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Characterization of a C12A7 electrified plasma-based cathode using different keeper orifice sizes

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Abstract

For the operation of electric propulsion systems in space, efficient electron sources are crucial components. Hollow cathodes have been established for many applications since they allow sufficient current ranges at reasonable power requirements and have been proven to operate for several thousands of hours. New approaches are being evaluated to improve these cathodes' general performance. This publication presents an extended characteristic of a heaterless plasma-based cathode using the emitter material C12A7 electrified. The focus is on the relationship between the discharge potential and total discharge power over the discharge current. Furthermore, a characteristic of the discharge performance at lower mass flow rates is presented and discussed. The discharge potential is generally quite constant for a wide range of discharge currents, typical in the range of 30 V and only increases steeply for low discharge current ranges. Successful heaterless ignition and stable operation have been achieved down to 2 sccm krypton flow rate.

Keywords: C12A7 electrified ceramic, Disc-shaped cathode, Heaterless cathode, Discharge characteristic, Keeper orifice size

Introduction

Sufficient electron and plasma sources are required to operate electric propulsion systems in space, like the gridded ion thruster or the Hall-effect thrusters. Furthermore, spacecraft charging effects due to the exposure to the plasma in orbit and the operation of the plasma thrusters, neutralization of the spacecraft by the emission of electrons will be required. Hollow cathodes are commonly used in the current range above several hundred milliamps for these tasks due to their much higher efficiency than pure thermionic or field emission devices. Recently, an extended review of the current state of these electron sources has been presented in the literature [1].

To improve the state-of-the-art of hollow cathodes, several approaches are under evaluation. This includes the heaterless ignition of the plasma discharge [2, 3], as it might allow a more accessible and more reliable design of the cathode and faster operation procedures. In addition to this, new emitter materials are being tested, like the C12A7 electrified.

From the authors, recent publications include the operation of a C12A7 electride cathode for more than 950 h continuously [4], as well as the ignition cycling of a heaterless C12A7 electride cathode for up to 3300 cycles (Drobny C, Tajmar M: Concerning the Ignition of a C12A7 Electride Plasma-Based Cathode, submitted). This publication will now focus on the general characteristics of the discharge, evaluating its performance with slight changes in the operation setup. Furthermore, slight variations in the design, i.e., the size of the orifice, allow a significant reduction in the mass flow rate for ignition and operation. For the testing, each configuration is tested over a range of emitter current limits, at which the cathode is ignited and operated shortly. Afterward, the discharge is ignited at a high emitter current limit and stepwise reduced to lower current limits. Each point of operation is repeated several times.

After a short literature review in the following section, the experimental setup and testing procedure will be described in [Experimental](#) section. Results will be presented for the ignition and operation conditions and the current sweep procedures in [Results](#) section. Eventually, a new approach with multiple orifices will be tested, as introduced by McDonald et al. [5], and the results will be discussed.

Review of literature

The peculiarities of the cathode from this publication include the heaterless ignition, the disc-shaped emitter design, and the use of C12A7 electride as emitter material. For the heaterless cathodes in literature, the focus is more on the ignition behavior and the verification of endurance operation, which is why no extended IV characteristic is shared. However, Conversano et al. report a discharge potential of 23 V at 4 A discharge current, which increases to 38 V at 1 A. The cathode was operated in a floating-keeper configuration at a mass flow rate of 3 sccm xenon. Other than that, Lev et al. [3] reported a discharge potential of 50 V for the mass flow rates of 2 sccm to 3 sccm xenon, which increases steeply when reducing the flow rate down to 1 sccm to above 100 V. The cathode was tested at discharge current from 0.5 A to 1.1 A also in a floating keeper configuration.

Not much data is available in the literature for cathodes using disc-shaped emitters. Jousset et al. [6] and Potrivitu et al. [7] reported slightly different characteristics of the LaB_6 cathode. While Jousset et al. report a nearly linear increase of the discharge potential from 15 V to 30 V at discharge currents from 2 A to 20 A, Potrivitu et al. report an increased discharge potential when decreasing the discharge current, starting from 20 V at 12 A up to 60 V at 2 A. In addition, Jousset et al. report a strict increase in the discharge potential for a reduction in the flow rate down to 2 sccm. The main difference in the operation of both publications would be the active heating of the cathode for the tests from Jousset et al., so it can be expected that the general increase in the low current regime for cathodes operating in self-heating mode results from the required heating power of the plasma discharge.

For the electride cathodes in literature, published results have been quite rudimentary. In most cases, reaching stable and reliant operating conditions seems to be still the most eminent challenge as to why repeated characterization can not be achieved sufficiently. Rand [8] reports an discharge potential of about 50 V over the discharge current range from 1.5 A to 4.5 A. The potential increases for lower discharge currents and both the

chosen orifice size and the flow rate (4 sccm to 10 sccm xenon) have a significant influence on the performance.

Guglielmi et al. [9] reported an increasing discharge potential of 60 V to 150 V at an discharge current range of 250 A to 100 A. Hua et al. [10] reported discharge potentials in the range of 30 V to 55 V for mass flow rates of 2 sccm to 10 sccm, for the discharge tested in the range of 0.5 A to 2 A.

Experimental

All tests have been conducted at the Institute of Aerospace Engineering at TU Dresden. The vacuum chamber has a total volume of 4.5 m³ and a 10 000 Ls⁻¹ cryogenic pump attached to it. The base pressure of the setup is in the range of 2×10^{-8} mbar. For the maximum flow rate of 20 sccm Kr, a pressure in the range of 1×10^{-4} mbar did settle, which reduced to around 1×10^{-5} mbar for only 2 sccm Kr flow rate.

Electride cathode design

A planar cathode setup has been used for the campaign, which was used in the nearly identical configuration for previous tests, like the endurance operation for more than 950 h [4] as well as the ignition cycling test (Drobny C, Tajmar M: Concerning the Ignition of a C12A7 Electride Plasma-Based Cathode, submitted).

Figure 1 depicts a cross-sectional schematic of the cathode. The cathode base is made of copper to extract excessive heat from the emitter disc, which is directly attached to it. To mount the emitter disc, a particular electrical conductive adhesive is used. An optimized electride material manufactured by Fraunhofer IKTS in Dresden was used for the emitter. To improve the material properties for its use in the cathode, a refractory metal is added before the final sintering process to the electride material, improving its thermal, electrical, and mechanical properties. This process has been described in the literature [11]. For this particular campaign, 30 Vol.% titanium had been added to

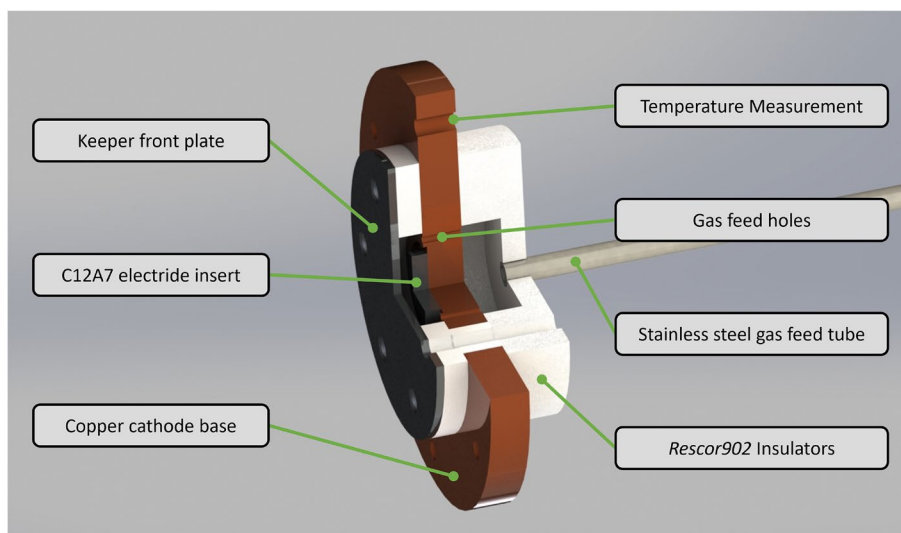


Fig. 1 Cross-sectional view of the planar cathode schematic with major components labeled

the electrified. For all tests presented in this campaign, one single insert was used for all configurations.

The keeper is made of sheet metal and positioned via an insulator made of the machinable ceramic Rescor902 about 1.5 mm in front of the emitter sample. Due to the keeper being made of sheet metal, a variety of orifice variations can be easily manufactured with a laser cutter. For the campaign, four different keeper configurations were tested: three having a single orifice with a diameter of 1 mm, 0.75 mm and 0.5 mm respectively. In addition to that, one *multi-orifice* configuration was tested, having 91 holes of 0.1 mm each, at a distance of 0.5 mm to each other. The multi-orifice is depicted in Fig. 2.

The cathode is operated in a diode configuration, with a half-sphere copper anode positioned about 3 cm in front of the cathode.

Electrical setup with separate branches

The cathode is being developed in the scope of the E.T.PACK-F Project, for which an in-orbit demonstrator is under development featuring an electrodynamic tether [12]. The cathode will emit the current collected by the tether to the space plasma. Since the potential of the anode (i.e., space plasma) can not be controlled, discharge control at the emitter had to be implemented for the laboratory testing, too. Furthermore, no significant potential was to be applied at the keeper due to the potential interaction with the surrounding plasma.

Throughout multiple test campaigns, an electrical setup suitable to fulfill all given requirements was established, which allowed reliable and efficient heaterless ignition and operation of the cathode. In principle, the emitter potential is controlled by two parallel branches: one generating the high voltage ignition potential, the other controlling the continuous discharge. With this approach, both branches can be optimized for the corresponding task, allowing improved characteristics of the discharge control. Furthermore, this approach will enable sufficient miniaturization of the power supplies for the corresponding branches. Details of the ignition process have

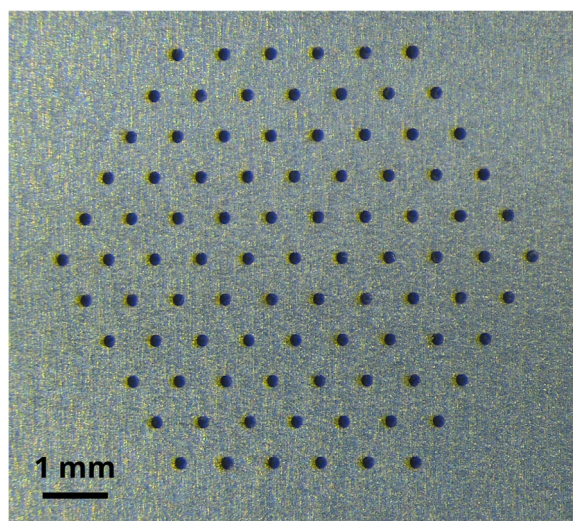


Fig. 2 Keeper multi-orifice with 91 holes of 0.1 mm each, 0.5 mm from each other

been discussed extensively in a separate publication (Drobny C, Tajmar M: Concerning the Ignition of a C12A7 Electride Plasma-Based Cathode, submitted).

A schematic of the branched electrical circuit is depicted in Fig. 3. While the emitter potential is controlled via the ignition and operation branches, the keeper and the anode are directly connected to the reference potential in the laboratory setup. 1Ω shunt resistors are added in each line to allow measurement of the current flowing and evaluation of the discharge stability using an oscilloscope. An additional load is commonly added at the keeper to reduce the current flowing at this electrode. Careful evaluation of this keeper pre-resistor significantly influences the discharge stability, the range of viable discharge currents (i.e., current reaching the anode), and the required power for the corresponding discharge current.

From the electrical setup, it is clear that the current controlled at the emitter will subdivide into the current at the keeper and the anode. Increasing the resistor at the keeper will reduce the current flowing at this electrode since the resistor will act as a current limiter due to the additional potential drop, pushing the ratio of keeper and anode current more towards the anode. However, much lower discharge currents have been achieved for lower keeper resistor values, which are required by the E.T.PACK mission, since the emitter current limit mostly limits the discharge. Consequently, a careful evaluation of a suitable electrical setup will be necessary, which is why for the test campaign presented here, each configuration was commonly tested for three different keeper resistors of 15Ω , 33Ω and 150Ω respectively.

The branched approach of the electrical setup will allow a dedicated miniaturization of the power control unit. Several miniaturized commercial-of-the-shelf converters have been tested successfully for the operation branch, the smallest being the Joy-It DPS5005 [13]. However, miniaturization has not been the goal of this campaign, but rather the generation of a broad set of data points to evaluate the performance of the electride cathode depending on several parameters. Therefore, the tests conducted here have been conducted using only the ignition branch, with significant resistors in line with the discharge control (i.e., 100Ω) to stabilize the discharge. A laboratory power supply (*Delta Electronika SM660-AR11*) has been used to control the discharge. For the measurement of the currents flowing and the discharge potential, as

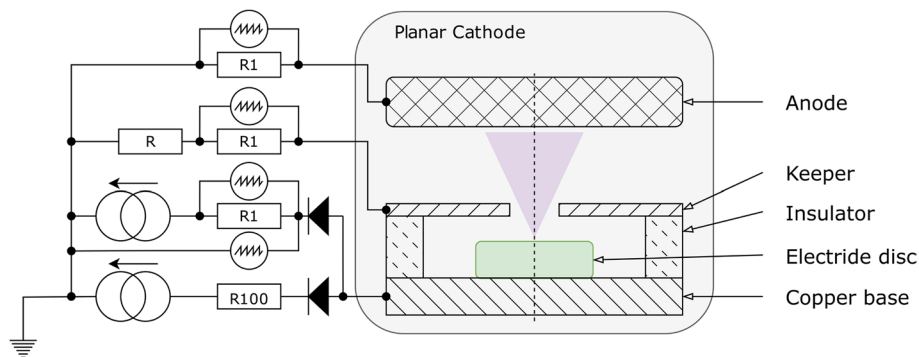


Fig. 3 Electrical setup used for the operation of the cathode. Emitter control with the parallel ignition and operation branch. Keeper with pre-resistor to control the current ratio at keeper and anode

well as the evaluation of the discharge stability, a differential oscilloscope with high-voltage probes has been used (*PicoScope 4444* with *PicoConnect 442*).

Testing procedure

To evaluate the performance of the cathode, two different approaches in the characterization have been conducted. For the *ignition-approach*, a set of parameters (see Table 1) was chosen, at which the discharge was then ignited by applying a [] potential of 400 V at the laboratory power supply. The discharge was held continuously for 10 s before being shut off by the automated script. Three such ignition and operation cycles were conducted at each set of parameters before changing to the next set. The data was logged using the differential oscilloscope with 10 MHz. For the data analysis, the mean of several such oscilloscope traces (each 100 ms long) was calculated for each point of operation. Only the first few seconds of operation were neglected to respect a certain unsteady behavior after ignition. Next to the mean discharge potential, peak-to-peak values of the oscilloscope traces were evaluated, to allow an indication of the plasma stability.

For the *sweep-approach*, the discharge is again set to a specific set of parameters (i.e., orifice diameter, keeper resistor, Kr flow rate) and ignited at the maximum emitter current limit of 2 A. At continuous operation, the emitter current limit is stepwise reduced in steps of 0.1 A down to 0.2 A every 10 s. For each stable discharge condition, a mean value is assessed from the data. Each of these sweeps is repeated three times back to back.

Results

Due to the reliability of the ignition and discharge conditions, an extensive set of parameters could be tested under stable conditions to evaluate the performance of the electrified cathode. The following section will introduce some of these results.

All tests were conducted with one single insert, with tests being conducted back to back with each other. More than 1000 ignitions were completed without any severe failures, and sufficient emitter material was available after the campaign to continue testing. To change the keeper orifice configuration, the vacuum chamber was vented, and the cathode was reassembled, during which the electrified was exposed to standard laboratory atmosphere conditions without any particular precautions. No special conditioning, backing for outgassing, or similar processes were required, but tests could be started once the dedicated pressure range was reached in the chamber.

As stated in the presentation of the electrical setup, the emitter current limit was varied to characterize the discharge of the cathode. However, the graphs are plotted

Table 1 List of parameters with corresponding values carried during the ignition approach and later during the sweep approach (but then with 0.1A emitter current limits steps)

Parameter	Unit	Values
Orifice Diameter	mm	1.0, 0.75, 0.5
Keeper Resistor	Ω	15, 33, 150
Kr Flow Rate	sccm	20, 15, 10, 6, 4, 3, 2, 1
Emitter Current Limit	A	2.0, 1.5, 1.0, 0.75, 0.5

over the discharge current, representing the current reaching the anode, i.e., leaving the cathode. As anticipated, the variation of the resistor in line with the keeper will influence the current ratio at the keeper and the anode. For the discharge current plots, this will shift the characteristic towards lower current values for a smaller resistor. To respect the influence of the keeper current on the total cathode performance, the total discharge power is plotted, which is calculated from the emitter current limit and the discharge potential.

Ignition cycles

So far, 1 mm orifices have commonly been used for our cathode, like during the endurance operation [4] requiring a mass flow rate of at least 10 sccm to ignite the discharge. However, with the reduction of orifice diameter, ignition was achieved at much lower flow rates. For the 0.75 mm orifice, ignition down to 3 sccm was commonly observed, while for the 0.5 mm orifice ignition even down to 1 sccm was achieved.

Figure 4 depicts the discharge current over the mass flow rate for a range of emitter current limits. Clearly, the much lower discharge current at similar parameters for lower keeper resistors can be identified. Furthermore, ignition down to 1 sccm Kr is achieved particularly for the higher emitter current limits. At the 15Ω keeper resistor, a particular reduction of the discharge current for lower flow rates can be identified, indicating much higher keeper currents at these conditions.

During the test of the 0.5 mm orifice, a severe noise was observed for flow rates below 4 sccm to a point where it would be unreasonable to operate the cathode. Although the discharge itself was stable, these conditions are deemed unfavorable. This can be particularly seen in the steep increase of the discharge potential for low flow rates, as depicted in Fig. 5. While operating in the range of 30 V for the higher mass flow rate quite consistently, the discharge potential quickly rises to the order of 50 V for the lower flow rates.

At the lower flow rates, no severe noise was observed with the 0.75 mm orifice. Figure 6 depicts the corresponding discharge potential over the discharge current for a range of emitter current limits. The arrows indicate the general trend of the characteristic for reducing the mass flow rate towards lower currents and higher potentials. The diagram suggests a much higher influence of the mass flow rate for the lower keeper currents due to the much wider spread, which was already observed by the drop in the current for the low current conditions. For the 0.75 mm orifice, the discharge potential is also in the range of 25 V to 35 V for nearly all the conditions, not increasing as sharply for the low flow rates as the 0.5 mm orifice depicted in Fig. 5.

Keeping in mind the requirements of the cathode, Fig. 7 depicts the total discharge power over the discharge currents for several emitter current limits, comparing the different orifice sizes at the constant keeper current of 33Ω. For the smallest orifice, this emitter current limit and, therefore, the total power can be much lower than for the larger orifices. In general, discharge condition below 20 W can be achieved for a few hundred milliamperes discharge current.

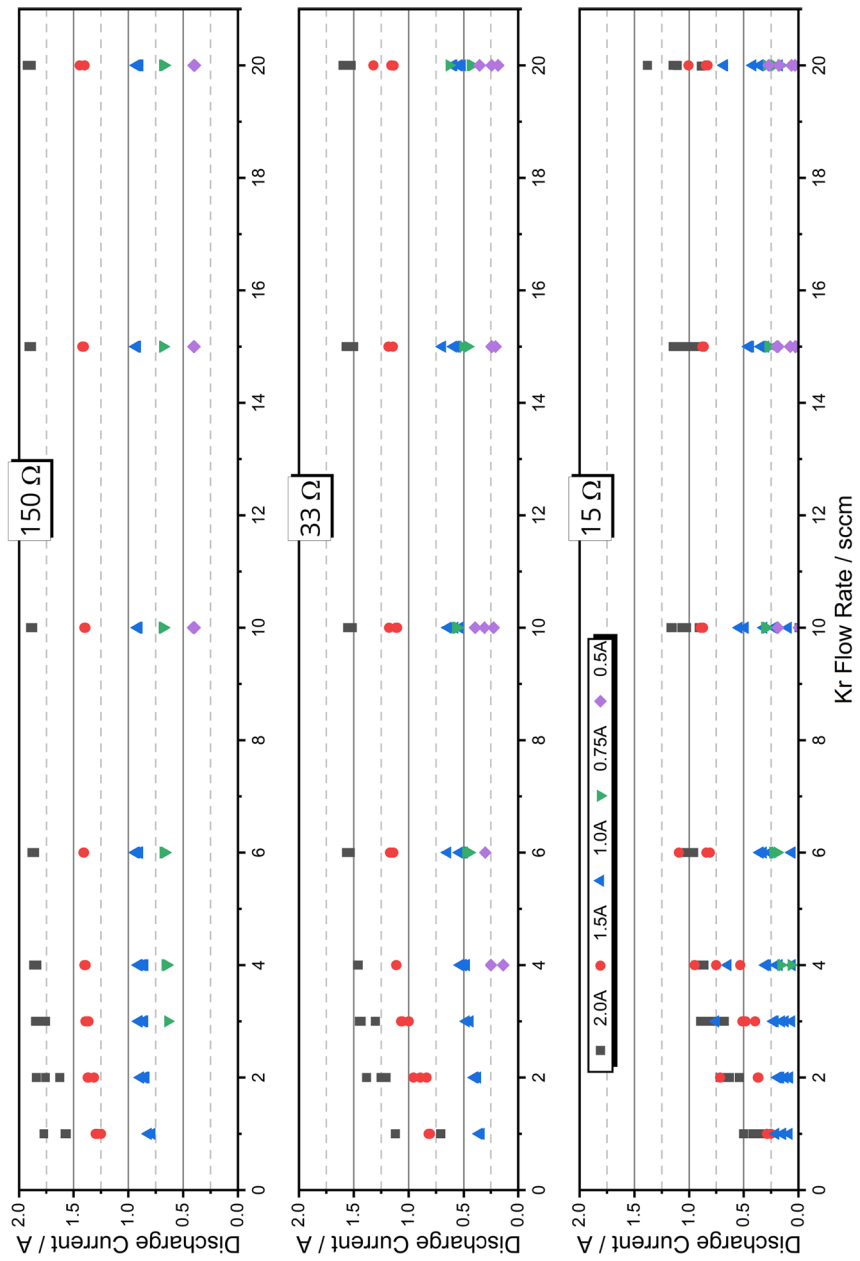


Fig. 4 Discharge current over mass flow rate at different emitter current limits for the smallest keeper orifice of 0.5 mm

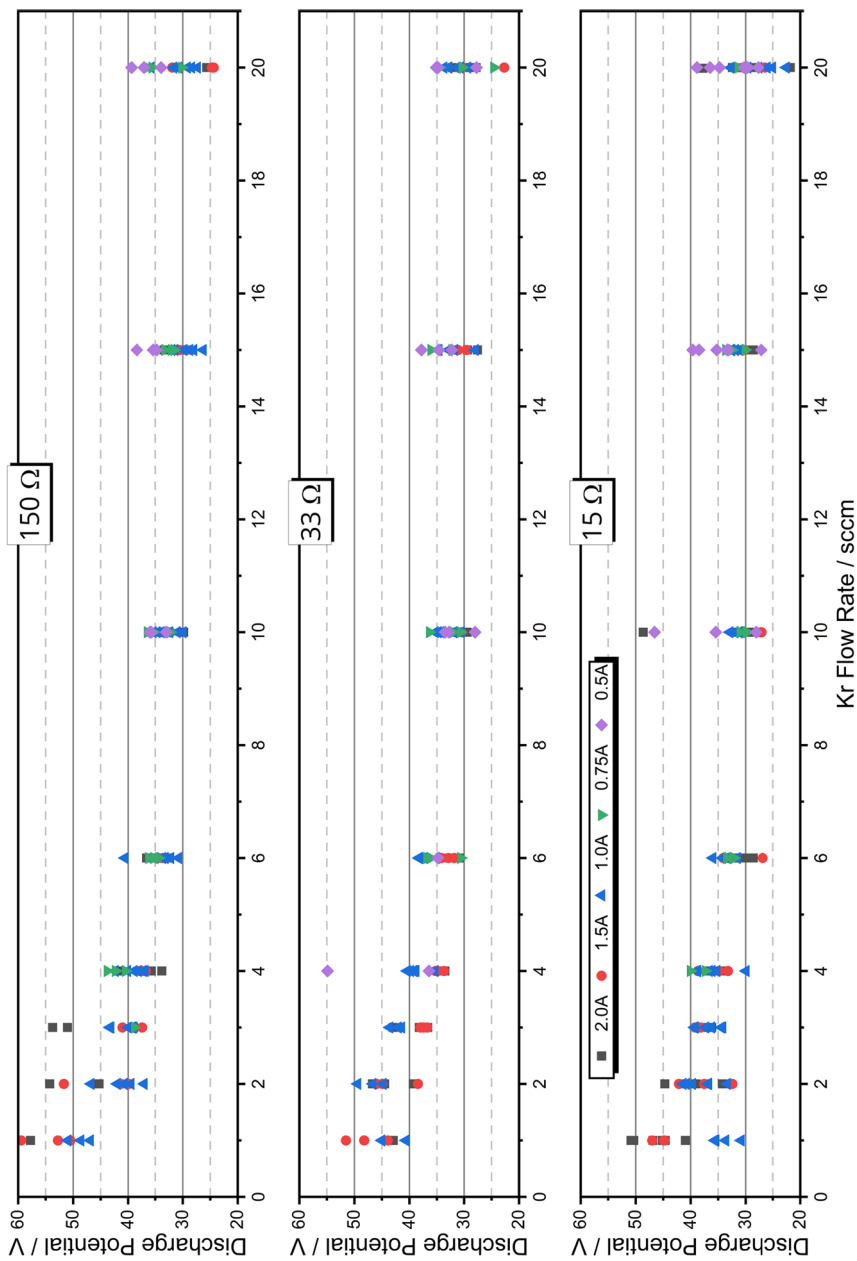


Fig. 5 Discharge potential over mass flow rate at different emitter current limits for the smallest keeper orifice of 0.5 mm

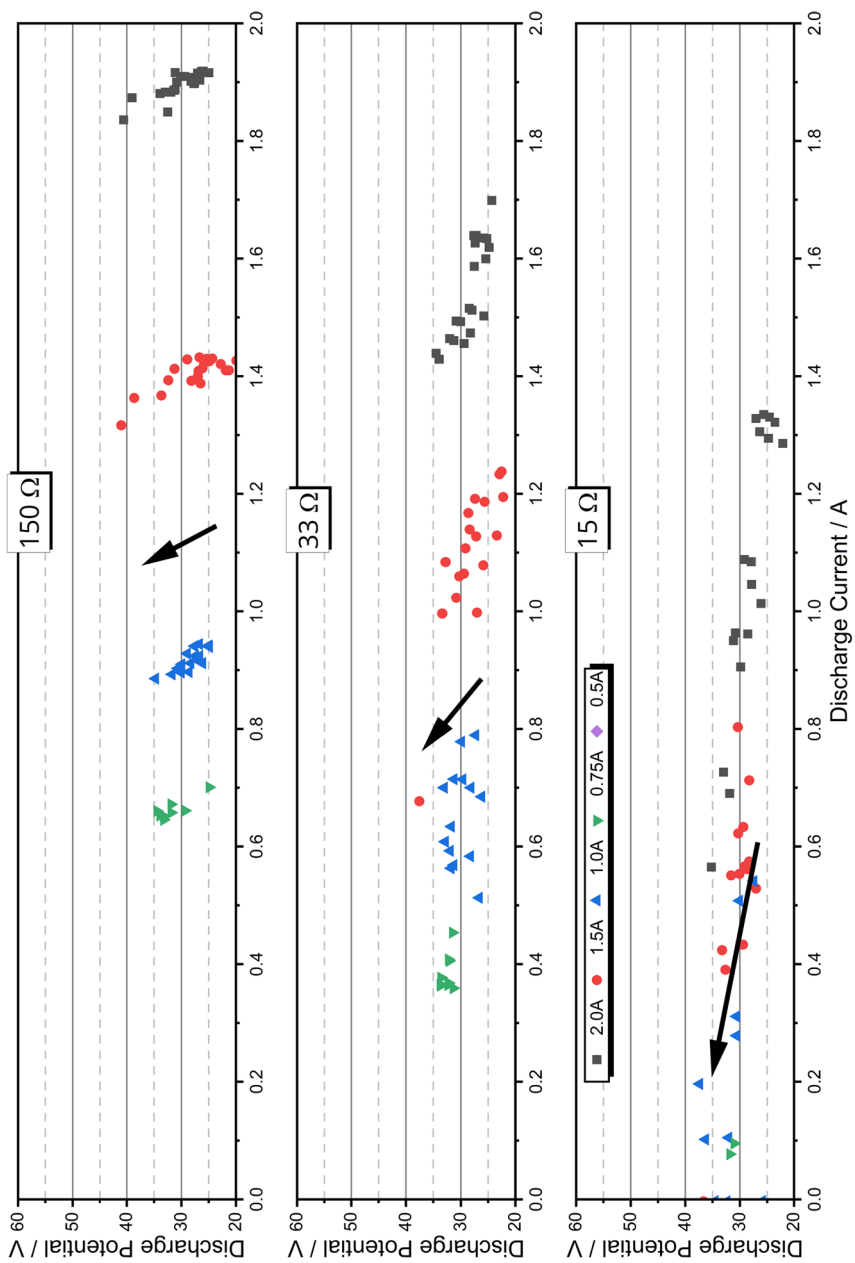


Fig. 6 Discharge potential over the discharge current at different emitter current limits for the 0.75 mm keeper orifice. The arrows indicate the decreasing flow rate

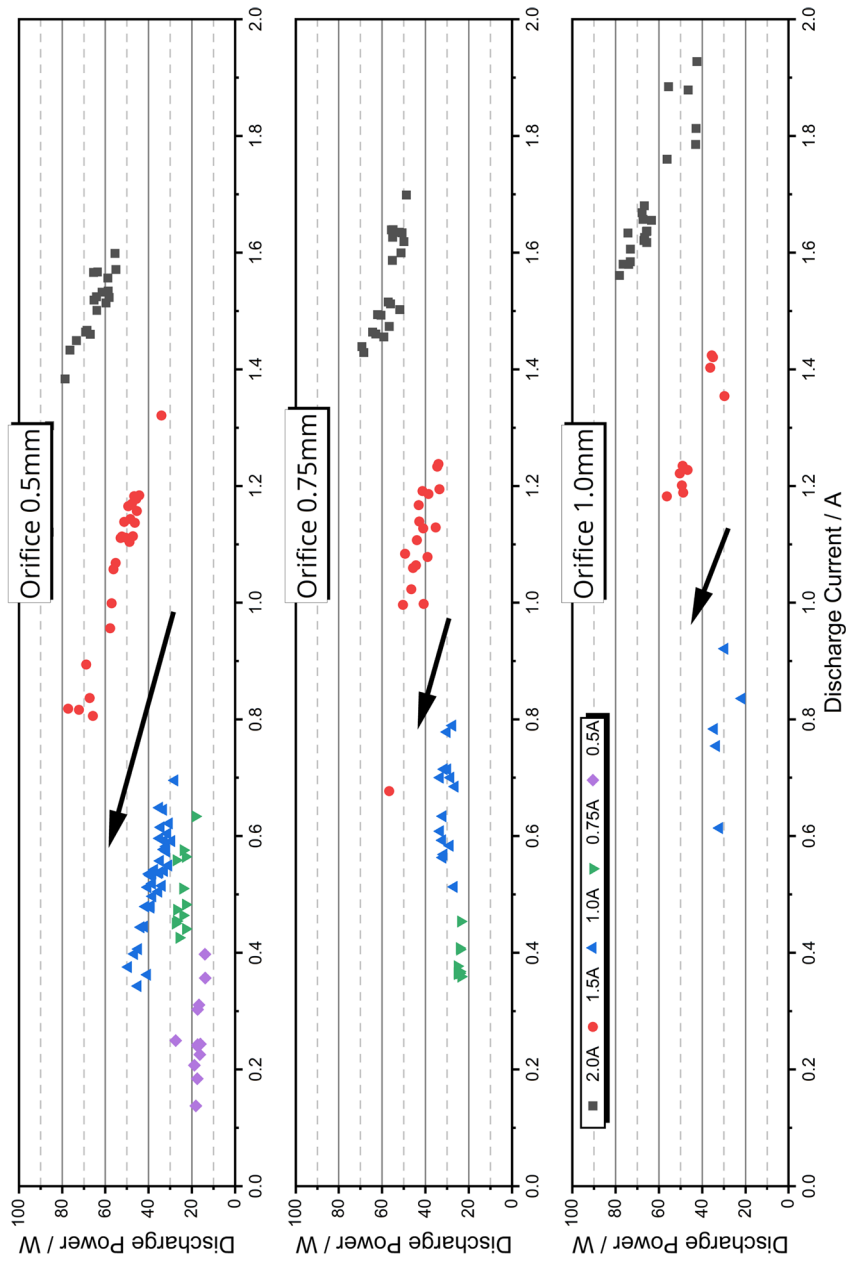


Fig. 7 Total discharge power over the discharge current at different emitter current limits for the keeper orifices at 33Ω keeper current. The arrows indicate the decreasing flow rate

Current sweeps

After the single ignition points, sweeps starting from the maximum emitter current limit were conducted. Although the discharge still needs to ignite at the set mass flow rate, the discharge was commonly more stable towards lower emitter current limits. This suggests the high influence of the set parameters for sufficient plasma control by the electronics. Furthermore, the discharge potential did not increase as severely for low discharge currents as observed before.

Figure 8 depicts the discharge potential over the discharge current for the smallest orifice. While for the 150 Ω keeper resistors, the consecutive emitter current limits are distinguishable, this is not the case anymore for the smaller resistor values due to the greater influence of the mass flow rate on the discharge current. While reducing the flow rate from 20 sccm down to 2 sccm, the discharge potential increases roughly 10 V. In addition, at 2 sccm the discharge conditions start to become more unstable, as observed by a wider variation in the characteristic particularly for the 150 Ω resistor. More stable discharge conditions are observed for all orifices, keeper resistors, and flow rates at low emitter current limits. Furthermore, the expected shift towards lower discharge currents for lower keeper resistors can be observed.

Due to the stable discharge conditions at lower emitter current limits, more characteristics at very low total powers have been observed, as depicted for the 0.75 mm orifice in Fig. 9. Now, conditions of 10 W and below have been repeatedly observed. Due to the slightly higher discharge potentials for the low flow rates, the total discharge power is also slightly higher for these lower flow rates. In addition, the characteristic with the 15 Ω keeper resistor exhibits a more inconsistent performance, indicating a much stronger influence of the variation in the keeper performance.

Lastly, the characteristic of the discharge power over the discharge current at the constant mass flow rate of 4 sccm (i.e., the baseline flow rate of the project the cathode is developed at) is plotted in Fig. 10. Since again ignition for the 1 mm orifice was not achieved below 10 sccm, no characteristic is added here. While both smaller orifices have similar trends in the characteristic, the 0.75 mm orifice requires a slightly lower discharge power. Furthermore, the high uncertainty in the signal for the 15 Ω keeper resistor makes this configuration non-ideal. However, both the 33 Ω and 150 Ω characteristics show pretty similar performances, with only a slight advantage for the 33 Ω configuration towards lower discharge currents.

Multi-orifice

The presented campaign results proved that reducing the single orifice diameter in the cathode design will allow significantly lower mass flow rates for the ignition and the operation of the electrified cathode. This aspect was to be tested for a multi-orifice configuration, which could be easily implemented in our design, as it was initially proposed by McDonald et al. [5].

In general, the cathode operated just fine with the multi-orifice configuration. Ignition occurred down to 3 sccm Kr flow rate, and the discharge potential was in line with the previously observed characteristics. The characteristic in Fig. 11 compares the performance of the multi-orifice keeper configuration to the single orifices at one

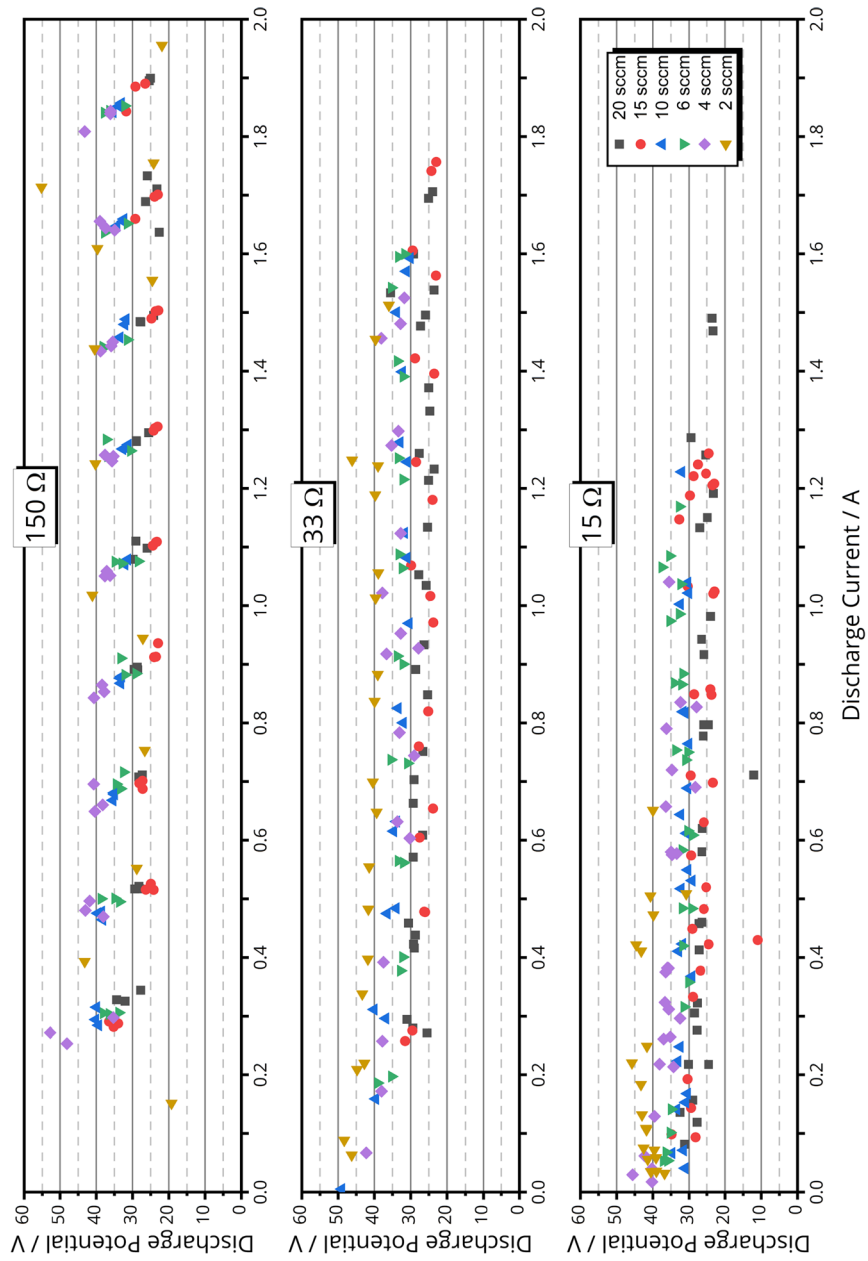


Fig. 8 Discharge potential over the discharge current at emitter current limit sweeps for the 0.5 mm keeper orifice

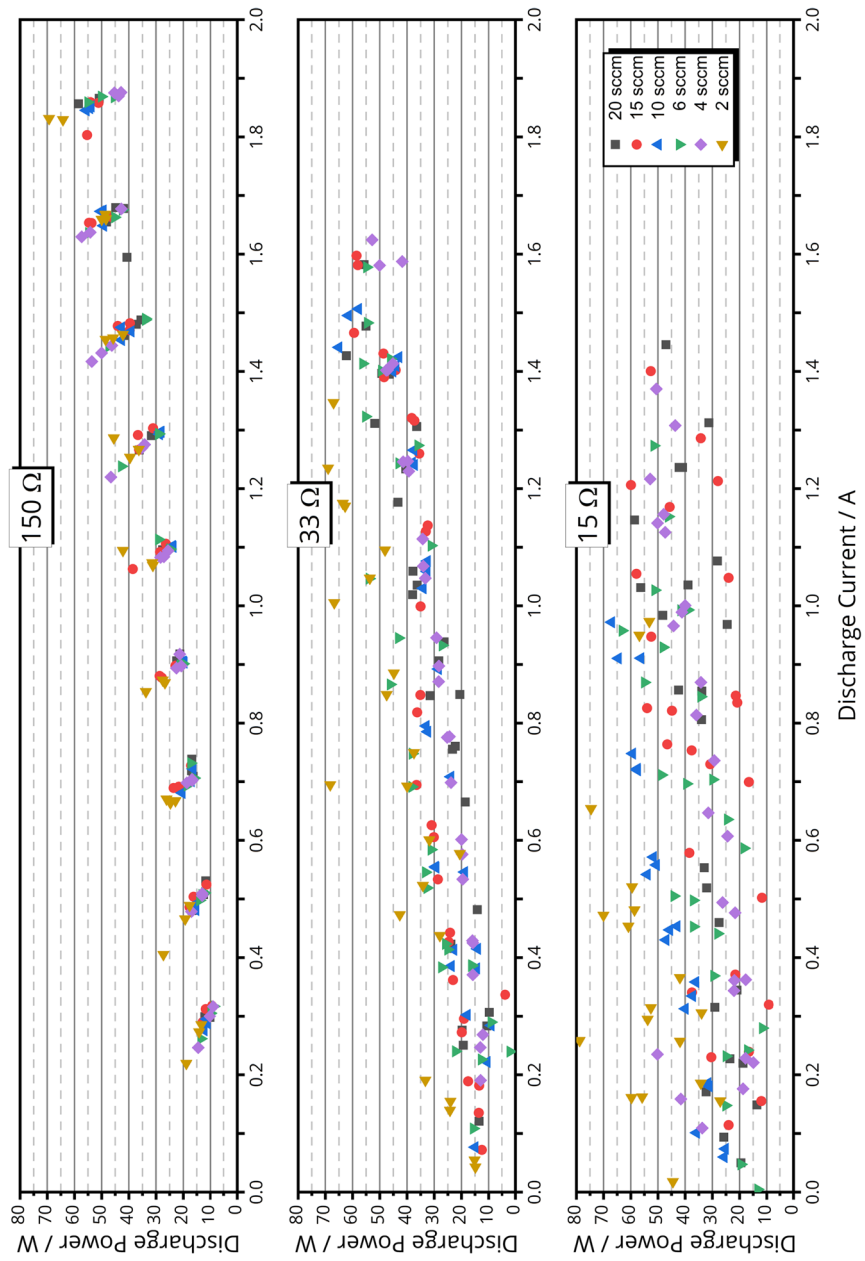


Fig. 9 Total discharge power over the discharge current at emitter current limit sweeps for the 0.75 mm keeper orifice

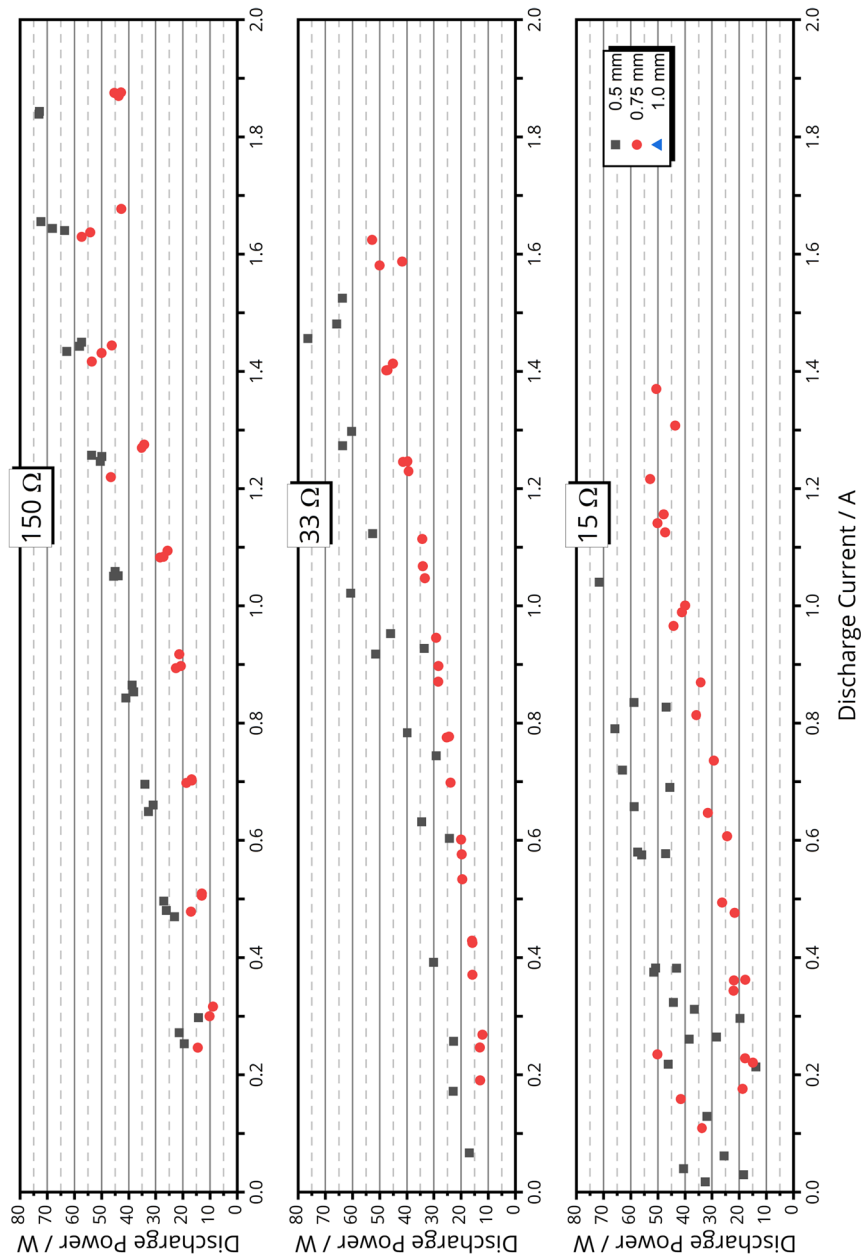


Fig. 10 Total discharge power over the discharge current at emitter current limit sweeps 4 sccm Kr flow rate

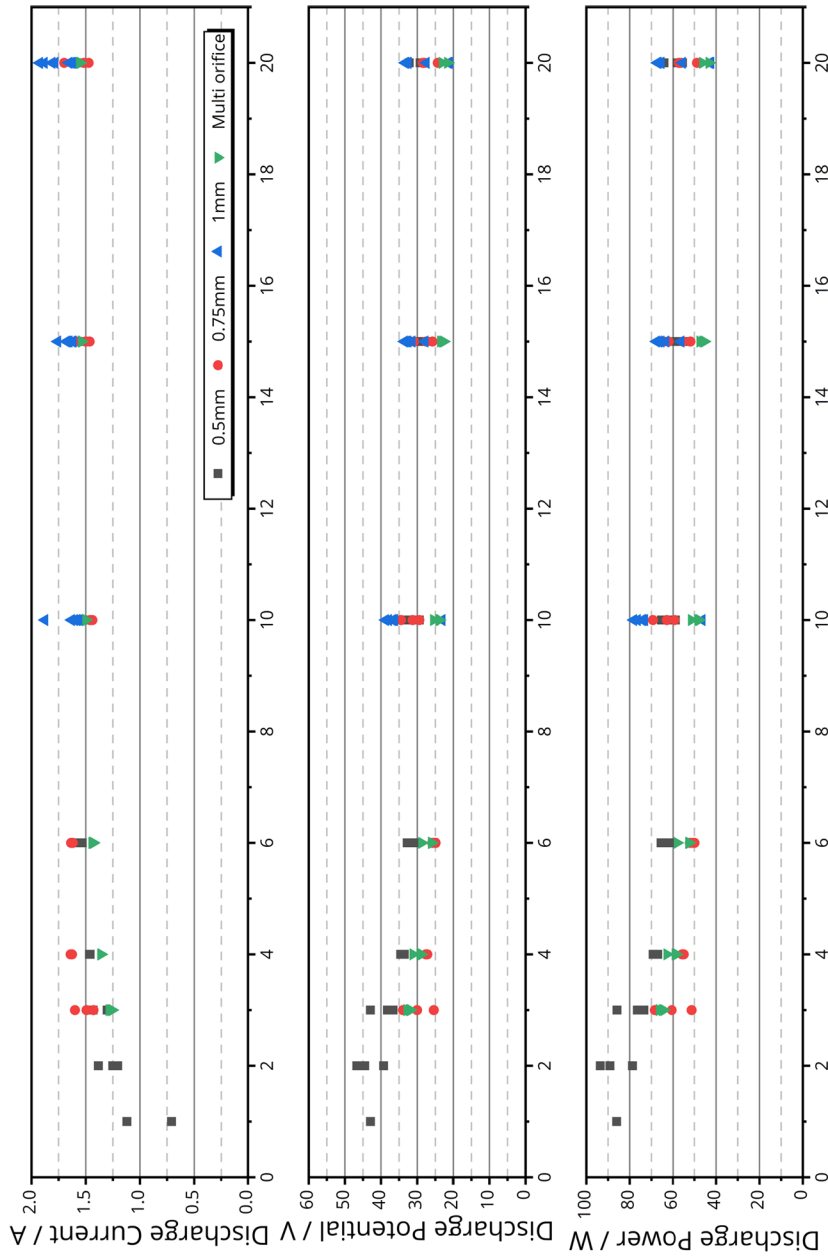


Fig. 11 Comparing Multi-orifice with single orifice configuration of different diameters. Discharge current, discharge potential, and total discharge power over the mass flow rate at emitter current limit of 2 A for the ignition testing. Keeper resistor at 33 Ω

representative configuration during ignition testing. It indicates a good alignment of the performance. Considering the discharge potential and viable flow rates, the performance comes closest to the 0.75 mm orifice.

In addition, Fig. 12 depicts the performance of the multi-orifice during emitter current limit sweeps at different mass flow rates. Again, a comparable performance, like for the single orifices, is observed, with a slight increase in the discharge potential at lower discharge currents. The general discharge potential ranges from 20 V to 50 V. The discharge potential seems to increase slightly for lower flow rates. However, quite indicative is the steep increase of the noise of the signal for the low flow rates tested (i.e., 4 sccm and 6 sccm in this configuration), making them undesirable.

The visual observation of the multi-orifice configuration has been quite interesting, as depicted in Fig. 13. The intensity seemed to vary over the position of the small orifices and did change its orientations with time. Although it was clear that the plasma emission occurred at most of the orifices, it was unclear at the time of testing why this was the case. Later tests indicated this had been a generally peculiar behavior of the electrified cathode using disc-shaped emitters, but it will not be discussed in detail here.

Discussion

With the reliable ignition of the cathode, a characterization of the discharge could be conducted over a wide range of parameters. The characteristics of the discharge had been discussed extensively in a different publication (Drobny C, Tajmar M: Concerning the Ignition of a C12A7 Electride Plasma-Based Cathode, submitted). During the campaign presented here, a single insert was used for all tests, with more than 1000 ignition instances. After all four orifice configurations were tested, sufficient emitter material was still available for further cathode operation.

The results of the test campaign indicate clearly that the electrified cathode can be operated at a wide range of parameters. This is particularly true for the mass flow rate, which has been an emphasized issue for previous results of the cathode [4]. In addition to the reliability of the ignition and operation process, this seems to be a significant advantage towards all other electrified cathodes that have been presented in literature so far and would be the first thorough characterization of an electrified cathode.

In this campaign, heaterless ignition down to only 1 sccm at a maximum ignition potential of 400 V has been achieved, which seems to be much improved compared to heaterless cathode reports in literature [2], in which higher flow rates and ignition potentials have been reported for heaterless LaB_6 cathodes. It may be expected that continuous operation could also be achieved at even lower flow rates for the electrified cathode since the ignition is most often the most critical situation concerning the mass flow rate. However, such a testing procedure was not implemented here and should be conducted in the future for the cathode.

Next to the seemingly advantageous ignition performance of the electrified cathode, the presented discharge potential in the order of 30 V is in the generally expected range also observed for similar cathode using both LaB_6 as well as C12A7 electrified. When comparing the performance, a slightly different approach to the operation of the keeper needs to be regarded. While with our cathode, a small but significant current at the keeper is adjusted to enable operation at a few hundred milli-amps of discharge current, many

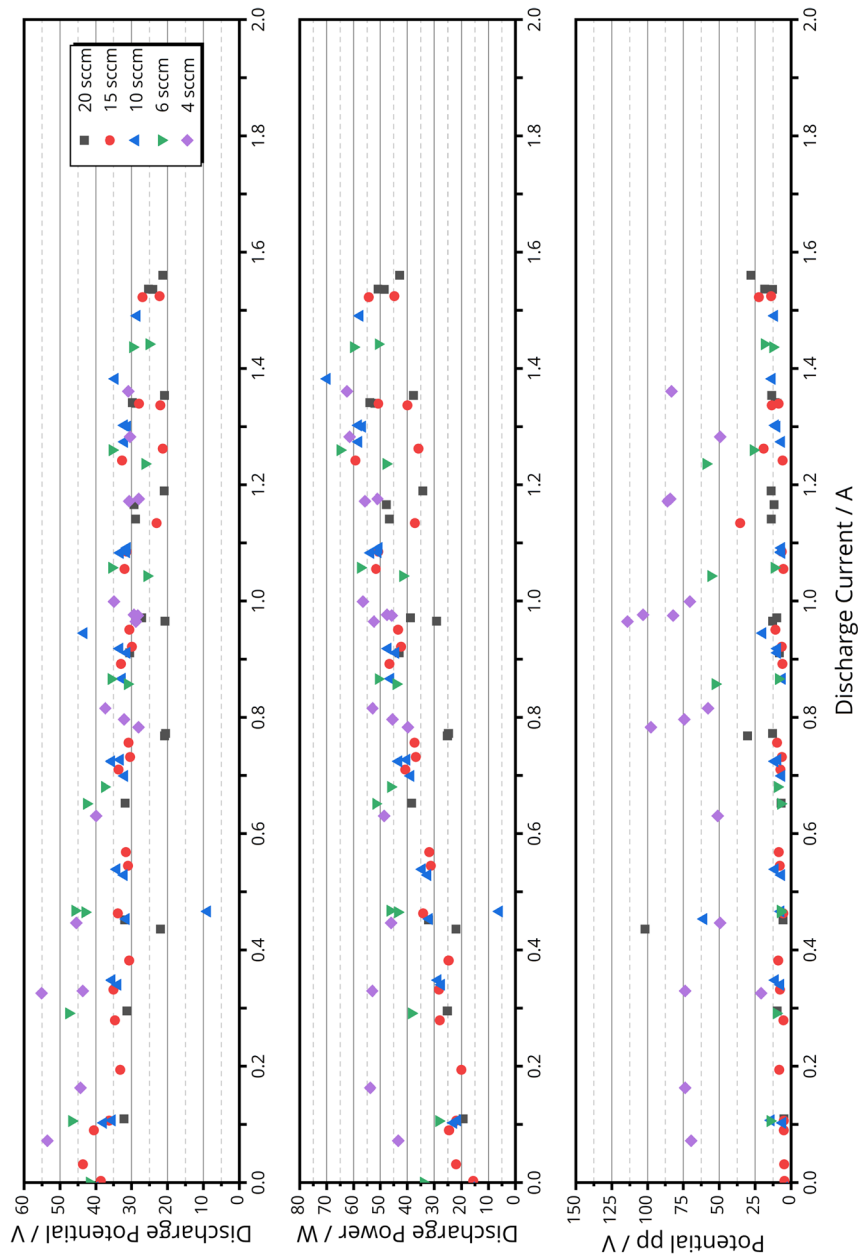


Fig. 12 Multi-orifice configuration. Discharge potential, total discharge power, and signal noise over the discharge current for different mass flow rates at the sweep testing. Keeper resistor at 33Ω

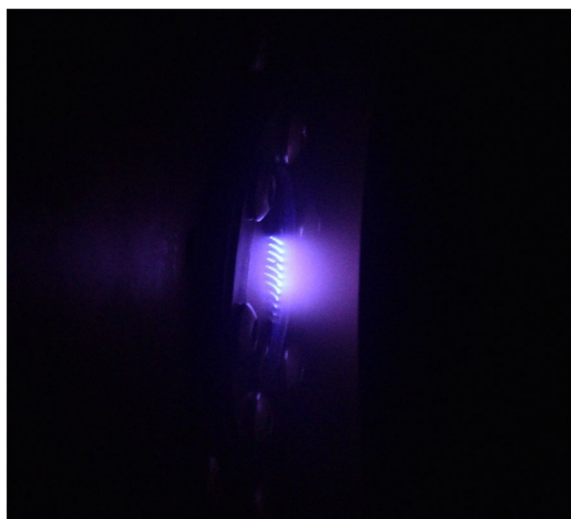


Fig. 13 Closeup view of the plasma operation of the keeper multi-orifice configuration

characteristics are conducted using a floating-keeper configuration. Eventually, a careful evaluation of the total discharge power over the discharge current will be necessary when comparing the results of the different cathodes.

During the test of the presented cathode, a severe noise on the signal was observed, particularly for the smallest tested orifice configuration of 0.5 mm. Although this orifice configuration enabled the lowest flow rates, the high oscillation in the plasma makes these conditions undesirable. This high noise also results in slightly higher discharge potentials. For the single orifices, the diameter of 0.75 mm seemed to show the best performance considering the low flow rate for ignition and operation, plasma stability, and discharge potential.

During the campaign, two different approaches for testing were conducted, one having single ignition and short operation points, the other sweeping the emitter current limit stepwise from the highest towards the lowest value. Both approaches should have yielded the same results in ideal configurations and operations at equilibrium. However, a significant variation was observed, resulting in lower discharge potentials for the sweeping approach. It is unclear, why such a difference was observed, but should be evaluated carefully in the future to understand the performance of the electrified material in a plasma environment. In this regard, Hua et al. [10] reported different ignition and operation temperatures for the electrified, but our available data are not sufficient to confirm such a theory. [...]

During the campaign, the multi-orifice keeper configuration was tested very successfully. It indicated a similar performance to the 0.75 mm orifice. This performance is particularly astonishing when considering the total cross-section of the orifice configuration, as summarized in Table 2. Although the 1 mm orifice could only ignite at a flow rate of 10 sccm, the multi-orifice tested ignited already at only 3 sccm at more than 3.5 times the total cross-section. This is in line with the performance of the 0.75 mm orifice, which has about half the cross-section of the 1 mm orifice. Overall, these operation results support the theory by McDonald et al. [5], by which the flow

Table 2 Types of orifices tested and compared, with an evaluation of the total cross-section area and minimum required flow rate for ignition

Orifice	Configuration	Cross section	Required flow rate
Orifice 0.5 mm	1 x 0.5 mm	0.2mm ²	1 sccm
Orifice 0.75 mm	1 x 0.75 mm	0.44 mm ²	3 sccm
Orifice 1.0 mm	1 x 1.0 mm	0.76mm ²	10 sccm
Multi-Orifice	91 x 0.2 mm	2.86mm ²	3 sccm

resistance will increase more severely than the electrical resistance by the increase of the orifice surface area.

A high noise was observed for the multi-orifice, particularly at low flow rates similar to the 0.5 mm orifice, for which no definite reason could be identified, yet. Still, such a configuration could be an exciting approach to optimize the performance of the cathode towards low flow, as there are so many options to work with (i.e., orifice diameters, orifice distance, number of orifices). More configurations should be tested to evaluate the best possible option. Furthermore, additional aspects like the vulnerability towards clogging, which might be expected for such small orifices, should be tested in endurance ignition and operation campaigns.

Conclusion

An extended overview of the discharge characteristics of a heaterless C12A7 electride cathode has been given over a wide range of parameters. In particular, the focus was on different orifice configurations for lower required mass flow rates. The results generally prove the cathode's viability to operate over a wide range of discharge conditions successfully. The cathode exhibits the typical increase in the discharge potential for lower discharge currents and the expected slight increase of the discharge potential for lower flow rates. A typical discharge potential in desirable discharge current ranges is in the order of 30 V. The lowest flow rate for ignition was observed at the smallest orifice configuration of 0.5 mm at 1 sccm Kr. The maximum ignition potential for all tests presented in this publication has been at 400 V. While the discharge potential is competitive to state-of-the-art cathodes, the cathode exhibits an improved ignition performance.

The operations in the campaign were conducted over a wide range. To allow a statistical analysis of the discharge data, the characteristic of the cathode should be repeated at one promising setpoint as identified by this underlying parametric study. [...] A design configuration using the 0.75 mm orifice with a 33 Ω resistor at the keeper should be used, as it seems to be an adequate balance of required mass flow rate, discharge potential, and total discharge power for the operation. In addition, the multi-orifice configuration has been proven as a viable option for the cathode design. It should be extensively studied in the near future to increase the understanding of the influence of specific configurations on the performance of the cathode.

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Authors' contributions

All authors contributed to the study's conception and design. Acquiring funding, programming of the software for data acquisition, and supervising of the project were performed by Martin Tajmar. Test preparation, data collection, and analysis were performed by Christian Drobny. The first draft of the manuscript was written by Christian Drobny, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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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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