Characterization of a Low Current Heaterless C12A7 Electride Hollow Cathode for an Electrodynamic Tether Deorbiting Device

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A hollow cathode is being developed as an active electron emitter for an electrodynamic tether demonstrater. For such an experiment, low emission currents in the range of a few hundred milliamps with a low overall power consumption of a few watts are required. Such requirements - especially the low current range - are difficult to meet for most state-of-the-art hollow cathodes. Our hollow cathode design, which has been specifically optimized towards these strict demands, uses C12A7 electride as emitter material. Using the advantages of this material - like heaterless ignition with a single high voltage pulses below 400 V **- the design has made significant progress through a rigorous test campaign. The cathode has been operated successfully with component-off-the-shelf miniature power supplies which represent the first step for an electronic supply system which can be integrated into a small-sat. The characterization of the cathode has been conducted in the range of 0.1 to 1.4** A **with a total power consumption between 8 to 50** W**.**

I. Introduction

With the increasing popularity of small satellite systems, the number of operative satellites in earth orbit is increasing rapidly, and will do so in the near future ever so much. Mega-constellations are on their way, and with the expected start of the operation of small-sat launch-providers, this trend will be pushed even more so. At this point, a considerate use of earth orbits will become increasingly more important, in order to prevent incidents that will render particular orbits unusable, for instance due to space debris.

In order to prevent effects like the Kessler syndrome, the save deorbiting of satellites needs to be guaranteed. Nowadays, many systems are being equipped with dedicated thruster technologies to ensure reasonable attitude and orbit control capabilities, where electric propulsion systems are continuously increasing their market share. These thruster options are often seen as solution to guarantee safe deorbiting at the end of the lifetime of the satellite system. However, this does not take into account the possibility of a full system failure deeming the control of the satellite impossible. Here, a safe and independent deorbiting kit based on an electrodynamic tether has been proposed by the E.T.PACK consortium.

E.T.PACK is a FET-open EU-Project in the scope of Horizon2020, in which the technology of Electrodynamic Tethers (EDT) is being matured significantly and is being evaluated for the use as a deorbiting mechanism of satellites [1]. Ideally, a low work function tether (LWT) will be used as a passive electron emitter, eliminating the need of a expellant for such a mission [2]. However, options of active electron emission are being evaluated as backup solutions. In particular, an in-orbit demonstration (IOD) mission is being prepared to validate the use of EDT as deorbiting technology. For this mission, a hollow cathode has been chosen as active electron emitter solution. The entire mission has been presented in more detail in reference [3]. Figure 1 shows a rendering of the IOD concept.

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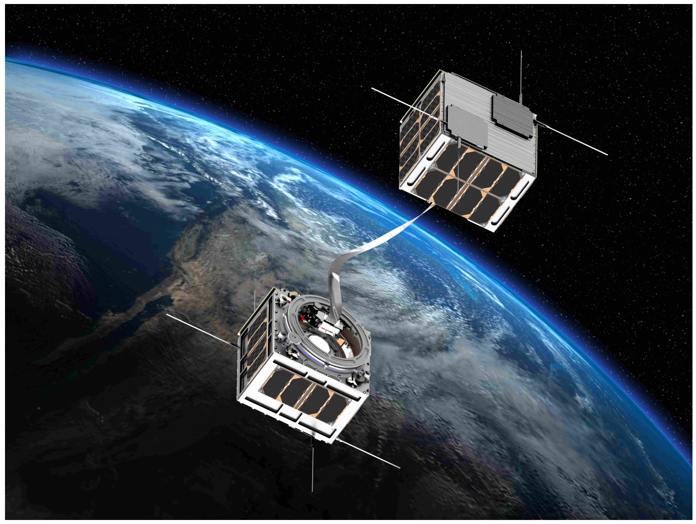

Fig. 1 CAD Rendering of the IOD mission concept currently under development. The snapshot shows the separation of both satellite modules during the initial tether deployment phase. The total length is 500 m. The lower Deployment Mechanism Module (DMM) contains the tether. The upper Electron Emitter Module (EEM) carries the emitter system containing the hollow cathode with its krypton fluid supply system and electronics. [3]

The hollow cathode for the IOD mission is being designed and developed at the Technische Universität Dresden, Institute of Aerospace Engineering. The cathode is designed with the strict requirements of the mission in mind, including the range of the discharge current, the available discharge potential as well as the low power requirements as well as size limitations of such a mission.

The hollow cathode that is designed is heaterless and features the emitter material C12A7 electride. This particular materials allows for a very low power ignition due to the ignition from room temperature as well as the short (non-existing) conditioning / heating time during start up of the plasma discharge. Furthermore, the small size of the system as well as the low operational temperature are ideal for the integration into a small satellite system.

The following paper will describe in detail the design of the cathode for a space based mission and will present the characteristic of the cathode using an adequate electronics setup (miniaturized component-of-the-shelve (COTS) discharge control) suitable as baseline for the integration to a cubesat mission.

II. E.T.Pack IOD mission requirements

The cathode will be designed to operate as the electron emitter for the E.T.Pack IOD EDT deorbiting mission. Consequently, the requirements defined by this mission will be the baseline for the development of the cathode. The following section will give an overview over top level requirements of the IOD mission towards the active electron emitter.

A full system view of the IOD mission has been presented previously [3]. The electron emitter will be integrated into a satellite module roughly the size of a 8U cubesat. Consequently, the power available for the operation of the electron emitter is limited to about 10 W. In orbit, the tether will collect electrons with its significant surface area, that have to be emitted back into the LEO plasma at one end to drive a current through the tether and therefore generate the thrust of the system (Lorenz-force). From a performance point of view, the higher the current flowing through the tether, the higher the generated thrust force will be. However, from a detailed stability analysis it was concluded, that the optimum tether current is in the range of 100 to 300 mA. Consequently, this current range has to be emitted to the space plasma by the electron emitter, which will be the baseline for the design of the cathode.

To operate the cathode, an expellant will be necessary to generate the plasma. To optimize the operational time of electron emission using the available expellant stored in the fluid system, the mass flow rate has to be as low as possible. A limit of 4 sccm was set for the cathode, to size the storage system for the nominal mission. Krypton will be used as expellant for the plasma operation of the cathode. A dedicated fluid system has been developed and is currently being tested, and will be discussed in a future publication.

The E.T.Pack IOD mission will operate in a LEO with increased inclination. Therefore, eclipse phases have to be considered. Besides the power constraints during these phases, electron collection from the space plasma will be significantly influenced by the different plasma parameters during eclipse. Consequently, electron emission shall be limited to illuminated phases of the orbit, requiring repeated ignition operations of the discharge. Overall, 500 ignition cycles and about 300 hours of total operation have to be ascertained for nominal mission operation.

Lastly, a small and low power ignition and operation electronics is required to ensure the integration of the cathode onto a cubesat sized satellite. Therefore, stable operation with a miniaturized and efficient vacuum compatible power supply has to be ensured.

III. C12A7 electride hollow cathode at TUD

A hollow cathode technology, using the emitter material C12A7 electride, has been under development for several years already at the institute of aerospace engineering at TUD. During this time, the emitter materials has been optimized continuously with our partner Fraunhofer IKTS in Dresden, and results are being published continuously. Most recently, our joint cooperation resulted into the acceptance of a patent concerning the manufacturing of a composite material of the electride [4], that will be used for electron emission in our electron emitters.

The corresponding cathode itself also has come a long way already. Starting from short operational bursts [5], we gained a significant understanding of the materials behavior and how to use it correctly [6]. This resulted, for instance, into the successful operation of the C12A7 electride cathode for more than 950 hours continuously, as it has been reported in literature [7]. Since than, also due to the alignment with projects available at the institute, we looked into a more sophisticated operation of the cathode at very low discharge currents with a low power consumption. The results of this optimization towards a low power consumption for emission currents in the range of 100 to 300 mA is the focus of this publication.

In general, the electride material shows promising results as an active electron emitter. Ignition can be achieved quite easily, endurance operation has been verified successfully, and the reported operating temperatures of the cathode setups itself are rather low. The discharge current can be set adequately low with realistic discharge parameters.

So far the focus has been the hollow cathode itself. However, for the successful operation on a small-sat the hollow cathode is only a subsystem of the electron emitter system. The two other subsystems include the krypton propellant system and the power system.

For preliminary laboratory tests, naturally a setup available at the laboratory has been used to control the discharge. However, a power supply in the size for a 19” rack and of multiple units height and several kW power will be insufficient when planing to operate the electride cathode on a satellite at some point. At the same time, the control characteristic of the power supply showed significant influence onto the discharge performance of the plasma inside the electride cathode. Therefore, the verification of the electride cathode operation using a miniaturized COTS power supply will be a major milestone towards the successful operation of an electride cathode on a satellite in orbit.

IV. Hollow Cathode Setup

For the test campaign presented here, a modular setup of the hollow cathode has been used. This setup allows for quick and easy adaptations of the design for an adequate evaluation of the emitter material performance. The following section will describe the design and setup of the cathode in detail.

A. C12A7 Electride Emitter Material

The cathode features the novel emitter material C12A7 electride, which is an electrical conductive ceramic with a relatively low work function. Details to the material properties have already been reported numerous times in the referenced literature [8]. In recent years, the interest of the space community for this material increased significantly, to be used as emitter material in plasma based systems like hollow cathodes or as thermionic emitters [9–12]. Therefore, dedicated test campaigns to evaluate the materials parameters have been reported from several institutions, with widely varying results [13–23]. To the best of the authors knowledge, the performance of the material is dependent on a wide range of aspects and can not be clarified completely, as of today. This includes multiple manufacturing details, sample characteristics as well as measuring methods and testing procedures.

The electride emitter material used for the tests reported in this paper has been manufactured by the Fraunhofer IKTS in Dresden. Details to the manufacturing process can be found in literature [24]. For the operation of the hollow cathode reported in this paper, an optimized electride composite has been used in a specific variation, that improves the discharge characteristics of the plasma as observed in numerous tests at our institute. Details to this optimization process can be found in literature [25].

B. Modular Hollow Cathode Setup

A modular setup was used for the characterization of the cathode. This setup is the baseline for any experiments with the cathode in our laboratory, as it allows for easy manufacturing of the components and quick exchange of components to study different aspects of the cathode.

The setup is based on a flat disc shaped C12A7 electride sample that is attached to a flat round copper plate. A cross sectional view of this general setup can be seen in Fig. 2 a). The reasoning for this setup is the efficient removal of excessive heat flow from the electron emitting material, since overheating has been a severe issue in the past with the electride material. Tests indicated, that different materials and geometries have an influence on the characteristic of the discharge, and will require optimization. The general layout of the test setup has been used in multiple test campaigns that have been reported in literature, including an 950 hour endurance operation test [7].

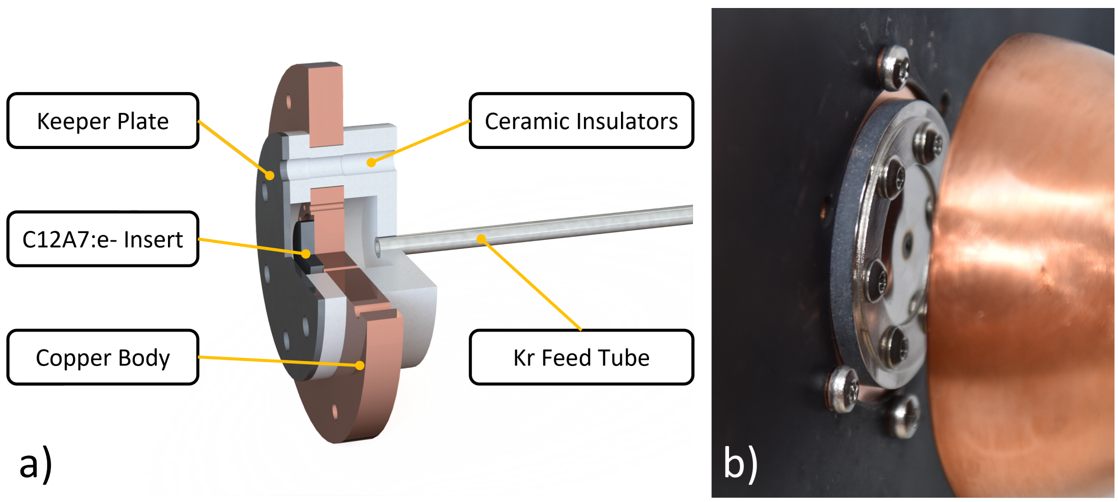

Fig. 2 Cross sectional CAD Rendering of the modular hollow cathode used for laboratory testing and characterization.

For the anode, a half sphere made of copper has been positioned about 1 cm in front of the cathode. The cathode has also been operated successfully with cylindrical anodes in front of the keeper, but the differences in those results will not be discussed in this particular paper. A picture of the setup of the cathode and anode in our vacuum chamber can be seen in Fig. 2 b).

C. Testing Facilities

The hollow cathode was tested in one of the vacuum chambers at the Institute of Aerospace Engineering at Technische Universität Dresden. The chamber is cuboidal with a total volume of 4.5 m^3. Attached to the chamber is a cryogenic pump with a nominal pumping speed of 10.000 $L\,s^{-1}$ N_2. The base pressure of the system is in the range of 1E-8 mbar. During operation, the background pressure increased to approximately 1E-4 mbar. The mass flow rate during operation is controlled by a *Brooks Instrument* mass flow controller, GF40 series.

D. Electrical Setup

The cathode discharge was operated in a diode configuration, meaning that a current was emitted by the hollow cathode to an external anode, which is positioned right in front of the cathode. To make the test environment as representative to the operating conditions in LEO environment, only the emitter potential can be controlled for the discharge. Meanwhile, the keeper of the hollow cathode as well as the anode were set at reference potential. However, shunt resistors to measure the current at the keeper and anode were added. To prevent significant currents to the grounded chamber walls, the reference potential of the entire setup was set significantly above the chamber potential.

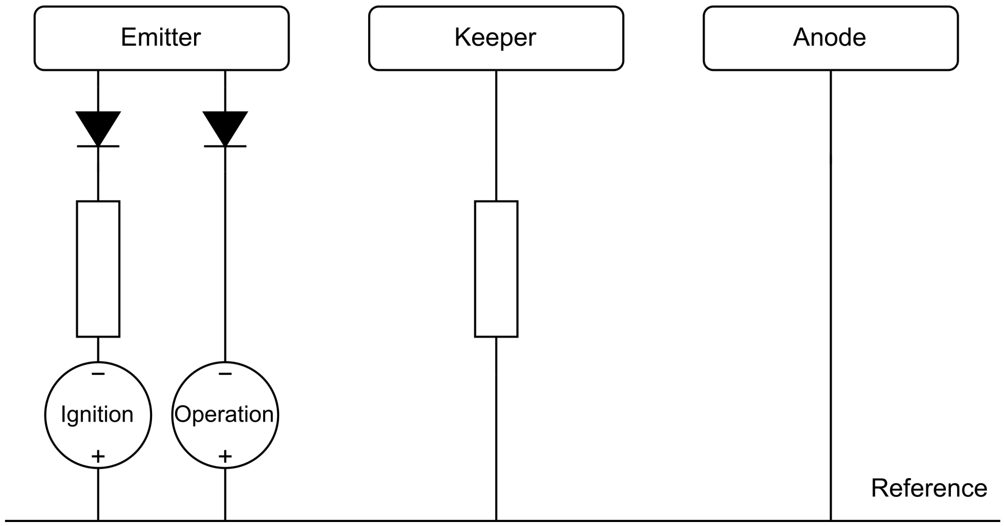

Fig. 3 General electrical schematic for high power ignition and operation of the cathode. Shunt resistors omitted, for improved readability.

The electronics controlling the emitter are subdivided into two main branches. The first branch ensures the ignition by short high voltage pulse. After this the second branch takes over by controlling the coninious DC discharge. Both branches are protected by diodes to prevent an unwanted interaction between them, which would lead to discharge instabilities or even the destruction of the power supplies.

Ignition branch For the ignition of the discharge, and potential difference in the order of 300 to 400 V between the electron emitter and the keeper is required. During breakdown, which is the plasma ignition, a certain energy has to be supplied to the plasma, to stabilize the discharge. In general, the ignition procedure can take place in less than 1 second, before a successful hand over to the second branch for continuous operation is achieved.

The tests reported here have been achieved with two distinct methods of ignition. First, a convenient and safe ignition procedure can be conducted, in which a high power power supply may generate the required ignition potential and drives a current at elevated levels, until a stable discharge can be observed by the operator, at which point this power supply may be shut off. As mentioned above, this process can be reduced to about 1 second of time. Figure 3 shows a electrical schematic of the corresponding setup.

For the second ignition approach of the system, a capacity of about 2 mF was connected via a current limiting resistor to a power supply, able to provide the ignition voltage of <400 V. The power supply will slowly (with a low current rate) charge the capacitor, until breakdown at the cathode occurs. The initial plasma will be supplied by the energy stored in the capacitor. Due to a large resistor in line of the power supply, the discharge cannot be sustained by this power supply itself. After successful plasma ignition, a hand over of the discharge control to the operation power supply is performed. Figure 4 shows again the electrical schematic for such a ignition.

Both described approaches do result in a reliable and stable ignition of the plasma discharge inside the electride cathode, as tested with our setup. Although the first option may be sufficient for a laboratory setup, the power requirements would be too high for any cubesat based operation. With our approach to develop a low power system, the ignition using a simple capacity will be the preferred option, as it can be operated with very limited power. Standard DC-DC converters can be used to generate the ignition potential, where the current will only limit the time required to load the capacitor, which is of no priority (the mission profile will have one ignition every 90 minutes). Since the capacity of the capacitor is still reasonable low, it will still be only a matter of seconds to charge it.

With the limited power approach in mind, we will focus on presenting the characteristics of the capacity based ignition of the discharge. However, for the characterization of the discharge of the cathode itself, most often the laboratory approach was used to ignite the discharge, since this branch will be shut off either way during continuous operation, but it will be more convenient to do so.

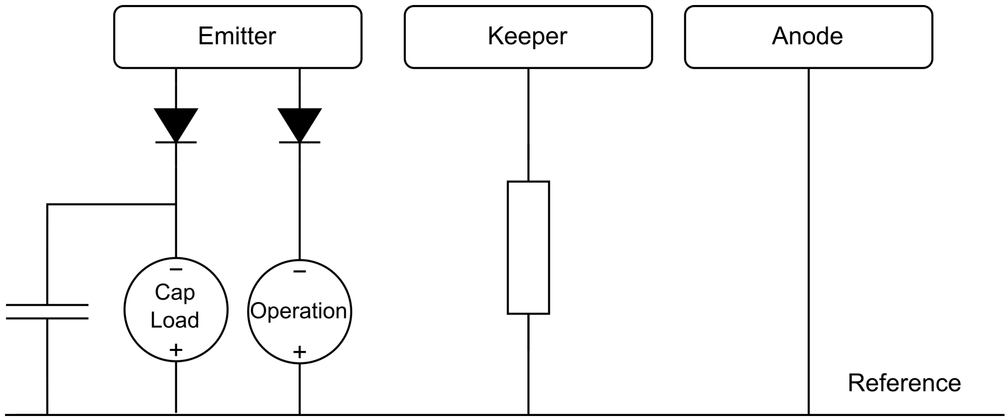

Fig. 4 General electrical schematic for capacity based ignition and operation of the cathode. Shunt resistors omitted, for improved readability.

Operation branch After ignition, the discharge needs to be supplied and controlled continuously. Due to the very flat current voltage characteristic of the discharge, as it will be discussed in section V.B, the power supply needs to be operated in a current controlled (CC) mode. Furthermore, as discussed previously, the discharge is to be operated with minimal power consumption and with a miniaturized COTS power supply. In previous experiments it was observed, that the electronics used to operate the discharge will have a significant influence in controlling a stable discharge. Furthermore, passive electronics may be required in some setups, to achieve stable operation. Since these will require additional power due to power losses at them, the setup used shall operate without such components.

So far, two different COTS power supplies have been used successfully to operate the electride cathode discharge. One of the supplies is depicted in Fig. 5. In general this proves the fact, that a successful control using such power supplies is possible, and that the electronics integration into a cubesat structure will be generally feasible. Furthermore, with small modifications on the electronics, both supply's can be made vacuum compatible, allowing a full integration

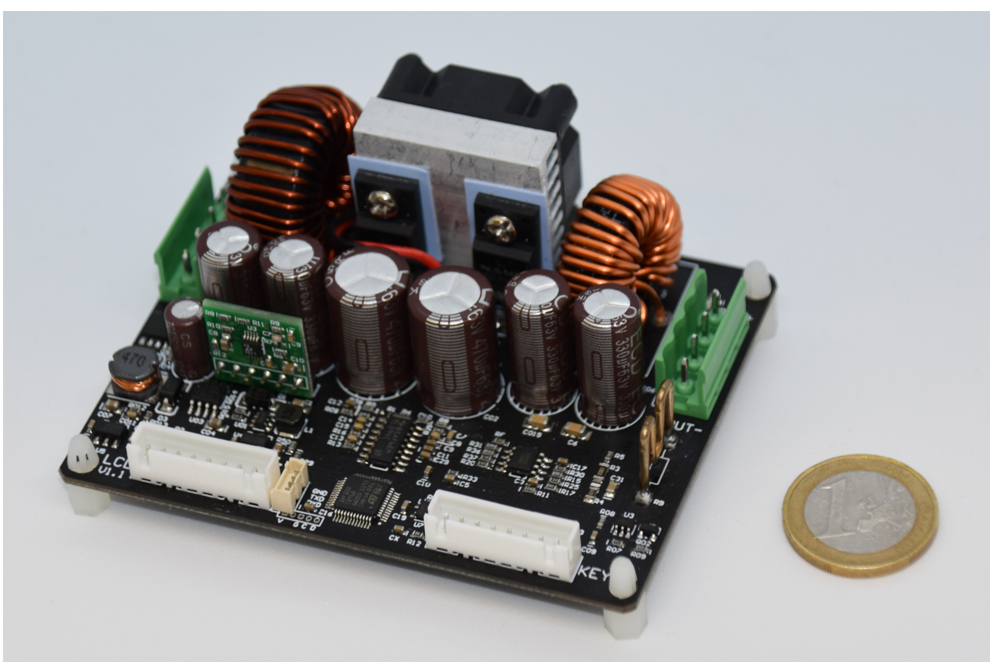

Fig. 5 Miniaturized COTS used to control the discharge. 100x35x70 mm^3**, 222** g**. Vacuum compatible with slight modifications.**

and testing into vacuum in near future. However, for the tests reported in this paper, the power supplies were still located outside of the vacuum chamber, for convenience. Although the exact version of the COTS may not be used for actual space based mission, they are a great showcase of the capabilities of these supplies and in general a great baseline for the further development of a sophisticated power supply to control the discharge.

V. Experimental results

The results presented in the following sections are part of an ongoing test campaign to push the optimization of the discharge characteristics of the hollow cathode. The main focus is set on the verification of the operation using miniaturized power supplies, and the development of a sophisticated power supply for the control of the discharge on a small satellite.

A. Ignition behavior of the Hollow Cathode

The ignition of the discharge with a capacitor was achieved by always following a similar procedure: A constant mass flow rate was set for the operation of the system, and the potential at the supply for continuous operation was set. After this, a dedicated power supply increased the ignition potential with the capacitor due to a set current limit slowly until the breakdown potential of the plasma was achieved. At this point, the sudden reduction of the effective internal resistance due to the high conductivity of the plasma led to high transient currents, that were supplied by the charged capacitor. These currents discharged the capacity and did fall off quickly in the matter of about half a second. Since the potential at the constant supply was already set, current could start to flow here right away, allowing a successful hand over of the discharge. At this point, a stable discharge, controlled by the miniaturized supply, was achieved, and the supply to load the capacitor for the ignition was turned off.

The characteristic of such a procedure can be seen in Fig. 6. It represents the measurements of the voltage drop at the shunt resistors of the electrodes for currents, and the potentials at the capacitor (i.e. the ignition potential) to the reference potential, using an differential oscilloscope. The measurements are normalized, since only the general behavior of the signals shall be discussed, and a more sophisticated measurement needs to be implemented for a detailed characteristic. Still, the diagram gives detailed insight into the general time resolved behavior of the ignition.

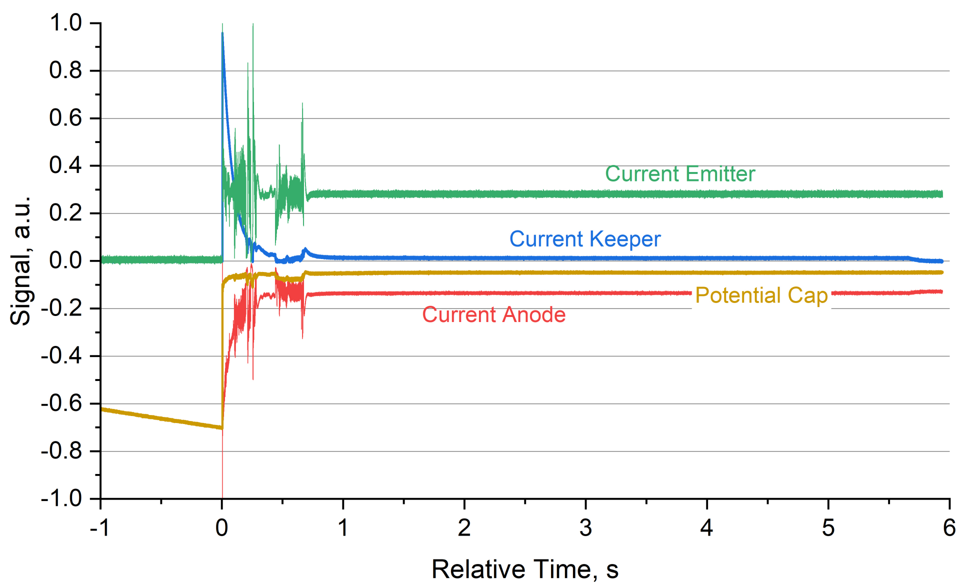

Fig. 6 Time resolved behavior during ignition of electrode currents as well as discharge potential. Stable discharge achieved after less than 1 second of discharge.

In the diagram, the *Current Keeper* and *Current Anode* graph represent the uncontrolled electrodes of the setup. Eventually, the anode current is the desired parameter, the cathode is designed for. The sum of the previous two should ideally add up to the *Current Emitter* which represents the controlled current at the miniaturized power supply. The *Potential Cap* represents the emission potential of the discharge. The plasma breakdown occurs after the capacitor has reached the ignition potential during its charge-up, inducing the mentioned high currents at the electrodes, supplied by the capacitor. The instability due to the ignition process takes less than one second, before the noise of the discharge is reduced significantly and stable operation is achieved.

Although only arbitrary units were used for the representation of the discharge, important conclusions can be drawn:

- Successful ignition can be achieved by the energy stored in a small capacitor
- The ignition process is stable after about 1 second
- The discharge can be started instantly from room temperature
- No further conditioning (heating procedure) of the emitter material to supply the discharge is necessary
- The peak current during ignition will be high, but due to its short time frame still be within acceptable limits.
- The ignition potential of the procedure presented in Fig. 6 has been below 300 V

Several key parameters to optimize the ignition process were identified: Ranging from the capacitance of the capacitor itself, over means to adjust the time constant of the discharge of the capacitor up until the characteristic of the miniaturized discharge power supply for successful hand over of the discharge control. In the end, a slight optimization of the electride material itself by Fraunhofer IKTS was a main contributing factor for the improvement of the overall performance. Unfortunately, no complete study, which evaluates the influence and cross-effects between different key parameters, could be done yet. This is the next step to further mature this hollow cathode design.

B. Continuous Operation using a miniaturized Power Supply

In addition to the sophisticated ignition procedure, continuous operation of the plasma discharge and emission of the desired discharge current is fundamental for the performance of the electride hollow cathode. So far, two different miniaturized COTS power supplies have been tested, which successfully controlled the discharge.

As discussed previously, the characterization of the discharge was achieved using a higher power ignition procedure, since it is more convenient during testing as of now. After setting a constant mass flow rate and the potential at the continuous supply, the ignition supply is activated drawing a significant current from the discharge. Once the discharge is beyond its initial instability, the ignition supply is shut off, and the discharge will now only be controlled by the miniaturized power supply. This procedure can be reduced to about 1 second, but it most often takes a few seconds since there are several manual commands required.

The current limit at the operational power supply can either be varied during operation, or at ignition itself. So far, no minimum current limit for the operational supply could be identified, but this may still be to be evaluated when in combination with the ignition using a capacitor.

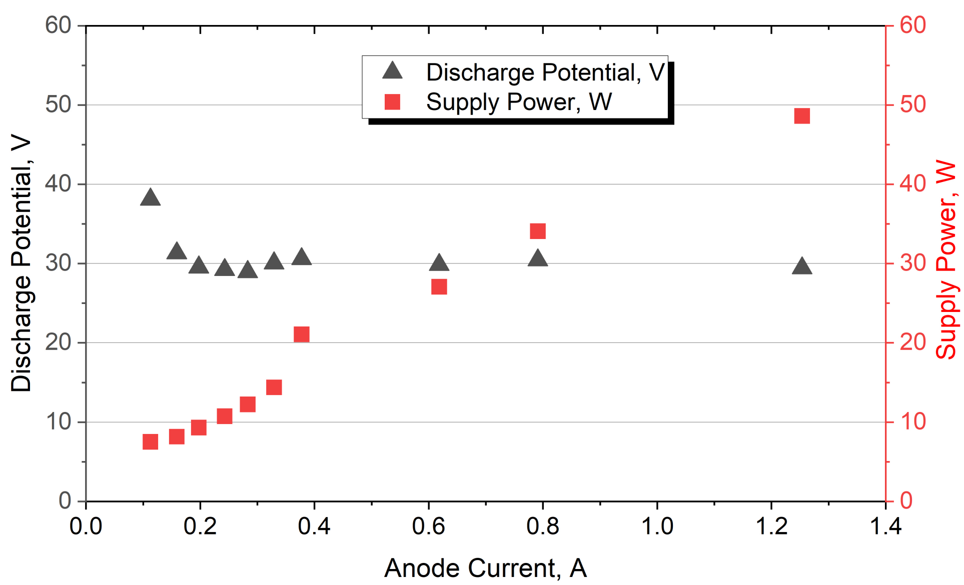

Fig. 7 Discharge potential and Supply power plotted over the measured anode current of the discharge operating with the miniaturized COTS power supply.

The I-V Characteristic of the discharge using the operational supply is plotted in Fig. 7. For the x-axis, the current measured at the anode was chosen, since it is the representation of the current emitted to the space plasma, which is the main goal of the active electron emitter for any EDT mission. Over the anode current, both the potential of the discharge as well as the overall power supplied to the miniaturized COTS supply are plotted. The discharge potential is an essential characteristic of the discharge, which is required for the performance of the tether. The overall power supplied to the operational control supply on the other hand, is the most important metric to evaluate the feasibility of supplying the discharge on a small cubesat sized mission.

From the characteristic in Fig. 7, several interesting affects can again be identified:

- A wide range of discharge currents can be operated stable by the cathode, ranging from 100 mA up to several amps.
- The voltage characteristic of the discharge is rather flat, meaning that there is a significant range of discharge currents without a significant discharge potential difference
- For very low operational set points, the discharge potential increases, due to the severe power limitations to heat the emitter material
- The overall power required for the discharge is low, and for the desired emission range in the required range.

Overall, the operation of the discharge using the miniaturized power supply was very convenient and reliable, once the particular setup and procedure was found. Already, some parametric studies have been conducted, but shall not be discussed in this paper due to the preliminary nature of those. These changes include a significant reduction of mass flow rate, which was set for this characterization at an over-sized value to keep it out of the equation. Furthermore, the addition of electronics at the keeper electrode, which would act as a current divider with the anode, could act as a mean to shift the characteristic shown in Fig. 7 along the A-axis without a significant change of the characteristic itself. Naturally, an extended test campaign will be necessary to find the optimal discharge points, which will be reported in due time.

VI. Discussion

Successful operation using a miniaturized vacuum compatible COTS power supply was reported, as well as successful and easy ignition using a simple capacitor. Both aspects provide a great baseline for further development and optimization of the overall system. So far, only a preliminary study with the latest design of the hollow cathode setup was conducted. During this study, many factors with a significant potential for the further optimization of the performance of the cathode were identified. Corresponding results will be published in due time.

However, the characteristics presented so far are quite promising. The ignition process of the discharge is very reliable and easy to achieve, and takes only a few seconds and a minimum of power. The plasma ignition instabilities are even reduced to about 1 second, after which nominal operation is achieved, not requiring any particular heating procedure. Stable discharge itself is achieved over a wide range of emission currents, ranging from 0.1 A to 1.5 A. The discharge potential itself may still be slightly higher than expected, but the characteristic itself shows a common hollow cathode behavior.

So far we have not considered the temperature as a metric of evaluation in this paper. Most tests were rather short - on the order of 30 minutes maximum. During that time, equilibrium temperatures at points of reference were not reached. Thermocouple measurements at the base body of the cathode indicated max. temperatures around 100celsius which can be easily insulated and are deemed acceptable for later integration of the cathode int the small-sat structure. However, the exact temperature of the emitter surface itself is still unclear.

Eventually, the cathode was designed in the scope of the E.T.PACK IOD mission, using the mission requirements. Analyzing the results presented in the paper, the development of the cathode seems to be on a good way to meet the requirements. The operation of the cathode in the desired current range was achieved successfully, and in particular the power range required for the operation is in the available range of the mission. Endurance operation as well as ignition cycles have not been tested so far, but multiple ignition attempts did not show any severe degradation, yet.

Finally, the results presented in this paper support the importance of the electride material quality and its characteristic. Next to the improvements and the general adaptations in the setup, the detailed characteristic of the emitter material used during the testing has been one major factor to achieve the results presented. It requires careful evaluation and optimization to reach this performance. Both the setup mechanically as well as electrically have to be adjusted to the electride material and vice versa. In the end, the C12A7 electride shows its capability to enable an efficient use in plasma based electron source as electron emitting material.

VII. Conclusion

The paper presented an overview of the most recent development results of the operation of an low power heaterless hollow cathode using the emitter material C12A7 electride. The main driver of the development have been the demanding requirements for the IOD mission developed within the E.T.PACK project in which the hollow cathode is the baseline electron emitter for an electrodynamic tether system. This sets strict limits on power consumption for an emission current which is otherwise difficult to obtain for most hollow cathode systems.

The cathode has been successfully operated using a miniaturized COTS power supply. The cathode has also been ignited successfully only by means of a loaded capacitor, in a matter of seconds. This very convenient low power and fast ignition procedure may be a great advantage to any state-of-the-art plasma ignition system. The use of such small power supplies may be great indications for the feasibility to operate the cathode on any space based system.

The results reported in this paper represent only one milestone in the effort to build a hollow cathode for the IOD mission and a design which is comfortable with the operation in low current ranges. A more detailed review of IV characteristics and the operating behavior shall be presented in due time.

Acknowledgments

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References

[1] Sánchez-Arriaga, G., Naghdi, S., Wätzig, K., Schilm, J., Lorenzini, E., Tajmar, M., Urgoiti, E., Castellani, L. T., Plaza, J., and Post, A., "The E.T.PACK project: Towards a fully passive and consumable-less deorbit kit based on low-work-function tether technology," *Acta Astronautica*, Vol. 177, 2020, pp. 821–827.

[2] Tarabini Castellani, L., Ortega, A., Giménez, A., Urgoiti, E., Sánchez-Arriaga, G., Borderes-Motta, G., Lorenzini, E., Tajmar, M., Wätzig, K., Post, A., and Plaza, J., "Low work-function tether Deorbit Kit," *Journal of Space Safety Engineering*, Vol. 7, No. 3, 2020, pp. 332–339. Space Debris: The State of Art.

[3] Tarabini Castellani, L., García González, S., Ortega, A., Madrid, S., Lorenzini, E., Olivieri, L., Sarego, G., Brunello, A., Valmorbida, A., Tajmar, M., Drobny, C., Wulfkuehler, J.-P., Nerger, R., Wätzig, K., Shahsavani, S., and Sánchez-Arriaga, G., "Deorbit kit demonstration mission," *Journal of Space Safety Engineering*, Vol. 9, No. 2, 2022, pp. 165–173.

[4] Wätzig, K., Drobny, C., and Tajmar, M., "Elektronen emittierende Keramik," , 2021. Deutsche Patentanmeldung DE 2020 032015533500.

[5] Drobny, C., Tajmar, M., and Wirz, R. E., "Development of a C12A7 Electride Hollow Cathode," *35th International Electric Propulsion Conference*, Atlanta, 2017, pp. IEPC–2017–373.

[6] Drobny, C., Wulfkühler, J.-P., and Tajmar, M., "Development of a C12A7 Electride Hollow Cathode and Joint Operation with a Plasma Thruster," *36th International Electric Propulsion Conference*, 2019.

[7] Drobny, C., Wulfkühler, J.-P., Wätzig, K., and Tajmar, M., "Endurance Test of a Hollow Cathode using the Emitter Material C12A7 Electride," *Space Propulsion 2021 Conference, Digital*, 2021, p. 153.

[8] Kim, S. W., and Hosono, H., "Synthesis and properties of 12CaO ·7Al2O3 electride: review of single crystal and thin film growth," *Philosophical Magazine*, Vol. 92, No. 19-21, 2012, pp. 2596–2628.

[9] Rand, L. P., and Williams, J. D., "A calcium aluminate electride hollow cathode," *IEEE Transactions on Plasma Science*, Vol. 43, No. 1, 2014.

[10] Hua, Z., Wang, P., Xu, Z., and Yu, S., "Experimental characterization of the C12A7 hollow cathode and its joint operation with a low-power Hall thruster," *Vacuum*, Vol. 192, 2021, p. 110443.

[11] Post, A., Plaza, J., Toledo, J., Zschätzsch, D., Reitemeyer, M., Chen, L., Gurciullo, A., Siegel, A., Klar, P. J., Lascombes, P., and Seifert, B., "Key design and operation factors for high performance of C12A7:e-based cathodes," *IOP Conference Series: Materials Science and Engineering*, Vol. 1226, No. 1, 2022, p. 012092.

[12] Reitemeyer, M., and Klar, P. J., "Neutralizer Design with a Flat C12A7:2e- Insert," *Space Propulsion 2022 Conference, Estoril*, 2022, p. 134.

[13] Toda, Y., Matsuishi, S., Hayashi, K., Ueda, K., Kamiya, T., Hirano, M., and Hosono, H., "Field emission of electron anions clathrated in subnanometer-sized cages in [Ca24Al28O64] 4+(4e–)," *Advanced Materials*, Vol. 16, No. 8, 2004, pp. 685–689.

[14] Toda, Y., Kim, S. W., Hayashi, K., Hirano, M., Kamiya, T., Hosono, H., Haraguchi, T., and Yasuada, H., "Intense thermal fiels electron emisiion from room-temperature stable electride," *Applied Physics Letters*, Vol. 87, No. 254103, 2005.

[15] Kim, S. W., Toda, Y., Hayashi, K., Hirano, M., and Hosono, H., "Synthesis of a Room Temperature Stable 12CaO ·7Al2O3 Electride from the Melt and Its Application as an Electron Field Emitter," *Chemistry of materials*, Vol. 18, No. 7, 2006.

[16] Toda, Y., Yanagi, H., Ikenaga, E., Kim, J. J., Kobata, M., Ueda, S., Kamiya, T., Hirano, M., Kobayashi, K., and Hosono, H., "Work Function of a Room-Temperature, Stable Electride [Ca24Al28O64] 4+(e–) 4," *Advanced Materials*, Vol. 19, No. 21, 2007, pp. 2564–2569.

[17] Yoshizumi, T., and Hayashi, K., "Thermionic electron emission from a mayenite electride–metallic titanium composite cathode," *Applied Physics Express*, Vol. 6, No. 1, 2012, p. 015802.

[18] Rand, L. P., "A Calcium Aluminate Electride Hollow Cathode," Dissertation, Colorado State University, 2014.

[19] Zou, W., Khan, K., Zhao, X., Zhu, C., Huang, J., Li, J., Yang, Y., and Song, W., "Direct fabrication of C12A7 electride target and room temperature deposition of thin films with low work function," *Materials Research Express*, Vol. 4, No. 3, 2017, p. 036408.

[20] Li, F., Zhang, X., Liu, H., Zhao, J., Xiao, Y., Feng, Q., and Zhang, J., "Rapid synthesis of inorganic [Ca24Al28O64] 4+(e-) 4 electride and its performance as an electron thermal emitter," *Vacuum*, Vol. 158, 2018, pp. 152–157.

[21] Zhang, X., Feng, Q., Zhao, J., Liu, H., Li, J., Xiao, Y., Li, F., and Lu, Q., "Sr-doping enhanced electrical transport and thermionic emission of single crystal 12CaO· 7Al2O3 electride," *Current Applied Physics*, Vol. 20, No. 1, 2020, pp. 96–101.

[22] Kottke, G., Vaupel, M., Wätzig, K., Schilm, J., Konrad, W., Tajmar, M., and Hey, F. G., "Investigation of C12A7 electride as a thermionic neutralizer," *Space Propulsion 2021 Conference, Digital*, 2021, p. 131.

[23] Toledo, J., Plaza, J., Post, A., Zschätzsch, D., Reitemeyer, M., Chen, L., Gurciullo, A., Siegl, A., Klar, P., Lascombes, P., et al., "Performance comparison of LaB6 and C12A7: e-emitters for space electric propulsion cathodes," *IOP Conference Series: Materials Science and Engineering*, Vol. 1226, IOP Publishing, 2022, p. 012093.

[24] Waetzig, K., and Schilm, J., "Electronic, mechanical, and thermal properties of [Ca24Al28O64] 4+(4e-) electride ceramic," *International Journal of Ceramic Engineering & Science*, Vol. 3, No. 4, 2021, pp. 165–172.

[25] Wätzig, K., Schilm, J., Drobny, C., Tajmar, M., and Kusnezoff, M., "Characterization of the thermal and mechanical properties of C12A7-Mo composites as electron-emitting ceramic," *ECerS Conference – Ceramic in Europe, 10-14 July, Krakow, Poland*, 2022.