Concerning the ignition of a C12A7 electride plasma-based cathode

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Abstract

Hollow cathodes are crucial components for many electric propulsion systems used for space applications. However, they also represent a challenging and sometimes even limiting element for the propulsion systems. Particularly in recent times when alternative propellants are under evaluation for the thruster, and the design and the limits of the cathodes are being pushed. Consequently, significant improvement in the technology is desired. This publication tests a heaterless cathode using the emitter material C12A7 electride, particularly reviewing its ignition behavior and performance during an ignition cycling campaign. Stable heaterless ignition has been reliantly achieved in only a few milliseconds at an ignition potential of less than 400 V and 20 sccm Kr flow rate. Furthermore, two ignition cycling campaigns at different flow rates are presented, one reaching 3300 ignitions, the other igniting at only 6 sccm Kr flow rate. The degradation of the emitter materials and the influence on the ignition performance is discussed.

Keywords: C12A7 electride ceramic, Heaterless cathode, Ignition behavior, Ignition cycling

Introduction

Efficient electron emission for space applications, be it for the neutralization of spacecraft or the operation of plasma thrusters like the Hall-effect thruster and gridded ion thruster, are crucial aspects with significant research interest [1, 2]. A recent review paper [3] focused on the state of electron emitters under development and discussed challenges for the emitter to be overcome. These include a miniaturized design, optimized performance, and a more sophisticated and reliant design. Possible solutions include heaterless cathode designs as well as the use of novel materials.

At the Institute of Aerospace Engineering at the Technische Universität Dresden, a heaterless C12A7 electride plasma-based cathode using disc-shaped emitters is under development. Recent publications include the cathode operation for 950 hours [4], far beyond any operation time reported from other groups. Furthermore, initial results for the discharge characteristic with miniaturized and low-power power supplies have been described [5]. Finally, a broad characterization of the discharge performance for the electride cathode has been published recently [6].

C12A7 electride hollow cathode The use of C12A7 electride as an emitter material in hollow cathodes for space allocations has been discussed extensively in recent years [5, 7–12]. The material has a relatively low work function, which could make it an interesting thermionic emitter, although the exact value varies for each publication. Significant challenges with the material for hollow cathodes that have been reported repeatedly are degradation due to excessive heating during operation, melting of the material, surface contamination, and rapid deterioration until failure. The following presents a comprehensive overview of the use of the electride material with a particular focus on the ignition characteristic from different research groups.

First tests of the material as emitter material for hollow cathodes have been conducted at Colorado State University. Rand [7] used an heaterless approach and required an ignition potential of either 1000 V at 25 sccm xenon mass flow rate or 400 V at 50 sccm. Furthermore, the cathode was also operated with iodine, suggesting compatibility of the electride material with this novel and rising propellant alternative for space applications.

McDonald et al. [8] used a more conventional design approach that allowed the testing of the cathode using a LaB_6 insert. For the electride emitter, a heating power of about 30 W to 40 W was required. A potential of 600 V was set at the keeper for ignition, and a high mass flow rush was needed to establish plasma ignition. In comparison, a heating power of 200 W was required to ignite a plasma discharge using a LaB_6 insert.

Other groups also compared the ignition parameters between LaB_6 and C12A7 electride, with similar results (i.e., higher heating power with LaB_6). Zschätzsch et al. [11] required at a heating power of 150 W an ignition potential of 900 V at increased mass flow rates compared to continuous operation of 5 sccm Xe. Guglielmi et al. [12] reported ignition at a few hundred volts and a heating power of 35 W.

Hua et al. [9] made an argument that overheating and degradation, which has been reported repeatedly for the electride, may only be an issue during the ignition procedure of the cathode since the operating temperature is well below the required ignition temperature. Consequently, a cathode featuring a heater was developed and tested. For ignition, the cathode was heated with 69 W external power, and 350 W at 5 sccm Xe were set to the emitter to enable the discharge.

In a later attempt to clean the emitting surface from degraded material, a heaterless ignition approach was also applied, requiring 500 V and 4 A at 18 sccm xenon mass flow rate. This ignition process was very unstable repeatedly for more than 50 seconds, with voltages ranging from tens of volts up to 500 V, before changing into a stable discharge.

The authors themselves have reported several ignition characteristics in several proceedings. Common for all reportings are heaterless ignitions from room temperature at 400 V and most often 20 sccm krypton. During first tests [13], an additional filament electron source was required to ignite the discharge at high currents, which was stable only for up to some minutes. In subsequent tests [14], ignition with 5 sccm was reported, but in particular, an on/off behavior of the discharge was reported. The discharge ignited and shut down repeatedly. Although the cathode ignited reliant at below 300 V, this would be no desired discharge characteristic. For an 950 h endurance test [4], a cathode using a disc-shaped emitter ignited reliant, but a considerable noise in the discharge potential in the first hours of operation was reported, which was significantly reduced at later stages at the test.

Finally, a separation of ignition and operation branch of the discharge was introduced [5], allowing a more sophisticated cathode operation and miniaturization of the required electronics. Ignition was achieved repeatedly at potentials below 400 V and took less than one second, although a significant range of this phase seems to be due to micro-arcs. Two distinct ignition types have been differentiated: A process in which the potential is reached with a dedicated power supply at significant current levels, labeled as *high-power* ignition. Furthermore, the ignition from a charged capacitor was verified, eventually minimizing the ignition procedure, which will not be discussed in this publication.

Heaterless hollow cathode Heaterless ignition of hollow cathodes has been evaluated as a viable means of improving the cathode performance, independently of using C12A7 electride as emitter material. Multiple tests and analyses concerning the ignition procedure using state-of-the-art materials like LaB_6 have been conducted and reported in the literature. The following will discuss the general characteristic of a heaterless ignition and provide an overview of heaterless cathodes, focusing on the ignition performance.

A comprehensive description of the ignition behavior for the commonly distinct phases of electrical breakdown, insert heating, as well as transition to steady-state operation has been given by Becatti et al. [15]. High mass flow rates or high ignition potentials are often applied to realize the ignition procedure. While excluding the heater can be a significant advantage for the design and operation of the cathode, high flow rates and potentials can be severe disadvantages to the overall system performance. Therefore, a careful evaluation of the required ignition parameters is needed.

Lev et al. [3] published the results of a 3500 ignition cycle test of a heaterless hollow cathode using LaB_6. The discharge ignited reliably with 100 % success rate at an ignition potential below 400 V-however, a suitable ignition scheme needed to be conducted to ignite the discharge from room temperature. No detailed information about this procedure is given, but it allows ignition in less than 10 s. Overall, no severe degradation was reported over the ignition cycling test.

Becatti et al. [15] reported a heaterless cathode cycling test of 25 000 successful ignitions. For the cycling test, a constant mass flow rate of 40 sccm xenon was set, which resulted in ignition potentials ranging from 400 V to 600 V. The keeper was limited to 0.5 A, and the anode current limit was at 2 A. After reaching the ignition potential, steady state operation was achieved in milliseconds. Only at later tests, micro-arcing became a challenge, which prolonged the time to establish stable discharge about 2 s to 3 s. Still, the ignition process is defined as quasi-instantaneous. Throughout the cycling test, no significant changes in the corresponding parameters were reported, and a material post-operation analysis showed no severe degradation of the emitter material.

Experimental

The tests presented in this paper have been conducted using a modular planar cathode. Figure 1 shows a cross-sectional view of the cathode. The same design baseline has been used in previous publications, featuring an endurance operation [4] as well as an extended discharge characteristic [6].
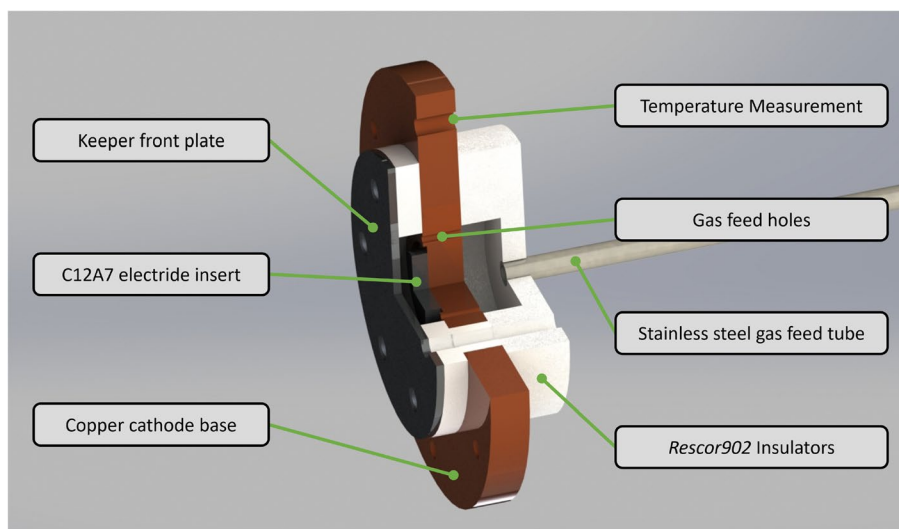
Fig. 1 Cross-sectional view of the planar cathode schematic with major components labeled [6]
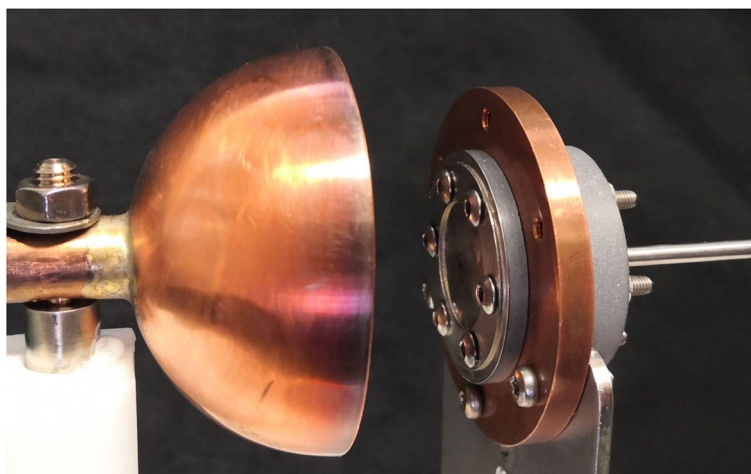
Planar cathode setup

The cathode setup uses a disc-shaped emitter of roughly 10 mm in diameter and of 2 mm height. The emitter is mounted on a flat copper body using a conductive adhesive. The flat design, as well as the choice of material, is to conduct excessive heat of the electride material. Overheating and melting the insert has been a severe problem in previous experiments. Other groups have also reported similar challenges in literature [8, 11]. Furthermore, the electride has reportedly lower operational temperatures than LaB_6 [8, 11, 12].

An optimized composite material was chosen for the emitter, which provided the best performance in preceding test campaigns. In particular, 30 Vol. % titanium was added to the pure electride before sintering the sample. The sample's manufacturing and characteristics align with reports of the molybdenum composite material often used at previous test campaigns at the institute and as described in the literature [16].

The keeper plate is positioned about 1.5 mm in front of the emitter, and the corresponding orifice has a diameter of 1 mm. The keeper and gas feed insulation are made of a machinable ceramic *Rescor902*. Sealing of the separate parts is provided to allow the ignition and operation at lower mass flow rates due to the restraint of leakage flow.

The cathode is tested in a triode configuration, with a half-sphere of copper in front. This distance to the anode is roughly 3 cm. Although the authors are aware that the geometry, as well as the position of the anode, has a significant influence on the discharge performance [17, 18], no such optimization has been conducted here. The triode setup (see Fig. 2) was mounted in a cubic vacuum chamber with 4.5 m^3, to which a cryogenic pump with 10 000 L/s N_2 is mounted, generating a base pressure of 2×10^{-8} hPa. For a flow rate of 20 sccm krypton, a chamber pressure of 1×10^{-4} hPa did set. At 6 sccm krypton a chamber pressure of about 1×10^{-5} hPa did set.

The cathode in question is designed for an electrodynamic tether mission in orbit in the scope of the European Union funded E.T.PACK-F project (Horizon2020 grant agreement number 101058166), which has been presented to the research community. A

Fig. 2 Triode setup of the modular cathode with a disc-shaped insert and the copper half-sphere anode right in front, as it is mounted into the vacuum chamber

detailed discussion of details of the project and the mission itself, the interested reader is invited to consult the references literature [19]. However, the most important for ignition behavior is that the emitter's potential shall only control the cathode discharge. Neither the anode (infinitive space potential) nor the keeper (close to satellite structure) shall be controlled actively. Consequently, both the high potential for ignition and the constant potential for continuous operation must be established at the emitter potential.

Electrical setup with separate branches

The heaterless ignition of the electride cathode will be challenging, particularly when trying to be efficient. It is the authors' strong impression that next to the material characteristic, the electrical setup used to generate the initial electrical breakdown severely influences the ignition performance. However, once a suitable set of parameters has been found, ignition can be achieved reliably, with limited degradation of the emitter material.

In many preceding test campaigns, it was found that resistors in line with the discharge control are beneficial for stable discharge conditions. However, these resistors can be critical for endurance operations, particularly when considering overall system performance and future satellite operations. An approach was tested that would subdivide the ignition and operation branch of the electrical controls. Although requiring two separate supplies, both can be optimized for the necessary operating range, significantly improving the discharge performance. Test results have already been discussed in literature [5].

For the ignition branch, two general designs can be distinguished: Namely, the *high-power ignition*, which uses the big laboratory supplies as well as resistance for ignition, as well as the *capacitor ignition*, which will be more of a miniaturized setup approach using charged capacitors for the ignition of the discharge. For convenience, and since the material characteristics were the most critical aspect to be evaluated, the high-power ignition was used for the ignition cycling test. Details concerning the capacitor-based ignition will not be discussed in this publication, but initial results can be found in the literature [5].

With the separation of the control electronics, the requirements for the separate branches can be redefined and adapted to the corresponding tasks. The ignition branch is now solely responsible for generating the ignition potential and the discharge control during the initial plasma phase. Eventually, the ignition branch has to enable a secure hand-off of the discharge control towards the operation branch, which is only designed for the operational potential below 50 V. Therefore, the operational supply must not control high transients so the system can be highly miniaturized.

Several different supplies have been tested to verify the electride cathode's discharge control and certain discharge stability regarding the power supply control characteristic. Next to laboratory supplies, this included, in particular miniaturized COTS converters. A detailed discussion about the characteristic of the operational branch and the corresponding characteristic of the C12A7 electride cathode towards operational parameters will be presented in a separate publication.

High power ignition procedure

Extended testing with the electride cathode and the heaterless ignition had shown that adding resistors in line with the discharge control can significantly improve the stability of the control using the given power supplies. With an insufficient setup, the discharge may ignite but will shut down immediately. This process will repeat itself with significant frequencies that may only be observed via oscilloscope measurements. In a data acquisition system with a low measurement rate, the discharge potential will vary over a wide range at a constant current, between 0 V and the ignition potential. The power supplies cannot control the high transients in voltage and current during the initial breakdown, so the discharge is shut down entirely due to over-control of the output parameters. Adding resistance in the discharge will limit the maximum current and decrease the sharpness of the transients due to the additional voltage drop at the resistor itself.

The high-power ignition procedure of the electride cathode makes use of the discussed resistor effect, driving a significant current of 2 A over a resistor of 100 Ω in the ignition branch, generating an additional voltage drop of 200 V. The electrical schematic with the high-power ignition branch is depicted in Fig. 3. *Delta Elektronika SM660-AR-11* power supplies are used to generate the ignition potential and drive the initial current at this branch.
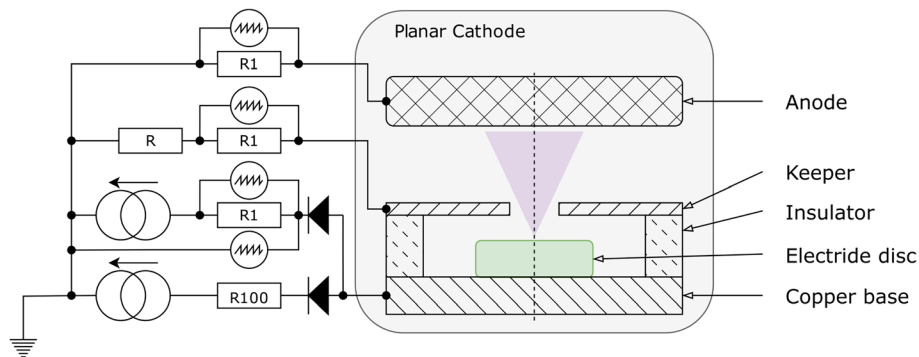
Fig. 3 Electrical Schematic for the high-power ignition procedure. Optimized for convenient laboratory ignition to characterize the materials' ignition behavior [6]

To characterize the electrical parameters during discharge, 1 Ω resistors are added in line with the keeper, the anode, and the ignition branch. The voltage drop over these shunt resistors is measured using a 4-channel differential oscilloscope *PicoScope 4444*, with high voltage probes *PicoSconnect 442* attached. The fourth channel records the actual ignition potential of the discharge. The oscilloscope is logged using the *PicoScope 6* Software.

Ignition cycling approach

Since there is significant uncertainty about the heaterless ignition potential of the C12A7 electride, the main objective of the cycling test campaign was to evaluate the characteristic of the material rather than the verification of the mission-relevant requirements. Therefore, no predetermined number of cycles was to be achieved after the test would be aborted. Instead, the performance of the cathode will be compared with similar cycling tests of comparable cathodes from literature [3, 15, 20] to assess its general viability.

For the execution of the test, an automated sequence was applied to the cathode, controlled via a dedicated *LabView* software. The following order of activities was implemented:

- Set constant mass flow rate to 20 sccm Kr
- Activate operational supply (50 V at 2 A)
- Activate the ignition supply (400 V at 2 A)
- After 2 seconds, shut off of ignition branch
- After 5 seconds, shut off of operation branch
- Shut off of mass flow rate
- Cooldown for 30 s (Later increased to 90 s)
- Start a new cycle

The cycling test was initially operated with about one ignition per minute, which was later increased to one ignition every two minutes. This allowed sufficient cooldown of the electride material and the cathode body to reduce cross-influences between the corresponding ignition cycles. Although the much higher frequency of ignition testing has been reported in literature [15] and much lower operational temperatures were expected in our test, a conservative approach was chosen since the radiated heat will also reduce significantly with lower operating temperatures.

For each ignition cycle, a dedicated oscilloscope trace of the measurement was saved to be analyzed. With a dedicated *MATLAB*-script, the peak potential of the ignition was established for each cycle. Furthermore, the script allowed the classification of the ignition cycles between ideal ignitions and different failure modes, allowing a quantitative analysis of the ignition performance. Although the discharge ignited into plume mode most often, at times, it also did so in spot mode. The ratio of the peak-to-peak emitter current over the total emitter current was used to evaluate the plasma condition.

In addition to the ignition cycles, IV characteristics were conducted at dedicated milestones in operation to evaluate any change in the performance of the cathode. For this, the cathode was ignited manually with the high power approach, and an automated characteristic sequence was applied that would step-wise decrease the emitter current

limit starting from 2 A. Here, multiple traces of the oscilloscope were averaged after sufficient time was granted for the discharge to settle at the set current limit.

Results

As shown initially, reliant and repeatable ignition of electride cathodes is a severe challenge. However, with the design and electrical approach described, a configuration was found that exhibits sufficient performance to justify a thorough description of the ignition process. A very reliant laboratory setup was established with the high-power approach that allows repeated characterization of the material's performance. The following subsections will detail the ignition characteristic and present the results of two ignition cycling campaigns.

High-power ignition

The high-power ignition approach, as it was introduced in "High power ignition procedure" section, has been used in countless test campaigns to evaluate the material's performance since it is very reliant with a success rate close to 100 %.

Figure 4 depicts an automated high-power ignition sequence as it was used during the ignition cycling campaign, with the sequence introduced in "Ignition cycling approach" section. The particular cycle represents an ideal ignition sequence. The ignition at a potential below 400 V can be identified, after which the ignition supply is operated for 1 s before being shut off, as determined by the drop of the current and potential at the emitter ignition branch to 0 V and 0 A respectively. Furthermore, the currents at the keeper and the anode are reduced. At the 5.5 s mark, the script shuts the discharge off.

Although noisy, the mean of the current is stable right from the beginning. Only a slight counteracting trend in the keeper and anode current is registered, which still adds to the set current limit at the operations supply. During the ignition sequence, a high peak, particularly at the anode current, is observed, which is depicted in more detail in Fig. 5, where the first 50 ms are plotted.
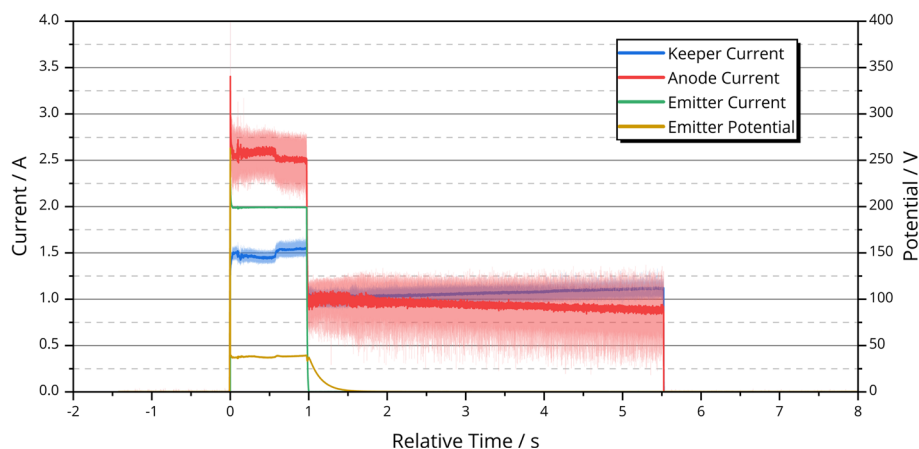
Fig. 4 Ideal automated high-power ignition sequence used during the ignition cycling test. The ignition and operation supply current limits are set to 2 A, respectively. Maximum ignition potential at 400 V
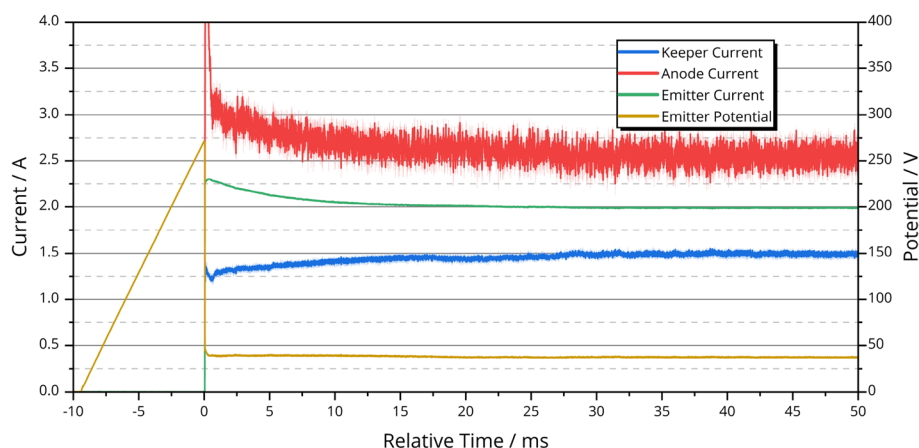
Fig. 5 Detailed view of the ignition sequence's ignition moment depicted in Fig. 4. Ramping of ignition potential and inrushing currents and transition to nominal operation in only a few milliseconds

In the more time-resolved characteristic, the ramping of the ignition potential can be observed much better. At the set current limit, the supply takes less than 10 ms to reach the ignition potential, in this particular case at around 275 V. At the moment of ignition, a high current reached the anode, while the keeper did not establish such a peak. It can be assumed that the resistor in line with the keeper acts as a current limiter. After only a few milliseconds, the discharge reaches a stable condition and continues to operate there for the remainder of the cycle, as discussed. Overall, this ignition sequence is incredibly fast and can be classified as quasi-instantaneous.

The high-power ignition procedure is also stable over a broader range of discharge parameters. This includes the current limits at the ignition supply, the current limits at the operations supply as well as the mass flow rate of the system. Here, much lower flow rates can be sufficient to ignite and operate the system. Also, the current limit can be reduced to operate continuously down to only some hundred milli-ampere. The results of such characterizations will be published in a separate paper.

Ignition cycling

A new emitter was installed in the cathode for the ignition cycling campaign, and a fully automated script according to the sequence introduced in "Ignition cycling approach" section was applied. Data acquisition was realized by the controlling LabView program and the attached differential oscilloscope. Not logged has been the temperature of the cathode body during the test. However, in a proceeding test, in which the viability of the script, data acquisition, and data analysis was tested, a constant temperature of around 30 °C was observed at the body after about 1 h of cycling, after which it stayed constant there.

In the cycling campaign, more than 3300 ignitions were reported in total, after which the campaign needed to be finalized since insufficient electride material was available to continue testing. However, next to the ideal ignition sequences presented in the previous section, different failure modes were observed, which needed to be analyzed. Furthermore, two shorts due to material degradation had to be resolved, for which the cathode had to be removed from the chamber. Figure 6 depicts the general
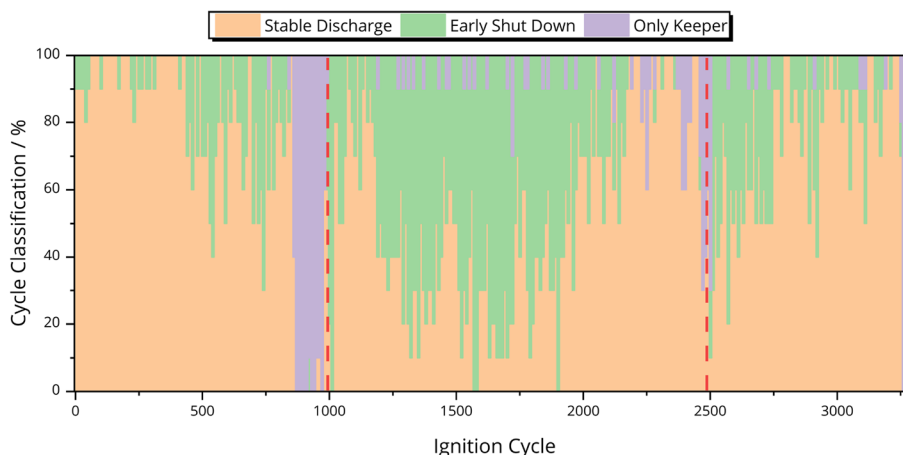
Fig. 6 Classification of discharges during ignition cycling. Batches are accumulated into batches of 10 cycles each. Depicted are ideal discharges and failure modes

development of the status throughout the test campaign, where the different classifications in batches of ten cycles each are plotted.

Failure modes during the cycling included:

- Micro-Arcing during the discharge operation.
- Premature shut down of the discharge.
- Premature ignition of the discharge only by the operating potential.
- Discharge / electrical short with current only at the keeper. No anode current.

While micro-arcing has not been a severe issue for the ignition behavior, premature shut downs and operations without anode current needed to be identified and analyzed. Indeed, phases with exclusive cycles without anode current indicate a clogging of the keeper orifice due to depleted electride material that did build up in the cathode.

From the schemata in Fig. 6, it can be seen that at close to 800 cycles, such a phase of only keeper current was established, which could only be resolved by dismantling and cleaning the cathode. In the range of 1250 to 2000 cycles, most cycles shut down early, indicating insufficient operational supply control. However, stable discharges are observed after this phase, possibly due to some internal conditioning at the electride emitter. At about 2500 ignition cycles, another phase with only keeper current starts, why the cathode was cleaned a second time. Afterward, the majority were again in good discharge conditions until a third phase of only keeper currents finalized the campaign.

Cleaning the cathode included venting the vacuum chamber, disassembling the cathode, and removing debris. Afterward, the cathode was reassembled and integrated into the chamber to continue testing. Small material chips were observed at the keeper insulator during these cleaning instances. Degraded emitter material was deposited between the emitter and the keeper. At some point, this excessive material reduced the resistance between the keeper and the emitter and clogged the keeper's orifice. Figure 7 shows some of the depleted material at the insulator.
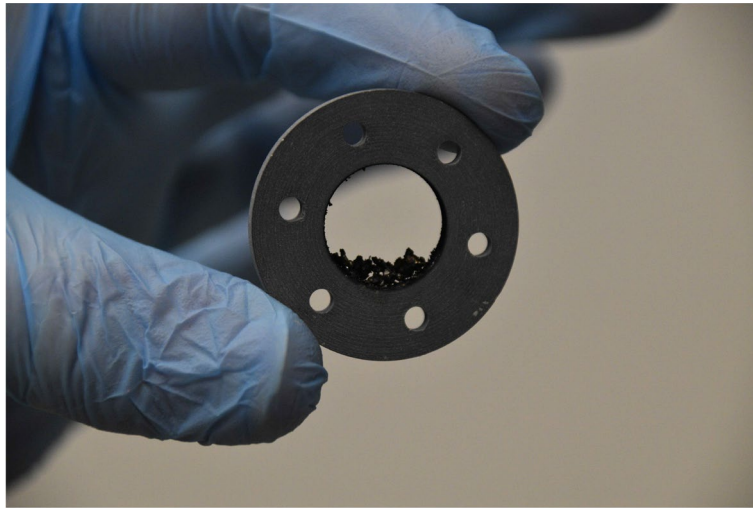
Fig. 7 Depleted emitter material that led to the clogging of the keeper orifice and had to be removed twice during the cycle campaign
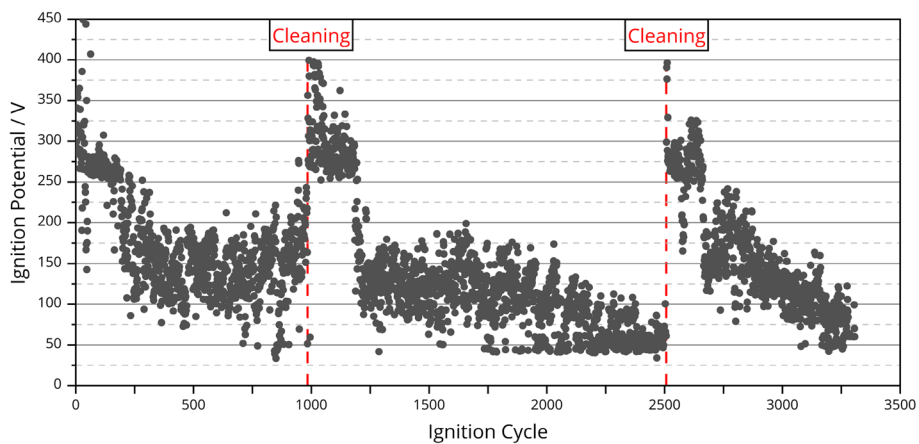

Fig. 8 Ignition potential for each cycle. Depicted are only stable discharge cycles and early shut downs

Quite interesting has been the analysis of the ignition potential for each cycle, evaluated by the maximum potential logged at the oscilloscope. Figure 8 depicts the corresponding ignition potential at each cycle. After about 200 cycles the potential decreases from about 300 V down to the range of 200 V to 100 V. After the first and second cleaning, the potential is back at 300 V before falling to the range of 200 V to 50 V.

It is expected that the reduction in the ignition potential appears due to the depletion of degraded material between the keeper and emitter potential. However, the exact mechanism is not clear yet. And that this data is not an error in the data acquisition system was supported by the fact that, at times, ignition occurred when only the operating supply was activated, which was set at a maximum of 49 V. Such an exemplary cycle is depicted in Fig. 9, in which clear currents at the keeper and the anode are observed before the automated script applies the ignition potential.

Lastly, IV characteristics were to be taken in regular intervals to evaluate the potential degradation of the cathode performance. Therefore, an automated script would operate
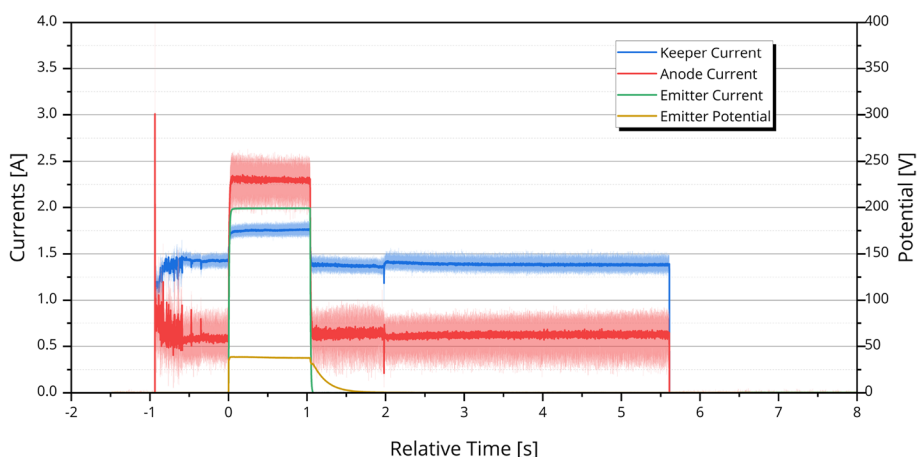
Fig. 9 Ignition of the plasma discharge only with the operating supply, set at a maximum potential of 49 V. In the automated script, the ignition supply is activated 1 s later
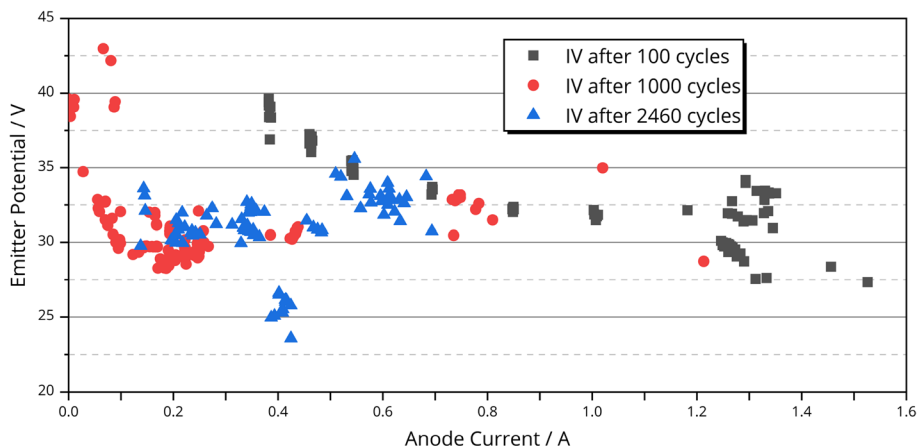
Fig. 10 Chracteristic of Discharge potential over the discharge current at different stages during the cycling test. The shift towards lower discharge currents can be correlated to a coating at the inner surface of the anode, changing the relation of currents towards the keeper

the cathode at different current limits after manual ignition, starting at 2 A emitter current limit and stepwise decreasing. However, due to the required cleaning procedures, the testing was not as regular as desired. Still, some data could be acquired. The relation between discharge current and discharge can be seen in Fig. 10.

Several interesting facts can be derived from the characteristics: In general, the discharge potential stays relatively constant, slightly above 30 V over quite an extensive range of discharge currents before slowly starting to increase and eventually steeply increasing at some hundred milli ampere. This characteristic has been observed repeatedly with the given cathode and would be in general in line with characteristics observed from other hollow cathodes in literature [18, 20]. A more detailed discharge characterization will be presented in a separate publication.

However, the shift towards much lower discharge currents is quite evident in the characteristic. Although tested at the same emitter current ranges, much lower discharge

currents are observed for the later characteristics. This aligns with the much higher keeper currents observed for the latter characteristics (not depicted). The reason for this was simply a coating of the inner surface of the anode, significantly increasing the resistance there. It is assumed that during the first phase of only keeper discharges, where more than 200 such cycles were conducted, depleted emitter material was sputtered out of the keeper orifice onto the anode. During the cleaning of the cathode, this (clear) coating was not discovered why it was not removed. Besides this general change in the current ratio at the keeper and the anode, no severe potential degradation is observed.
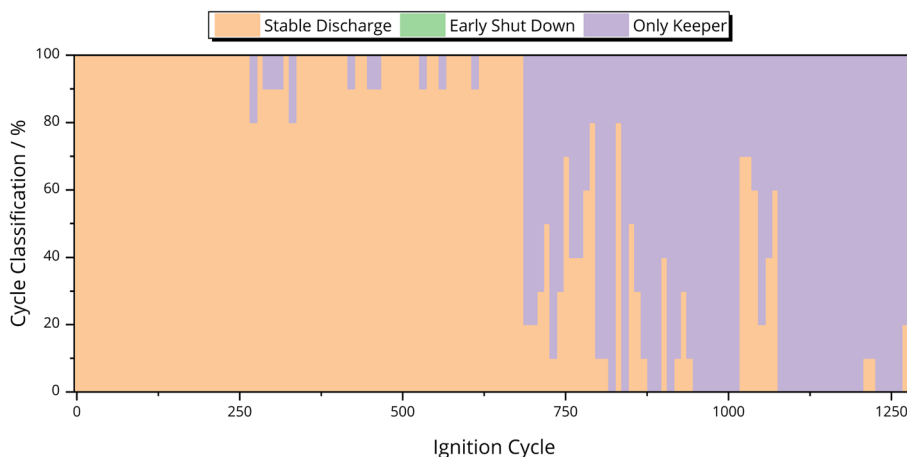
Low flow rate ignition cycling

One of the most severe points of criticism for the electride cathode will be the required mass flow rate for the ignition and operation of the discharge. While 20 sccm Kr flow rate might be reasonable for the heaterless ignition compared to reported values in literature [15], it is much too high for continuous operation. In a dedicated campaign, ignition and operation of the cathode were achieved at much lower flow rates, down to even 1 sccm Kr. Details of this campaign will be presented in a separate publication shortly.

Still, a second ignition cycling campaign was conducted at a lower flow rate, for which 6 sccm was chosen, as it promised reasonable performance with the selected cathode design. The only change in the design was the reduction of the keeper orifice diameter down to 0.75 mm. However, the electrical setup and procedure for the cycling campaign was slightly adapted: since the focus was on the material characteristic, only the ignition branch was used. After applying the ignition potential, the discharge was operated for 5 s before being shut off.

Like before, the first several hundred cycles were nearly perfect. Most cycles were classified as only keeper discharges after around 700 cycles. This is depicted in Fig. 11.

Also, the ignition potential exhibits similar behavior as before, the corresponding characteristic depicted in Fig. 12. For the first bunch of cycles, a plateau is established. At 6 sccm, this seems to be at around 400 V, so slightly higher than for the 20 sccm campaign. Still, the maximum ignition potential of 400 V at the supply was sufficient to

Fig. 11 Classification of cycles with 6 sccm Kr flow rate. Again, cycles are accumulated to batches of 10
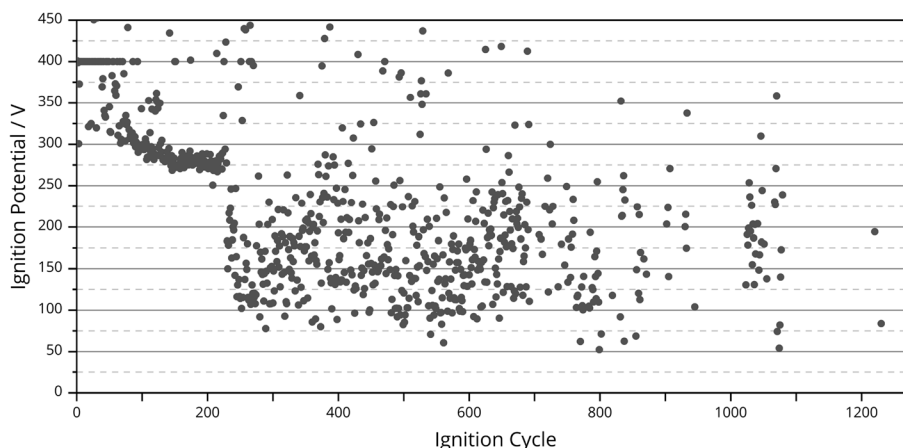
Fig. 12 Ignition potential for each cycle at 6 sccm Kr flow rate

achieve reliant and immediate ignition. Afterward, the ignition potential drops again to a range of 250 V to 100 V.

Since only the ignition supply was used for this campaign, no early shut downs were reported. However, the occurrence of only keeper cycles indicated a degradation of the emitter material as well as the clogging of the keeper, as observed before. This was confirmed once disassembling the cathode. Although sufficient electrode material was available, the cycling campaign was not continued, as the number of cycles for the project the cathode was developed in was already reached.

Discussion

A thorough evaluation of the performance of a plasma-based cathode using the C12A7 electride is mainly limited by the repeatability of operations and the fast degradation of material during operation. So far, only single discharge operations seem to be reported [8, 11, 12], or failures after a minimal amount of ignition attempts are reported [9]. However, with the presented design using the peculiar emitter geometry, the optimized composite material, and the dedicated electrical setup, a reliant design has been established, allowing detailed analysis of the discharge performance.

The focus of this publication has been on the ignition cycling performance of the cathode, while the characterization of the continuous operation will be discussed in a separate publication. For the ignition, a reliant approach was found that allows repeated automated testing of the cathode. Both ideal ignitions and failure modes have been presented that require a careful evaluation of the design in the future.

Due to the non-reliant operations of the electride cathodes reported so far, a comprehensive comparison of results is quite difficult. However, from the references introduced initially, the presented cathode seems to have a better heaterless ignition performance (i.e., ignition potential and required flow rate), a higher ignition cycling result, a wider range of operation (i.e., discharge current range), and a lower discharge potential during operation.

The work function of the C12A7 electride material is a much-discussed property that will have a crucial impact on the materials' performance for numerous applications.

However, the presented values in the literature do vary quite significantly. Multiple aspects do influence this material property, like the method of manufacturing and the method of measurement. However, in most reports, work function values in the range of 2.4 eV to 2.8 eV are reported.

This would be in the range of LaB_6, a common and well-known emitter material. Consequently, quite similar characteristics would be expected. No such direct comparison can be presented for our very own cathode since the cathode has not been tested with LaB_6 inserts. However, others have conducted similar tests, as presented initially, with a pretty clear trend that the electride will require lower heating power for operation.

Furthermore, with a similar work function to LaB_6, it can be questioned why the electride cathode is being tested in a heaterless configuration. Indeed, Hua et al. [9] argue that the high-voltage pulse might be the leading degradation mechanism of the emitter, which is why a heated cathode was designed. Eventually, the heaterless ignition is used to clean the emitter material's surface, improving the nominal operating conditions [21].

Still, the results of the test campaigns presented here show that heaterless ignition of the electride cathode can be achieved entirely reliant and repeatable. Several thousand such ignition cycles may be a decent starting point for the first reported tests with the material in literature. However, the performance will still lack the number of cycles behind the most mature systems using LaB_6 [3, 15]. Still, the nominal ignition potential and the required flow rate can be at least on par with the results presented in the literature. With thorough analysis and testing, similar results of an electride cathode should be feasible. Eventually, repeated ignition at only 6 sccm of Kr is quite impressive.

The most crucial challenge observed during the campaign was the degradation of the material, which led to the depletion of small emitter flakes between the emitter and the keeper, eventually altering its performance. Ultimately, the keeper orifice clogged, preventing current emission over the plasma toward the anode positioned in front of the cathode. This would be a severe lifetime-limiting factor that will require careful evaluation in the coming future.

However, this degradation might also have indicated some interesting characteristics: as reported, the ignition potential fell significantly with progressing degradation and, consequently, depletion of the material inside the cathode. Eventually, the cathode ignited already at merely 50 V, as observed during both ignition cycling campaigns independently. This would be a perfect characteristic for any heaterless cathode. However, although this behavior was observed repeatedly, no clear reason for such a low ignition potential could be identified. Theories include the very short distances between the emitter and the keeper, ohmic heating, which leads to thermionic emission of the material, or higher gas pressure in the emitter surface region. Either way, replicating this effect will be a huge advantage of this cathode.

Conclusion

A detailed description of the ignition characteristic of a C12A7 electride cathode has been presented. With careful cathode design and the electrical setup to control the discharge, reliant and repeatable ignition can be achieved. This allowed the conduction of two ignition cycling campaigns. In the first, 3300 heaterless ignition cycles have been completed successfully. However, due to material degradation, the cathode needed to be

cleaned manually twice. In a second test, several hundred ignition cycles were reported at only 6 sccm Kr mass flow rate and an ignition potential below 400 V.

With the degradation of the emitter material during the cycling, a significant reduction of the ignition potential was observed. In the most extreme case, heaterless ignition was achieved at only 50 V. Unfortunately, the exact reason for this behavior could not yet be identified. Overall, further improving the resilience of the electride composite material will be necessary to improve the cathode's performance, and using the low ignition potential performance will provide a significant advantage for the cathode compared to state-of-the-art cathodes.

Availability of data and materials
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability
Not applicable.

Declarations

Competing interests
The authors declare no competing interests.

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