly and improving a 3D printed laboratory breadboard of the whole DM.

The 3D printed breadboard was at first manually operated to prove the validity of the DM design and is now being motorized to operate in a computer-controlled deployment mode. The design of the deployer mechanism was also completed and the construction has already started. Short-distance deployment maneuvers have also been conducted by using the friction-less table (i.e., the SPARTANS facility at the University of Padova) [26]. Figure 4 shows a snapshot of a deployment test carried out over the 2m x 3m glass table with the spacecraft mockup suspended by air-pads, propelled by gas thrusters and with the tape deployment controlled by the drive pulleys in configuration #1 [11].

[1]Due to IP-related issues, details about the DM cannot be disclosed

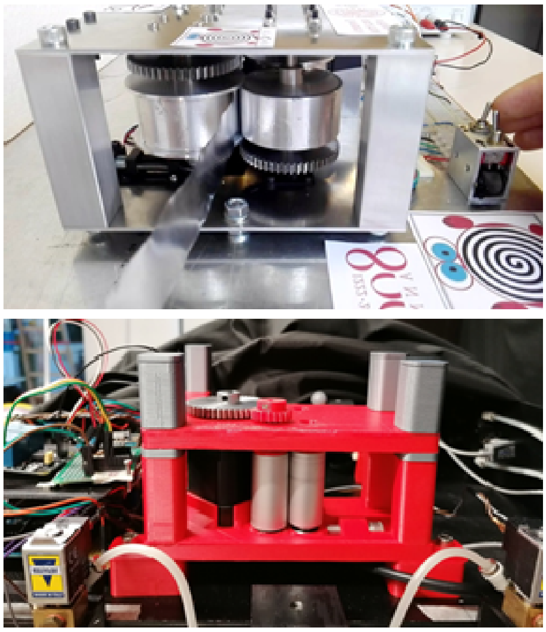

Figure 3. Drive pulleys assembly breadboards. (a) larger-diameter configuration and (b) smaller-diameter configuration.

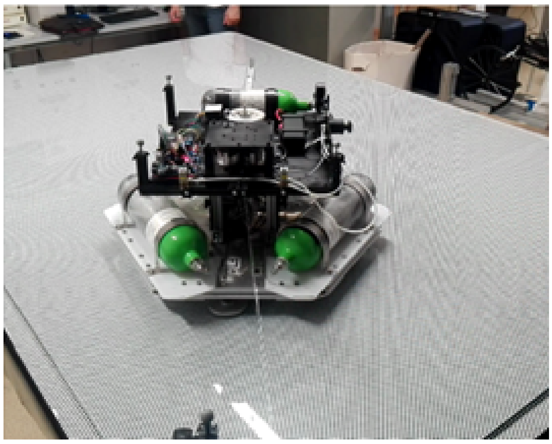

Figure 4. Snapshot of the short-range deployment test conducted on the friction-less table (i.e., SPARTANS facility at the University of Padova) with configuration #1 of the drive pulleys assembly.

3.3. Electron Emission

As shown in Table 1, E.T.PACK's team is working on three electron emitter technologies to be combined with a bare electrodynamic tether. The baseline design is a heater-less hollow cathode with a $C12A7 : e^-$ emitter operated with krypton gas, which is being evaluated for currents between 0.3 and 0.5 Amps, as required for the EDT-D (see top panel in Fig. 5). The hollow cathode is jointly developed with a custom propellant supply system which includes all necessary components from filling valve to storage tanks to pressure reducer and passive flow control and is small enough to be integrated into the *electron emitter module* of the EDT-D shown in Fig. 2. Another electron emitter that is being considered is a cold Electron Field Emitter (EFE) based on carbon nanotubes (see bottom panel in Fig. 5). This design was recently evaluated within a 1400 h endurance test and has shown good emission characteristics with acceleration voltages below 1 kV, a power demand of roughly 1 W/mA and an extractor efficiency of up to 90% [28]. Preliminary studies on a simple gridded Thermionic Emitter (TE) based on a barium oxide dispenser cathode were also conducted [29]. Although the EFE and TE currently seem not to meet the requirements of the EDT-D due to power constraints, they could be valuable candidates for other types of tether technologies using thin-film solar cells [22] or if a potential customer of the EDT-D could provide power and the actual autonomy requirement of the EDT-D is relaxed.

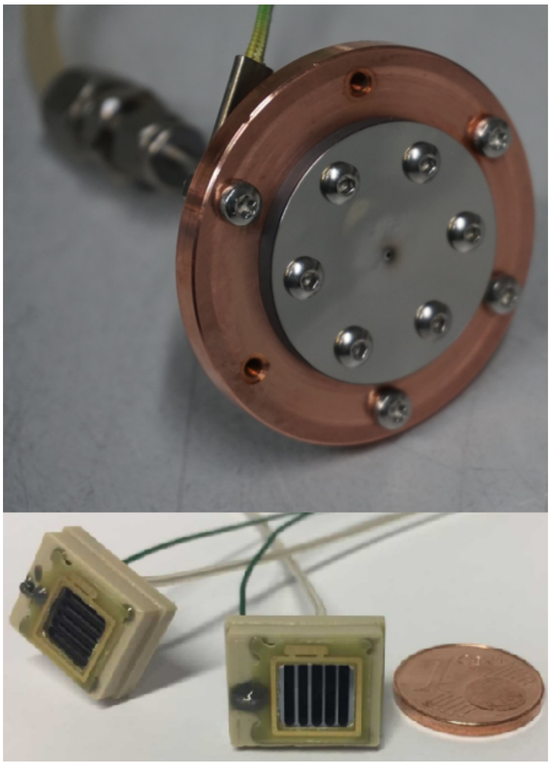

Figure 5. Hollow Cathode Emitter (top) and Electron Field Emitter (bottom)[9].

After making trade-off analysis, the $C12A7 : e^-$ electride was identified as the most promising material for LWT applications. This cage-structured material was prepared in the E.T.PACK project by melting CaO and Al2O3 in ratio of 12:7 followed by milling or by direct synthesis as fine powder. For substitution of the O2- ions in the cages a reductive heat treatment is needed. The resulting electron concentration is influenced by the temperature, dwell time and atmosphere during the heat treatment. Finally, C12A7 powder with a specific surface of 5.8 m^2/g ($< 2\mu m$ particle size) was synthesized. This powder was used to prepare screen printable pastes, which were printed on Titanium substrates in combination with a metal braze. By optimizing the synthesis, paste preparation and printing technique, a C12A7 coating of less than 30 μm was achieved (see Fig. 6). Low-ohmic contact between C12A7 particles and Ti substrate is resulted by joining under vacuum at a temperature of $\sim$1000 °C. The work function of the C12A7 coated Titanium was tested under vacuum up to a temperature of 900 °C. In this first test, a current density in the range of $\mu A/cm^2$ was measured. In the next year, it will be improved by optimization of the metal contact between C12A7 particles embedded in the metal filler on a thin foil. This coating technique, which is different to the pulsed laser deposition and magnetron sputtering techniques already considered for LWT manufacturing [14], is expected to be scalable to reach km-long LWT.

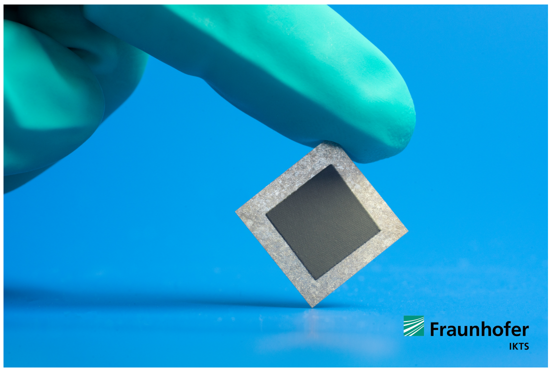

Figure 6. Sample of LWT

3.4. Software development and simulation

The hardware design and testing has been performed in parallel to the generation of software packages specialized for the simulation of the dynamics of an EDT system and its control. Due to its importance, three different partners have developed and improved their numerical tools to simulate tether dynamic and performance as well as the avionics system. Such a strategy allowed to cross-verify the implementation of the software and also study the future in-orbit demonstration of the EDT-D with models of different complexity. Besides the activities on the avionics summarized in Sec. 3.1, the software FLEX and BETsMA, originally developed under the previous EC FP7-SPACE project *BETs* [20], were used to investigate tether performance and dynamics as well as the requirements for related elements like the in-line damper and the electron emitter, among others.

Additionally, a simplified version of BETsMA v2 has been made available in a public website [18] (see Fig. 7), where EDT simulations results can be requested via a friendly graphical user interface. The software can be used to determine the performance of bare EDTs with electron emitters and LWT in both deorbit and re-boost scenarios. One of its goal is giving access to non-tether experts to a tool for making preliminary analysis of missions using EDT technology. Users with access to the service can define the mission (S/C mass and initial orbit) and the properties of the tether system (tether type and geometry) by using the on-line interface. The simulations run remotely and the results are sent by email together with some programmes to plot the results.

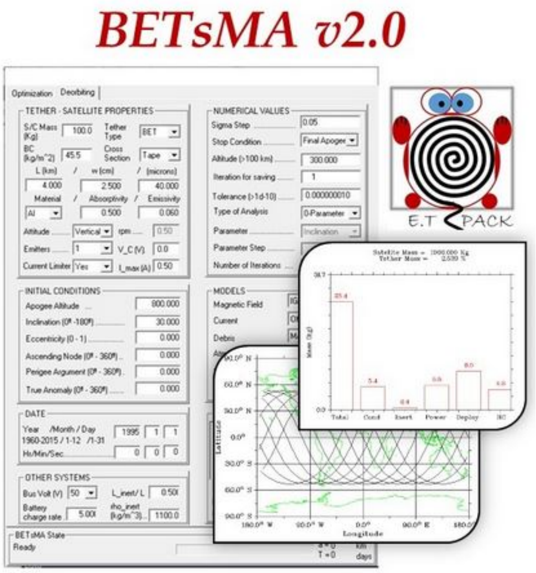

Figure 7. The BETsMA v2.0 software. On-line service of the software is available at [18]

Regarding tether modelling, two Vlasov-Poisson solvers to study the current exchange between LWT and the ambient plasma have been developed. The first solver is restricted to EDTs with cylindrical cross-sections. It has been used to generate a broad database with current-voltage characteristic curves as a function of five dimensionless parameters that involves tether design considerations (like work function and size), tether operation conditions (temperature), and ambient-related variables (plasma density and temperature). The database has a direct application to both LWT modelling and plasma diagnostics (Langmuir and emissive probes). It will be made available at the website of the project by the end of May 2021. The second Vlasov-Poisson solver, which can handle any tether cross-section geometry, has been used to study the electron collection and emission of tape-like LWTs.

3.5. Lateral activities on the $\mathrm{C12A7:e^-}$

Two devices based on the $C12A7 : e^-$ electride, which are not part of the EDT-D, are currently under development in the project: an electrothermal thruster and a PETE device. The electrothermal thruster has been designed and manufactured during the project, and some preliminary testing activities have been recently started (find more details at Ref. [5]). Regarding the PETE device, one of the most important achievements has been the development and fine-tuning of the sputtering deposition technique for the deposition of C12A7:e- electride thin films, which has paved the way for the development and manufacturing of a first PETE prototypes in the project. Rutherford Backscattering Spectrometry analysis of the deposition confirmed the C12A7:e- electride structure of the deposited thin layer. The Ca/Al ratio measured for the thin film ranges between 0.80 and 0.83, while pure C12A7:e- electride Ca/Al ratio is 0.86. Additionally, preliminary testing activities on these PETE device prototypes have shown electron emission under both temperature and photon excitation.

4. CONCLUSIONS

After a 6-month rescheduling due to the COVID-19 situation, the work plan of the E.T.PACK project is progressing as expected. The team is focused on the development of an EDT device (EDT-D) to be tested in a future in-orbit demonstration (IOD). One of the most important achievements of the project has been the design of a full device that is compatible with demanding volume, mass, and power constraints, together with being autonomous and able to perform collision avoidance maneuver. The baseline configuration is a bare EDT with a hollow cathode emitter. Whether a segment of LWT will be part or not of the EDT-D will depend on the electron emission capabilities of the coating to be improved and tested until the end of 2022. The IOD is conceived as an experiment and its main goal will be to test tether-related technologies. For this reason, the incorporation of several cathodic contactors is an open possibility. Since the deployer mechanism can handle different tether thicknesses, adding a photovoltaic tether segment is a possibility under investigation. In this respect, E.T.PACK team is promoting a parallel action to manufacture and test a tether segment made of thin film solar cells. This would be a cornerstone for the EDT-D because electron field emitters and thermionic emitters, which are expellant-less, would be compatible with the power envelope while preserving the autonomy requirement.

Independently on the result of high-risk activities, like the development of the $\mathrm{C12A7:e^-}$ coating for LWTs, the EDT-D will reach TRL 4 by the end of 2021 equipped with a hollow cathode emitter. The roadmap of the consortium considers a follow-up project of 2 years of duration to increase its maturity and test the system with an IOD. It is also remarkable that the European Commission funded recently the Innovation Launchpad Project with acronym BMOM, a 1-year project starting in May 2021 dedicated to carry out market analysis and prepare a business model for the EDT deorbit device. As part of this activity, the consortium will interact with potential customers to align the performance and design of the deorbit device to their needs.

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