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Long-Life C12A7 Heaterless Cathode for Electric Propulsion Thrusters

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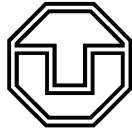
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C12A7 Electride at TU Dresden

Final Report (Year 3) for the Development of a Long-Life C12A7 Heaterless Cathode for Electric Propulsion Thruster

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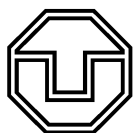
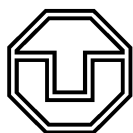


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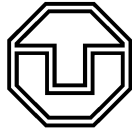
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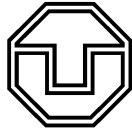
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1 INTRODUCTION

Since 2017, a heaterless hollow cathode has been developed at the Technische Universität Dresden, using the emitter C12A7 electride $[\text{Ca}_{24}\text{Al}_{28}\text{O}_{64}]^{4+}(4\text{e}^-)$. During this time, many findings have been reported in the corresponding interim reports. This report will give a detailed overview of the development of the hollow cathode and the achievements and results in the corresponding work packages over the course of the entire project. Some findings during the last year with the zero cost extension will be added as well as dedicated discussions to the work packages itself.

Figure 1.1-1 shows the updated work package plan for the project. The project is divided into several work packages concentrating on the manufacturing and characterization of the material, design and optimization of the heaterless electride hollow cathode, the testing of the cathode for endurance operation and with thrusters and the development of an analytical model.

	Year 1				Year 2				Year 2.1				Year 3			
Workpackages	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WP1: Preparation of C12A7 Samples																
WP2: Work Function Testing: Setup, Manufacturing, Testing, Implementation of Plasma Cleaning																
WP3: Heaterless Cathode: Design, Manufacturing, Test Setup																
WP4: Cathode Characterization: Testing of Cathode																
WP5: Cathode Optimization: Implementation of lessons learned, manufacturing																
WP6: Cathode Long-Duration Testing																
WP7: Hall Thruster - Cathode Testing: Test setup, manufacturing, testing																
WP8: Analytical model																
WP9: Final Report																

Figure 1.1-1 Work package plan after zero cost extension of year 2.

This report will give an overview of the results of the project and present the technical findings in detail in the corresponding chapters. Finally, the results of the project will be discussed thoroughly to give an evaluation of the potential of the heaterless electride cathode as electron source for plasma thruster systems.



1.1 Accomplishments

The main research objects of the project can be summarized to the following tasks:

- Manufacturing of high quality C12A7 electride samples
- Determination of C12A7 electride work function
- Design and Operation of a heaterless hollow cathode using C12A7 electride
- Endurance Operation of the electride hollow cathode
- Joint operation of the electride hollow cathode with a plasma thruster
- Evaluation of an analytical model of the hollow cathode

The following subsections will describe briefly the scope of the main objectives and the major challenges and findings.

1.1.1 Manufacturing of high quality C12A7 electride samples

In close cooperation with the Fraunhofer IKTS in Dresden, the manufacturing process of the electride sample had to be optimized to increase the electron emission performance of the material. Initially, this included the optimization of material composition as well as the variation of the sintering parameters during manufacturing.

Over the course of the project, numerous different sintering parameters like temperature and time have been evaluated. In addition to that, the material composition have been optimized, realizing smaller particle sizes and higher phase purity of the C12A7 powder. This approached lead to a more homogeneous sintering of the material with lower defect rates as well as higher electron densities in the electride after manufacturing, which is an indicator for the quality of the electride material.

In addition to that, due to inputs from another project, new composite materials have been tested and evaluated, including the addition of titanium or molybdenum to the electride to enhance the electron emitting performance of the material. This new adaptation showed a great improvement of the performance of the electron emission as well as the hollow cathode operation and was therefore a great success!

Overall, the objective of the proposal has been entirely fulfilled.



1.1.2 Determination of C12A7 electride work function

A thermionic diode was to be set up to evaluate the electron emission behavior of the electride material supplied by the Fraunhofer IKTS. This may be a valuable indication of the performance of the material and a necessary input for any analytical hollow cathode model.

While testing with the thermionic setup, numerous challenges occurred in the operation of such a setup, requiring continuous optimization of the setup. This optimization was a major task to achieve a clear reading on the characteristic of the samples. Although many aspects have been significantly improved and our understanding of the system has been increased significantly, there are still minor inconveniences that make measurements challenging. Still, a setup has been achieved that can verify the performance of the material with reasonable accuracy.

Overall, the thermionic emission of the material is much lower than expected initially. In addition, the work function is not in the order of 0.6 eV, but rather in the range of 2.6 eV. However, due to unclear effects in particular when doping with titanium, no work function values have been determined any more in the end, but rather focusing on the current density during thermionic emission.

Overall, the objective of the proposal has been mostly fulfilled. The evaluation of work function values from thermionic discharge characteristics has been postponed due to artefacts in the characteristics that are yet to be detailed.

1.1.3 Design and Operation of a heaterless hollow cathode using C12A7 electride

A heaterless hollow cathode had to be designed and characterized. The design was to be optimized with lessons learned over the course of the project.

Numerous iteration with dedicated improvements have been conducted, leading to a smaller and easier setup of the cathode. The reasoning behind the changes is discussed in detail in the corresponding technical sessions. Finally, a modular setup for fast testing iterations had been achieved and successfully tested and verified. With this setup, reliable ignition at a variety of discharge parameters has



been reported, concluding the successful design of a heaterless hollow cathode using the C12A7 electride.

Overall, the objective of the proposal has been entirely fulfilled.

1.1.4 Endurance Operation of the electride hollow cathode

The electride hollow cathode had to be tested for endurance operation in the range of 1000 hours.

A first successful continuous operation of the cathode was achieved already in the first year of the project, with more than 300 hours of time. However, the discharge at the anode has not been continuously and at much lower current limits.

A dedicated campaign was done in summer 2019, where more than 950 hours of operation at 2A discharge current has been achieved continuously. The operation was only short the 1000 hours due to a mismanagement of the propellant supply. At this point it was decided to make a preliminary analysis for the interim report required at this time, rather than wait several weeks before the new propellant would have been delivered. A second test of the cathode for about 1000 hours was not possible due to the Covid-19 restrictions in the laboratories at the institute.

Overall, the objective of the proposal has been mostly fulfilled, only lacking a second endurance test for verification.

1.1.5 Joint operation of the electride hollow cathode with a plasma thruster

Since hollow cathodes are routinely used with plasma thrusters, a joint operation of the electride cathode with such a thruster had to be verified.

The cathode was tested with a Hall-effect thruster TUD-H3-P at our institute successfully. A wide range of operation parameters of the thruster with the cathode have been reported. Further operations with a new iteration of the Hall-effect



thruster at the institute has not been successful due to challenges in the design of the thruster. Although ignition had been successful, steady operation failed.

Overall, the objective of the proposal has been totally fulfilled.

1.1.6 Evaluation of an analytical model of the hollow cathode

To support the understanding of the operation of the hollow cathode using the emitter material C12A7 electride, advances for an analytical model of the hollow cathode were to be made.

For the modelling of the cathode, a numerical simulation using the COMSOL Multiphysics tool were made. However, the results obtained here were not conclusive. Therefore, a 0D analytical model from literature was implemented and first tests and cross references with measurement data were made. At this point, several major challenges did arise, including unclear material parameters of the C12A7 electride (work function as well as the difference between thermionic emission and hollow cathode performance) as well as the unique design of the hollow cathode used for testing (planar setup).

Due to these severe constraints onto the model, the modelling of the cathode was not put into focus. However, such an approach should still be done in the future to improve our understanding of the hollow cathode operation.

Overall, the objective of the proposal has been not fulfilled. Although first advances for the implantation of a 0D analytical model were made, no reasonable version of such a model could be provided in the frame of this project. The focus was set more on finding practical measurements of the electride cathode.

1.1.7 Dissemination

The results of the project have been reported very detailed in the annual interim reports of the project. In addition to that, several conference presentations with corresponding proceedings were made public, as listed below. As of right now, two papers are in the making covering the thermionic setup for evaluation of the work



function as well as a detailed analysis of the endurance operation of the heaterless electride hollow cathode.

- *"Detailed Work Function Measurements and Development of a Hollow Cathode Using the Emitter Material C12A7 Electride"* at the Space Propulsion Conference 2018 in Seville, Spain (SP2018_92)
- *"Novel Heaterless Low-Power Electron Emitters for Tether Applications"* at the 2019 International Conference on Tethers in Space in Madrid, Spain
- *"Development of a C12A7 Electride Hollow Cathode and Joint Operation with a Plasma Thruster"* at the International Electric Propulsion Conference 2019 in Vienna, Austria (IEPC-2019-629)
- *"Endurance Test of a Hollow Cathode Using the Emitter Material C12A7 Electride"* at the Space Propulsion Conference 2020+1, online (SP2020_153)



1.2 Impacts

This work had a profound impact on the field of electride hollow cathodes, triggering a number of other projects, both from us but also from a number of other teams. The potential has been recognized and plans to test such cathodes in orbit are already underway.

Highlights and lessons learned were implemented in our “Electric Propulsion and Advanced Concepts” lecture at TU Dresden. A number of Master thesis finished as well as two PhD thesis on this topic are currently underway.

With the advances in the performance of the heaterless electride hollow cathode as well as the improved performance due to the optimization of the electride material, follow up projects have been acquired at the institute.

1.3 Changes

Overall, the general plan of the project could be fulfilled successfully. Only minor changes in the approach were taken.

For the manufacturing of the C12A7 electride material, we optimized the sintering parameters and started the composition of the electride material mixed with refractory metals, in particular titanium due to its oxidizing behavior. Although the handling of titanium is challenging, the results are promising.

In one of our follow-up projects we researched the manufacturing of electride with molybdenum due to its beneficial thermal and electrical conductivity. We used this experience with samples also for this project and conducted several measurements as well as hollow cathode operations, due to the superior behavior. With the additional options of the material and the continuous optimization necessary with the thermionic diode setup, the task of material characteristics was prolonged, covering most part of the project.

For the hollow cathode itself, no deviations from the initial proposed plan were taken. However, the efforts for the analytical model were reduced at some point, due to severe challenges with the material characteristic and the design of the cathode.



Severe delays in testing had been experienced due to the restrictions active on our laboratories due to the Covid-19 pandemic, which led to a zero-cost project extension.



2 WP1 – PREPARATION OF C12A7 ELECTRIDE SAMPLES

The requirements and specifications of the material samples were elaborated by TU Dresden together with Fraunhofer IKTS and then the samples were manufactured by Fraunhofer IKTS.

WP1 was scheduled for the first year of the project. Because the fabrication and optimization of material samples was continuously ongoing, WP1 stretched far longer than initially anticipated.

2.1 Sample form and size

In general, the sample sizes can be differentiated into three different categories, depending on the use case of the samples. An overview is given in Table 2-1.

Table 2-1 Sample geometries manufactured over the course of the project.

Geometry	Size	Usage
Tablet	Ø 25mm – 30mm H 1mm – 3mm	Thermionic emission test
Tablet	Ø 10 mm H 1mm – 3mm	Initial Thermionic emission tests Planar hollow cathode setup
Hollow Cylinder	OD 4mm – 6mm ID 0.8mm – 3mm L 12mm – 25mm	Hollow cathode setup

Rather large samples have been used for the thermionic setup to have a higher surface area for emission and measure higher currents. However, this size was deemed too large for the hollow cathode, why much smaller tablets have been manufactured for the tablet shaped cathode. Finally, hollow cylinder inserts had been manufactured to test the standard hollow cathode configuration initially as well as later on as cross reference to the tablet shaped cathode operation.

For the hollow cylinder, different combinations of diameters have been tested to prevent melting and clogging during operation. However, this challenge persisted

over the course of the project, hence the later focus on the tablet shaped insert. This will be discussed accordingly later in the report.

2.2 Sample electride composition

During the first phase of the project, the electride material was tested with varying the sintering parameters e. g. sintering temperature, dwell time, atmospheric conditions but also slightly varying of the stoichiometric ratios (Ca:Al) to find the optimal material properties for thermionic emission and hollow cathode operation. In particular, tabular inserts have been manufactured to test the material in the thermionic diode for electron emission. The pure electride material has a black color and the surfaces of the samples were dry-polished. A picture of these samples is shown in Figure 2.2-1. The surface of the pure electride is electrically insulating.

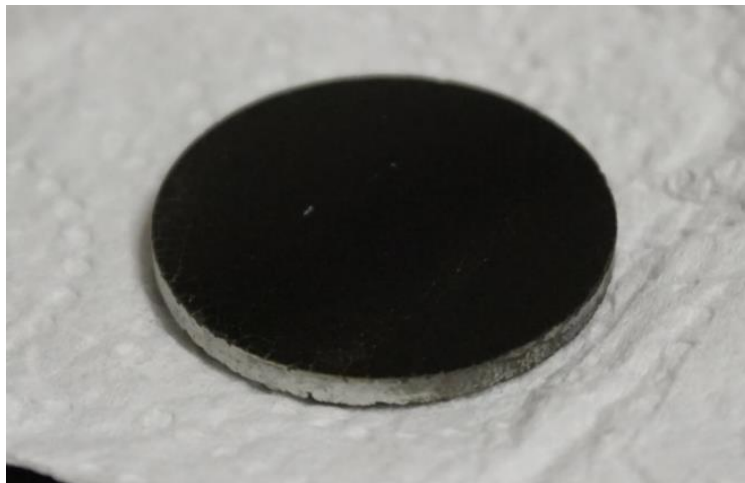


Figure 2.2-1 Pure C12A7 electride sample with polished black surface. The outer diameter is 25 mm and the height is 2 mm.

The tests will be summarized in chapter 3. However, one conclusion of these tests as well as the operation of the samples in a hollow cathode was the lack of thermal conductivity as well as the lack of electrical conductivity on the surface of the electride material. Hence, two different refractory metals were added to the samples, which creates composites with good electrical conductivity and increased thermal conductivity.



Figure 2.2-2 Sample with 30 vol.% of titanium. The diameter is 20 mm, the thickness 1 mm. The electrically conductive surface is very rough compared with the other samples

The first additive was titanium, which was mixed with a concentration of 30 vol.% to the C12A7 electride material [1]. One of those material samples is displayed in Figure 2.2-2. The surface as well as the edge of these samples is quite brittle and inhomogeneous, compared to any other samples manufactured. Titanium was chosen due to its generally great oxidation behavior and good results with titanium atmosphere in literature [2].

Our idea was to use another metal phase in combination with C12A7 to get high thermal and electrical conductivity. Molybdenum is well known as highly conductive metal. Therefore, the second group of material samples contains 10 vol.% to 20 vol.% molybdenum instead of titanium. A picture is shown in Figure 2.2-3. To the best of our knowledge, this is the first time that molybdenum has been used as an additive for C12A7 electride.

Later in the project, the focus of optimization was on the improvement of preparation of the source material for the electride. Approaches to reduce the amount of unwanted eutectic phases in the electride have been tested, which lead to an improved electride material used for manufacturing.

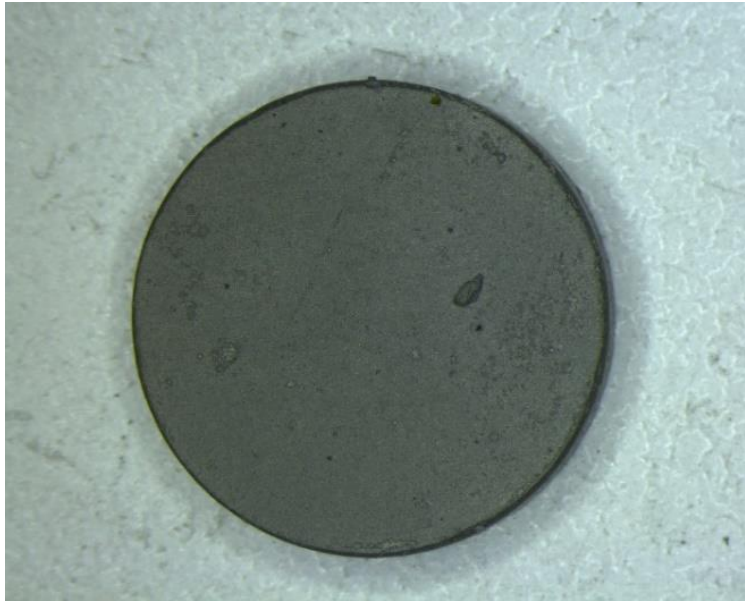
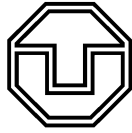


Figure 2.2-3 Sample with a diameter of 10 mm, a thickness of 10 mm and with 20 vol.% of molybdenum. The electrically conductive surface has a dark grey color tone.



2.3 Characterization of Material Samples

The material samples were analyzed at IKTS with respect to their microstructure, UV-VIS spectra and specific electrical resistivity.

2.3.1 Determination of the Material Density before and after Sintering

The material density of the C12A7 electride samples was determined before and after the sintering process. The sintering process clearly increases the final density that is close to the theoretical density of the material. In [3] a density of 2.69 g/cm³ is given for pure C12A7 material, which might be slightly lower for polycrystalline samples. The framework micrographs presented in the next section show nearly no signs of pores in the material.

The density of the samples with molybdenum additives is higher due to the higher specific density of molybdenum.

Table 2.3-1 Comparison of the density of the material samples in before (green) and after sintering.

	green density (g/cm ³)	sintering density (g/cm ³)
C12A7	2.03 ± 0.01	2.60 ± 0.01
C12A7 + 10 vol.% Mo	2.45 ± 0.06	3.29 ± 0.08
C12A7 + 20 vol.% Mo	2.90 ± 0.08	4.03 ± 0.03

2.3.2 Microstructure and Phase Composition

Analysis of the microstructure and phase composition of all three types of material samples were conducted. Figure 2.3-1 shows the microstructure of pure C12A7 electrider. The main C12A7 phase contains few pores as well as impurities from calcium-rich phase (C3A).

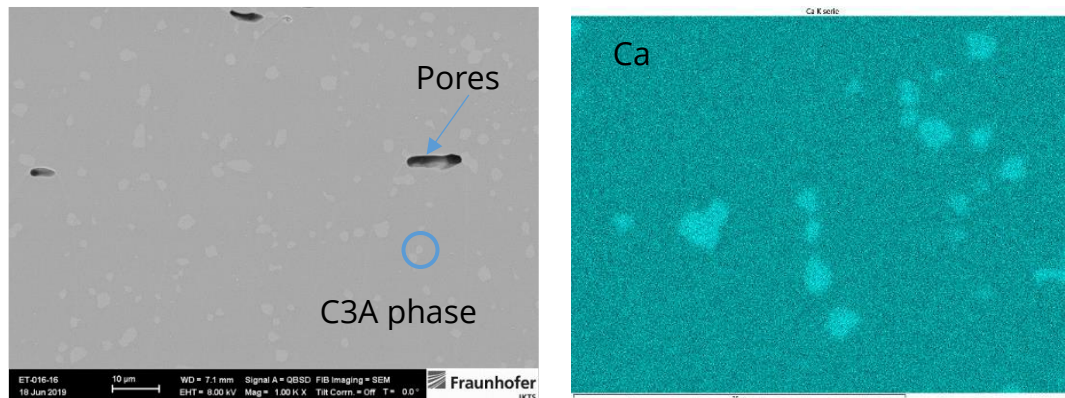


Figure 2.3-1 The analysis of the microstructure of the pure C12A7 electrider shows the presence of few pores and small amount of C3A ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$) detected by higher Ca concentration and XRD (fig. 2.3-2).

For increasing the C12A7 phase content, the stoichiometric mixture of the precursor powders was evaluated. In a first step the aluminum content was

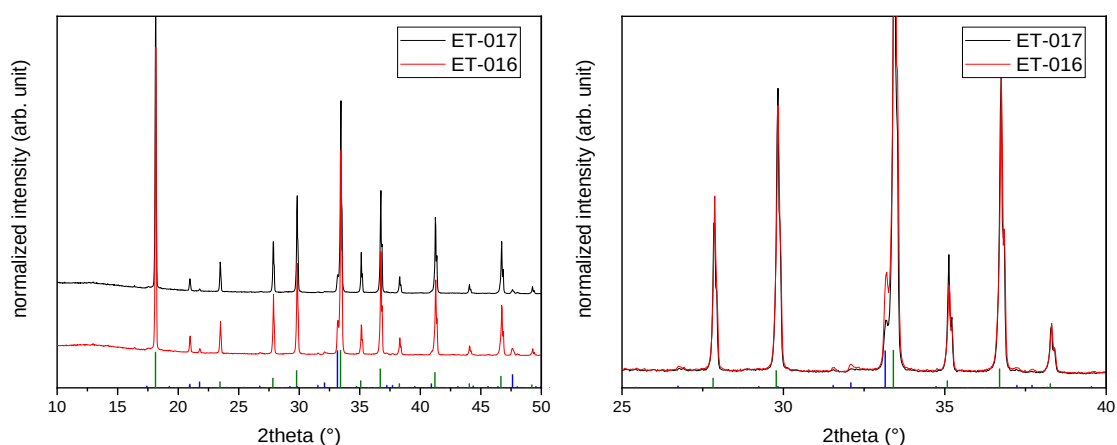


Figure 2.3-2 XRD analysis of old (ET-016) and new (ET-017) C12A7 electrider material. In the material, the content of the C3A phase is smaller but still present.

increased, resulting in a lower fraction of C3A. This was validated by an XRD analysis, as shown in Figure 2.3-2.

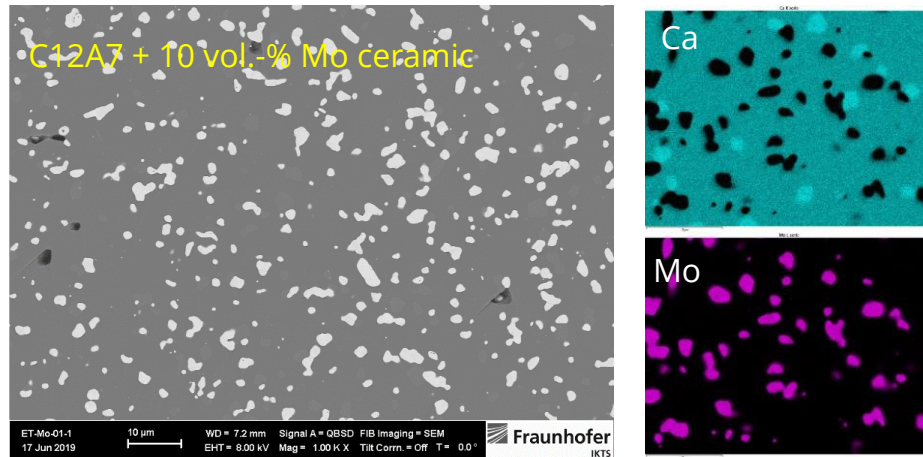


Figure 2.3-3 Microstructure of the samples with 10 vol.% of molybdenum shows a well distributed molybdenum metal phase.

The samples with 10 vol.% molybdenum show a very homogeneous distribution of the metal phase in the C12A7 material, as shown in Figure 2.3-3. The distribution of titanium in the base material seems to be slightly less homogeneous because the grain size of the individual phases is larger, as shown in Figure 2.3-4. This might be caused by coarser titanium powder and higher content (30 vol.%). The EDX analysis of the titanium samples shows that the titanium does not oxidize during the manufacturing process (Figure 2.3-5).

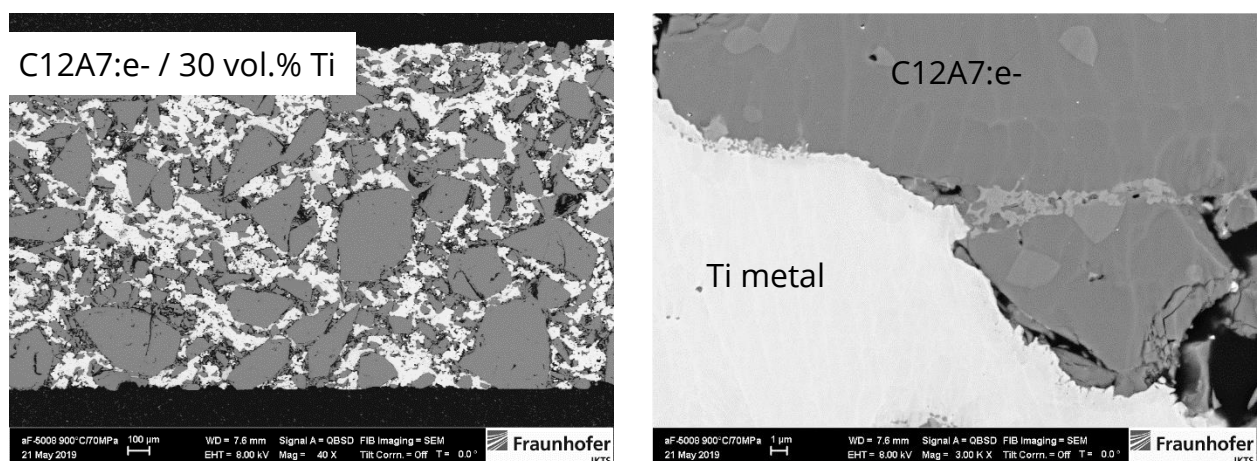


Figure 2.3-4 Microstructure of the C12A7 samples with 30 vol.% of titanium.

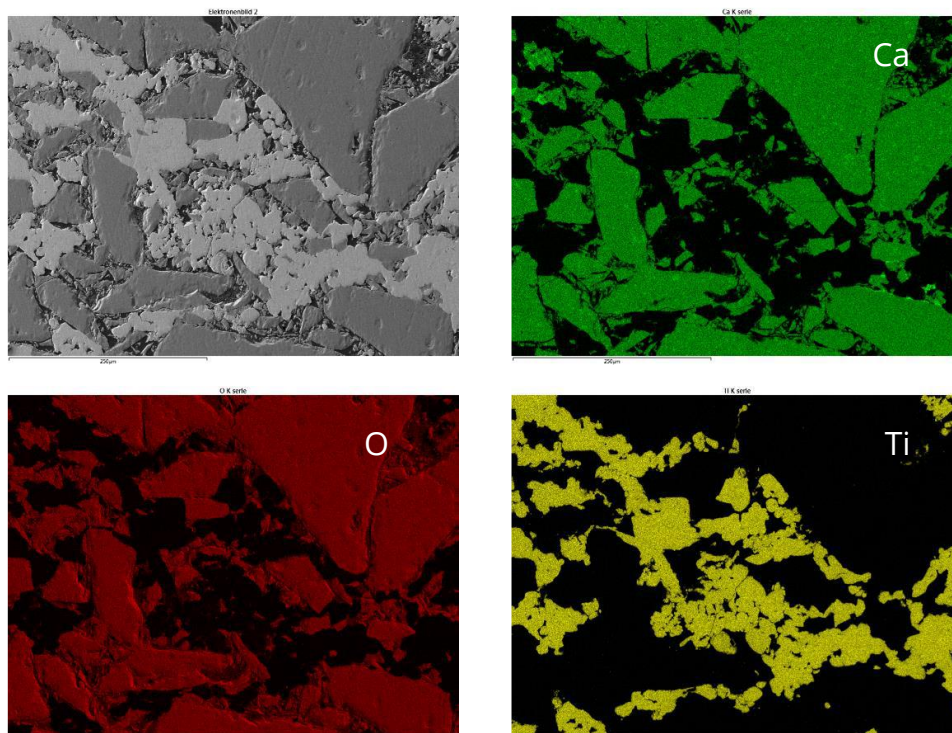


Figure 2.3-5 EDX analysis of C12A7 samples with 30 vol.% titanium. The different phases are clearly separated. The titanium phase shows no sign of oxidation.

2.3.3 Coefficient of Thermal Expansion

Part of the characterization of the thermal properties of C12A7 electrider was the measurement of the coefficient of thermal expansion of the material. The results are shown in Figure 2.3-6. The average coefficient is $5.7 \times 10^{-6} \text{ K}^{-1}$ between 400°C and 1000°C .

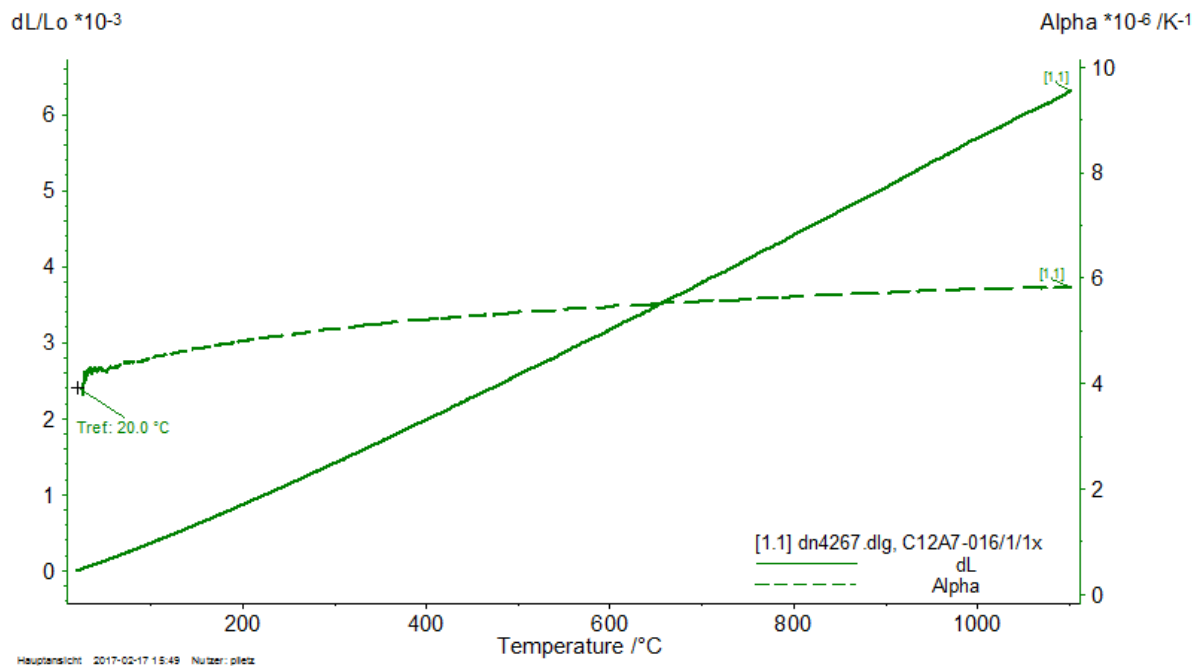


Figure 2.3-6 Coefficient of thermal expansion of pure C12A7 electrider between 20°C and 1000°C .

2.3.4 Measurement of the Specific Electrical Resistance in dependence of the Temperature in an Inert Atmosphere

To measure the specific electrical resistance of the pure C12A7 electrified samples, the wire probes were connected to the front and backside of the samples using a silver-based paste. For this, the sample was heated in a nitrogen atmosphere to 800°C to bond the contact paste with the samples and the wire probes. As it can be seen from Figure 2.3-7, the specific resistance becomes as small as 0.6 $\Omega \cdot \text{cm}$ at 750°C. Rough measurements of the specific resistance of the samples with titanium and molybdenum additives shown in Figure 2.3-8 indicate a very high electrical conductivity.

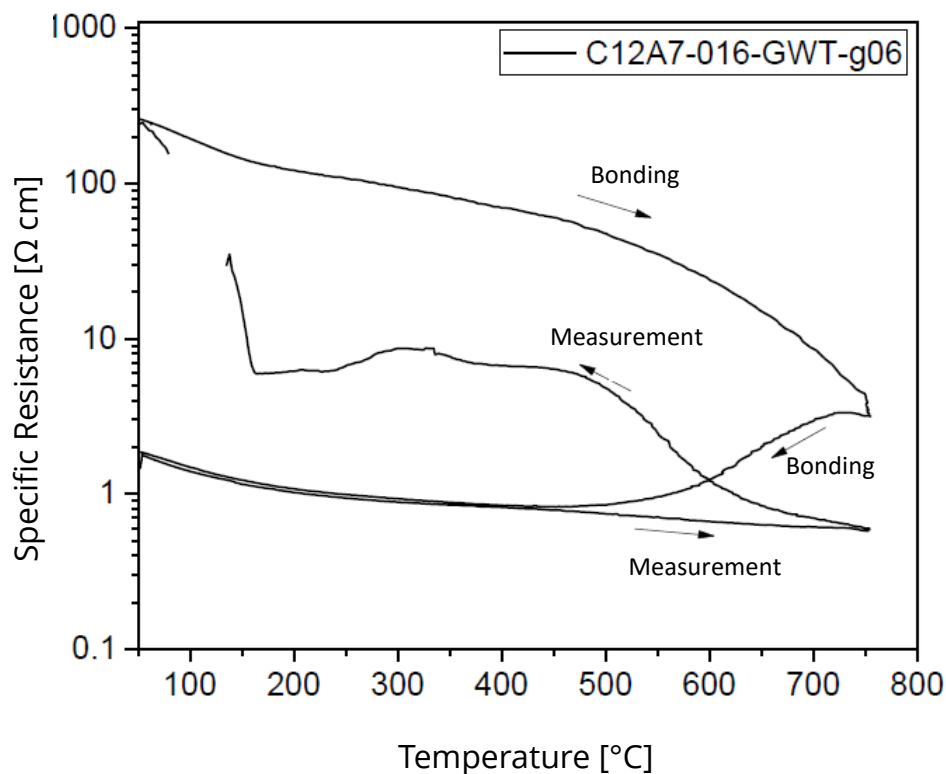


Figure 2.3-7 Measurement of the specific resistance of pure C12A7 electrified. Silver-based contacting paste was used to “burn in” wire probes at high temperatures in a nitrogen atmosphere.



Figure 2.3-8 Rough measurement of the surface resistance by means of the probes of a digital multimeter. The resistance becomes smaller with rising molybdenum content.

2.3.5 UV-VIS-Spectroscopy for Absorption

The UV-VIS Spectra of pure C12A7 electride samples with different sinter temperatures show a similar behavior with regard to their absorption and reflection characteristic in the visible spectrum (see Figure 2.3-9).

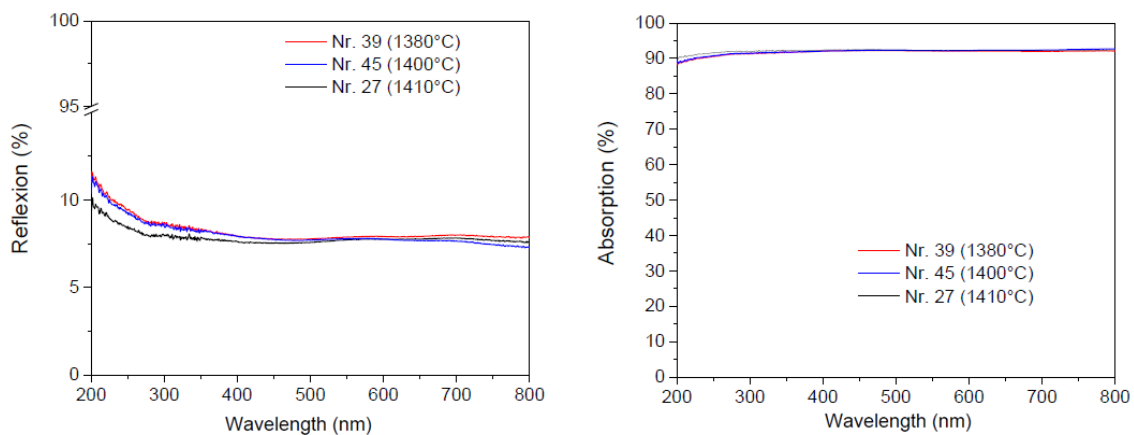


Figure 2.3-9 UV-VIS Spectroscopy of pure C12A7 electride samples that were sintered at different temperatures.

The absorption of the molybdenum specimens is smaller and on the order of 70% to 80% for smaller wavelengths and increases for higher wavelengths, as shown in Figure 2.3-10. However, the drop of the absorption coefficient to zero for wave

lengths below 400 nm as well as the high noise level beyond 1500 nm are related to the reflection of the metallic character by adding Mo metal.

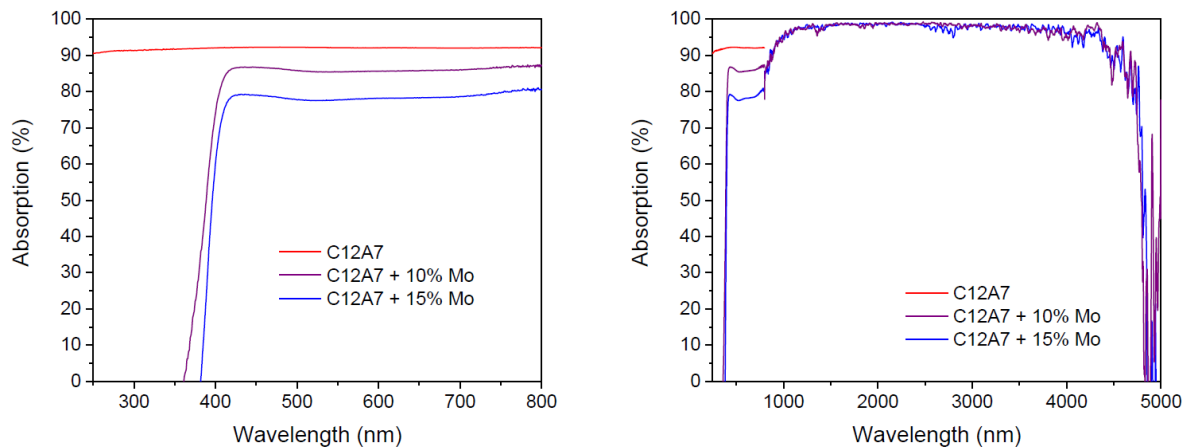


Figure 2.3-10 Comparison of the UV-VIS Spectra of pure C12A7 electride to C12A7 electride with 10 and 15 vol.% molybdenum.

2.4 Conclusion WP1

For the first time in literature, C12A7 electride was mixed with refractory metal to increase the performance of the ceramic. In particular successful was the achievement of a reliable surface contact as well as increased thermal conductivity. The thermionic emission tests, which will be presented in chapter 3, showed much better performances using the optimized materials.

A large number of samples have been delivered and tested in the thermionic diode as well as in the hollow cathode. Several of these samples had been returned to the Fraunhofer IKTS for post-mortem analysis. The results of such analysis at the corresponding chapters. The manufacturing of samples with titanium additive proved to be difficult due to the flammable characteristics of fine milled titanium and a slightly different manufacturing process. For most hollow cathode samples, 20 vol.% molybdenum was chosen as reference material.

Overall, the optimization of the material over the course of the project led to enhanced performance characteristics of the material in many ways. Several measurements done during the project had not been previously reported in literature.



- Fabrication of samples for work function measurement → done
- Fabrication of samples for hollow cathode operation → done
- Implementation of refractory metals in ceramic → done
- Analysis of samples been operated → done
- Improvement of fabrication process → done



3 WP2 – WORK FUNCTION TESTING

C12A7 electride is a rather new material with unique and special features [2]–[4]. Especially interesting for the use in a hollow cathode is obviously the low work function of the material. A number of publications reported rather different values for the work function, ranging from 0.6 eV to 2.4 eV [5]–[7]. Reasons could for instance be different fabrication processes, different quality of the material samples and even surface contaminations. Furthermore, different measurement methods could influence this value.

The task of WP2 is the measurement and characterization of thermionic emission current and the determination of the work function of C12A7 electride material samples. This task was originally scheduled to be completed during the first year of the project. However, due to challenges with the setup and its continuously improvement, as well as due to the optimization of the material over the project timeline, measurements were continued over the timeline of the project.

A number of analyzing tests have been done directly by the manufacturer, the Fraunhofer IKTS. In addition to that, a so-called “thermionic diode” test setup was designed and manufactured at our institute. This allows us to measure the thermionic emission current emitted from the samples at high temperatures, from which the value of the material’s work function may be determined. This measurement method has the advantage that it simulates the environment of a hollow cathode, where also elevated temperatures occur.

Several challenges did occur with the thermionic diode. This includes, but is not limited to:

- Leakage currents that occurred during the tests
- Signs of contamination and/or decomposition at the samples after being exposed to high temperatures in vacuum
- Temperature gradients in the setup itself
- Temperature gradients in the sample leading to unknown surface temperatures
- High current measurements at wrong potentials
- Bad and insufficient mounting and contacting of the sample onto the setup



These challenges were approached accordingly and stepwise improved. This led to many different iterations in our thermionic setup, which can be found in the corresponding interim reports. Section 3.2 will give an overview of the used setup for measuring thermionic emission from C12A7 electride samples.

During the first year's test campaign, four material samples were tested and thermionic emission was observed. However, the currents remained smaller than expected and reached only 10 μA to 100 μA and the recorded IV traces were not consistent enough to derive values of the work function.

During the second year's test campaign, samples with molybdenum and titanium additive have been tested. The samples with molybdenum showed much better characteristics than the pure samples, and first indications of work functions were derived. A detailed discussion about the work functions values will be done in Section 3.4.3. However, the samples with the best thermionic emission have actually been those with titanium additive. Here, thermionic currents above 10 mA/cm^2 have been achieved, being several orders of magnitude above any other sample. However, several unclear effects did occur, that needed closer evaluation.

During the zero cost extension of the project, another test campaign was done using samples with titanium addition, due to its great performance before. With slight optimizations in the setup as well as the mounting, currents close to 100 mA/cm^2 have been reached. However, due to the high current, significant power was added to the sample resulting in severe temperature changes. Due to this non-stable temperature equilibrium, no work function fits have been added any more. Although these results are by far the best achieved with thermionic emission at our institute, they are still far from the hollow cathode performances.

3.1 Description of the Measurement Method

This section briefly summarizes the measurement principle of the thermionic diode and how the value of the work function (and the correction factor of the Richardson constant) can be determined from the recorded IV (current voltage) curves.

The setup for the measurement of the work function of the C12A7 electride is based on the principle of a thermionic diode [8]. The specimen is placed on a metal plate, the so-called substrate holder, which acts as cathode and is heated from



beneath by a resistive heating element. The substrate holder will sometimes be abbreviated as "SH" in the text. A second electrode – the anode – is placed within a certain distance (2 to 5 mm) above the specimen. A potential difference is applied between both electrodes to measure the thermionic electron emission of the specimen in dependence of the temperature. The schemata are shown in **Fehler! Verweisquelle konnte nicht gefunden werden..**

According to the Richardson-Dushman equation, the specimen with temperature T will emit an emission current density j of:

$$j = \lambda A_0 T^2 \exp\left(-\frac{\varphi}{k_B T}\right)$$

With λ being the correction factor of the Richardson constant $A_0 = 120 \text{ A}/(\text{cm}^2\text{K}^2)$ and the Boltzmann constant k_B .

By transforming the equation above with the natural logarithm, it takes the linear form of:

$$\ln\left(\frac{j}{T^2}\right) = \left(-\frac{\varphi}{k_B}\right)\frac{1}{T} + \ln(\lambda A_0)$$

This can be best understood by looking at the visualization of this equation, which is called the Richardson-Plot and is shown in Figure 3.1-1. The work function can be determined from the slope of the plotted line.

For strong electric fields E during the emission process the Schottky effect needs to be considered, which reduces the effective work function by:

$$\Delta\varphi = \sqrt{\frac{e^2 E}{4\pi\epsilon_0}}$$

Because the electric fields (200 V over a distance of 5 mm) were quite small during the tests, this effect can be neglected.

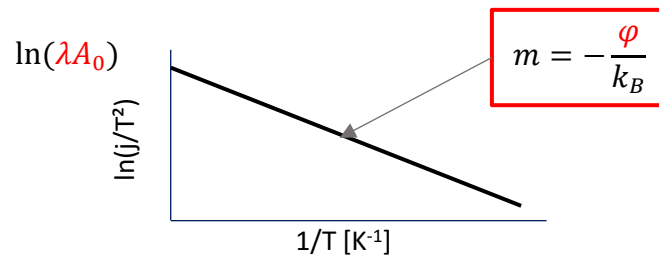


Figure 3.1-1 Richardson plot. The value of the work function can be determined from the slope.

3.2 Thermionic Diode Setup

The complete setup is depicted in Figure 3.2-1. The foundation is an aluminum breadboard placed on top of a POM plate, so that the setup is electrically insulated when placed inside a vacuum chamber and the ground or reference potential can be freely chosen. On the left, the heater support and the closed shield can be seen. On the right side, the linear table that holds the anode is positioned behind an extra heatshield.

A top heatshield screens the setup inside the vacuum chamber from the direct line of sight with the cool surfaces of the cryogenic pump and is intended to protect the first stage of the cryogenic pump from heat radiation.

A version of the thermionic diode is shown in **Fehler! Verweisquelle konnte nicht gefunden werden..** The specimen is placed on top of the substrate holder, a 60 x 60 mm² molybdenum plate with a thickness of 2 mm. The large size of the substrate holder allows for the analysis of material samples with up to 50 mm diameter. The substrate holder is pressed onto the surface of the heater beneath by means of four molybdenum screws and a 0.2 mm thick molybdenum sheet at the backside of the heater. The substrate holder features a 30 mm deep Ø0.6 mm

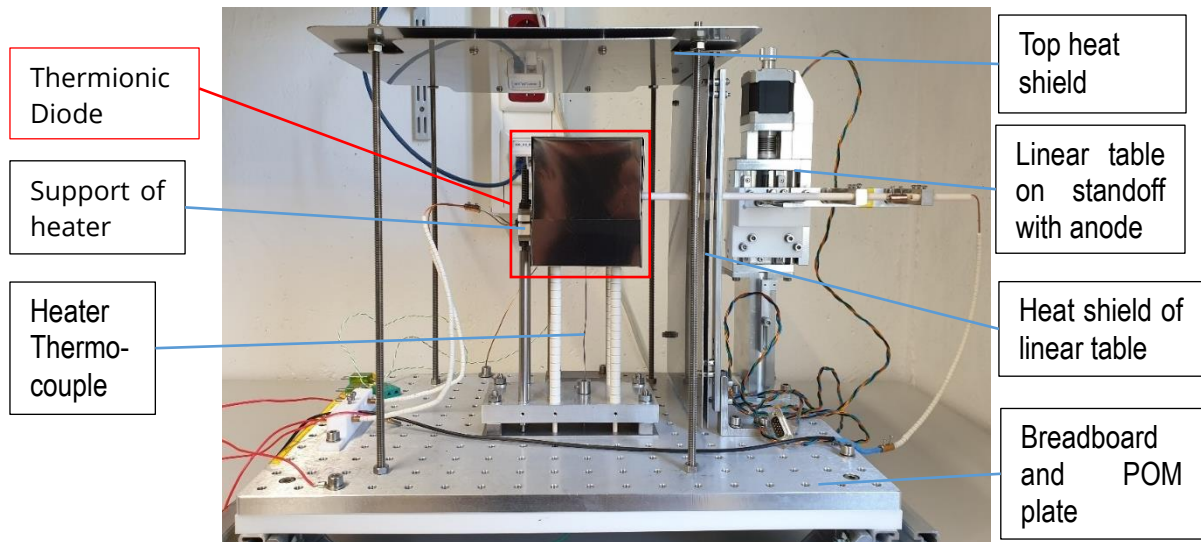


Figure 3.2-1 Entire setup for work function and its main components.

borehole, in which a sheathed type K thermocouple can be inserted. This allows for temperature measurement inside the substrate holder less than 1 mm below the center of the specimen placed above.

Since such a mounting of the setup needed a contacting paste to hold it onto the heater as well as to ensure good conductivity, an alternative solution was looked into. In particular, the specimen are now pressed onto the heater directly via a faceplate. This ensures good thermal and contact to the heater as well as good electrical contact of the sample itself. This will be discussed in more detail in section 3.4.4.

The heaters were purchased from Bach Resistor Ceramics GmbH and were used in different size configurations throughout all experiments. The heater consists of silicon nitride (Si_3N_4) with an insulating surface and embedded heating paths that were made electrically conductive by a doping process. The specified operating limit is 1000°C . However, in consultation with the supplier, this limit might be extended up to 1200°C for a short amount of time. The temperature itself is measured with a sheathed type K thermocouple, of which the tip fits snugly into a small borehole at the center of the bottom side of the heater. The heater is powered by a Delta Elektronik SM 660-AR-11 power supply, operated in floating mode.

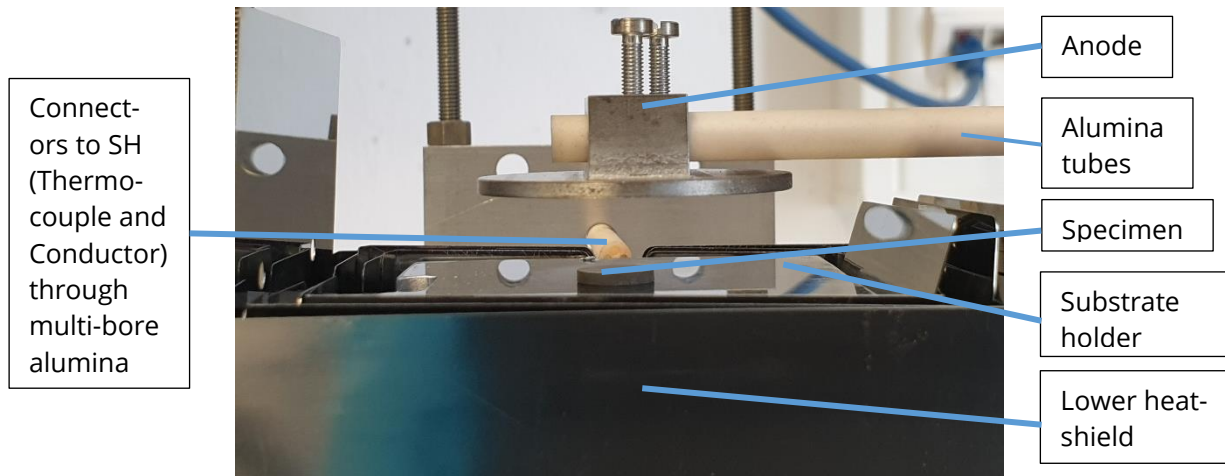


Figure 3.2-2 Clamping of the specimen onto the heater for the most design of the thermionic diode setup.

(both pins of the heater are connected to the plus and minus pole of the power supply with no extra connection to ground).

The anode above the heater is made from molybdenum and is constant for all tests. It is held by three alumina tubes that can be connected to a linear actuator (Owis LTM 60 25 MSM). This allows the variation of the distance between the sample and the anode between 2mm to 25 mm. However, this function has not been used often, because the focus was on making the heatshield of the design as closed as possible. A movable anode would require a larger gap in the heat shield. The current between the anode and the substrate holder, which is grounded like the rest of the setup, is measured by a Keithley 6487 picoamperemeter or a Keithley 2450 sourcemeter. Both allow for measurements in the sub-nanoampere range and for output voltages of 500 V and 200 V respectively.

The thermionic diode is enclosed by a heatshield. This is made from sheets of 0.2 mm thick molybdenum, bent into box shaped geometry and arranged in three layers. These individual layers are separated and kept in place by ceramic rods and spacers made from alumina and steatite, respectively. All parts of the heat shield are electrically connected to the rest of the setup by a single molybdenum rod. This has a very small diameter ($\varnothing 2$ mm) to reduce heat loss due to heat conduction.

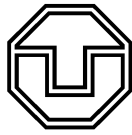


Table 3.2-1 Overview of most important improvements of the setup over the course of the project.

Component	Challenges	Optimization
Heatshield	High thermal losses	3 layers in every direction: → Reduced heating power (by approx. 30 to 40%)
	Might interfere with emission current measurement	Electrically grounded: → Improved current measurement
Substrate holder	Slower heating, high thermal gradient in material	SH first reduced in size, later sample attached directly to heater via clamping without any SH.
	Bad thermal contact between thermocouple and SH surface lead to unreliable readings	Heater with borehole for central heater attachment.
Improved insulation of anode	loose insulation at high temperatures	Additional insulation of alumina tubes by PTFE holder
Specimen	Thermal contact to the heater, electrical contacting	Clamping of the specimen ensure good contact and no detachment during the experiment due to thermal expansion.

3.3 Characterization of the Setup

3.3.1 Temperature Measurement and Heater Control

Before any iteration of the setup could be tested, a thorough characterization of the setup was conducted with regard to the performance of the heater and the temperatures at the heater itself and the substrate holder. Due to changes in the size of the heater, the size of the substrate holder, connecting mechanisms as well as heat shields, the performance did vary significantly.

A typical Heater temperature and heater power characteristic can be seen in Figure 3.3-1. For a given setup, the heater showed very stable behavior over the course of the test, with constant VI traces, and temperature to heating-power dependencies. The heating power increases significantly above 800°C, which is to be expected as thermal radiation from the hot surfaces becomes significant and is proportional to the fourth power of the temperature according to the Stefan-Boltzmann law.

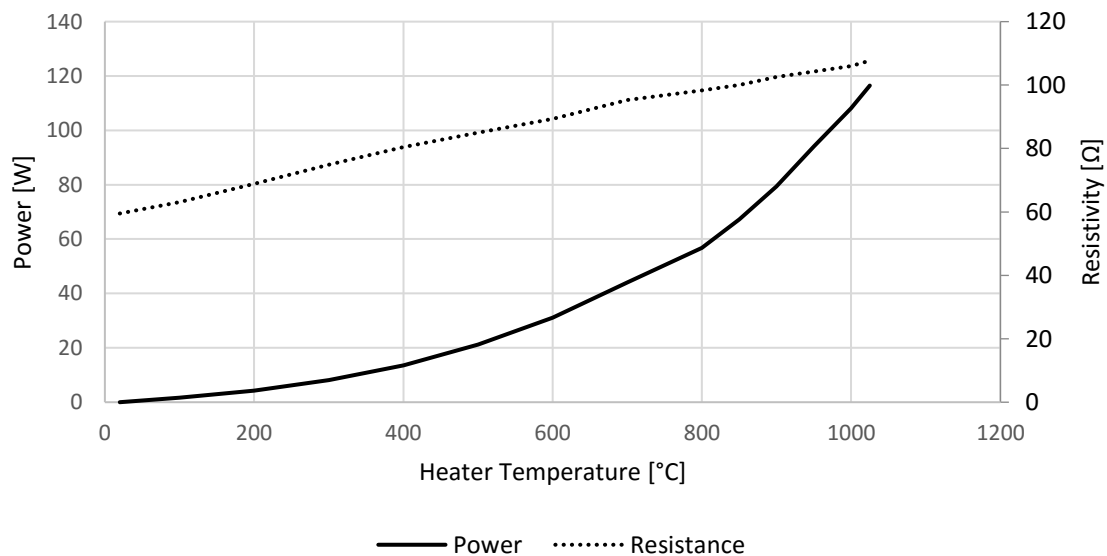


Figure 3.3-1 Heating Power and internal resistivity of the heater vs. temperature.

Another significant challenge was the temperature difference between the place of measurement and the electron-emitting specimen. Since we can not measure

the temperature directly at the surface of the specimen, assumptions have to be made. In reference experiments, temperature differences between the actual specimen and the measurement point have been made. An exemplary graph of the temperature difference can be seen in Figure 3.3-2.

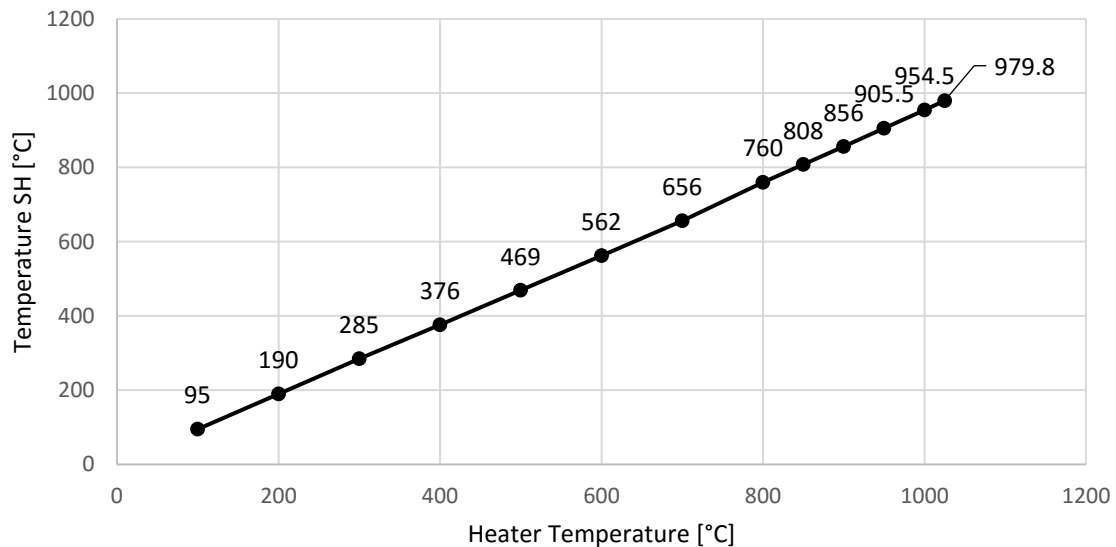


Figure 3.3-2 Temperature of the substrate holder vs heater core temperature. A gradient of up to 50 K develops at high temperatures.

As expected, the temperature difference increases at higher temperatures, in this particular case up to 40 K to 50 K at 700°C to 1000°C. In general, this temperature difference was minimized, for instance with more layers of heat shield, in order to have a more even temperature distribution at the heater and specimen. The discharge itself was controlled using the original measured temperature. For the evaluation of the performance of the electride, the temperature was adjusted using the data available from the initial calibration of each setup.

3.3.2 Zero Measurement and Bakeout

As mentioned above, the setup of the thermionic diode setup suffered from leakage currents at heater temperatures above 800°C. During the tests with the first iterations of the thermionic cathode, a dedicated study to the source of these cur-

rents was done. It was concluded that those currents do not originate from insufficient electrical insulation of the heater circuit or the anode and they are not influenced if the substrate holder is grounded or left floating during the measurement. Indeed, these currents seemed only to occur if a voltage was applied between the anode and the substrate holder (the cathode). If both anode and substrate holder were set to the same potential and a voltage was applied between these two parts and the rest of the setup, no leakage currents were observed. Therefore, we suspect that the leakage currents are a result of impurities in the molybdenum material.

For the later iterations of the setup, the heat shield and any other high temperature part were made from new parts of 3N5 purity molybdenum. All parts were thoroughly cleaned with isopropanol in an ultrasonic bath. However, during the first test leakage currents occurred again at heater temperatures of about 800°C. These leakage currents behaved very similar to those during the first test campaign:

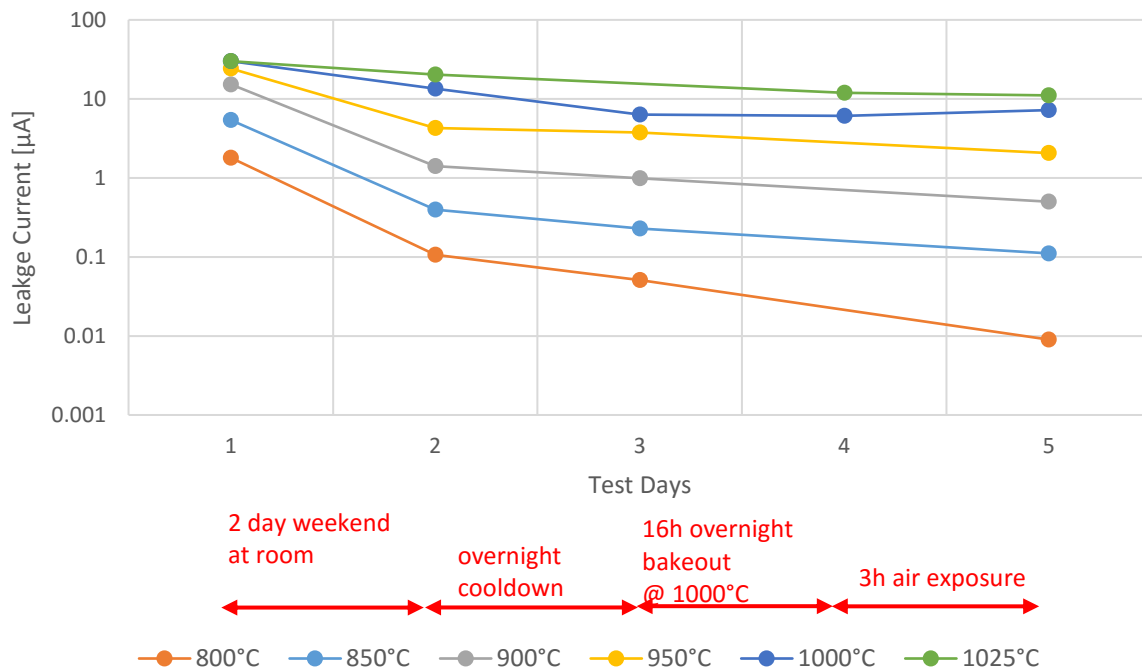


Figure 3.3-3 Reduction of leakage current over multiple days of bake out, anode voltage +20 V

- They occurred during high temperatures starting at about 800°C
- They increased with rising temperature
- They required between 10 to 30 minutes to reach an equilibrium
- When the voltage is increased from 20 V to 200 V the currents only increase by a factor of two and do not significantly increase for higher voltages.
- Currents also occur for negative anode polarities but with different amplitudes. This behavior had already been observed during the first test campaign and was not further characterized.

This time, the long-time behavior of the leakage currents at high temperatures was analyzed. For this, the setup was multiple times heated up and let cool down and the leakage currents were measured. The results are depicted in Figure 3.3-3 and Figure 3.3-4.

As shown in Figure 3.3-3, leakage currents were observed at 800°C and higher. At lower temperatures, they were below the noise-level of 1 nA. On day one, these currents were at the order of 1.8 μA , and they increased to nearly 30 μA at 1025°C. After the setup had cooled down and stayed in vacuum for two days over the weekend, the current levels decreased notably (test day 2). An overnight bakeout

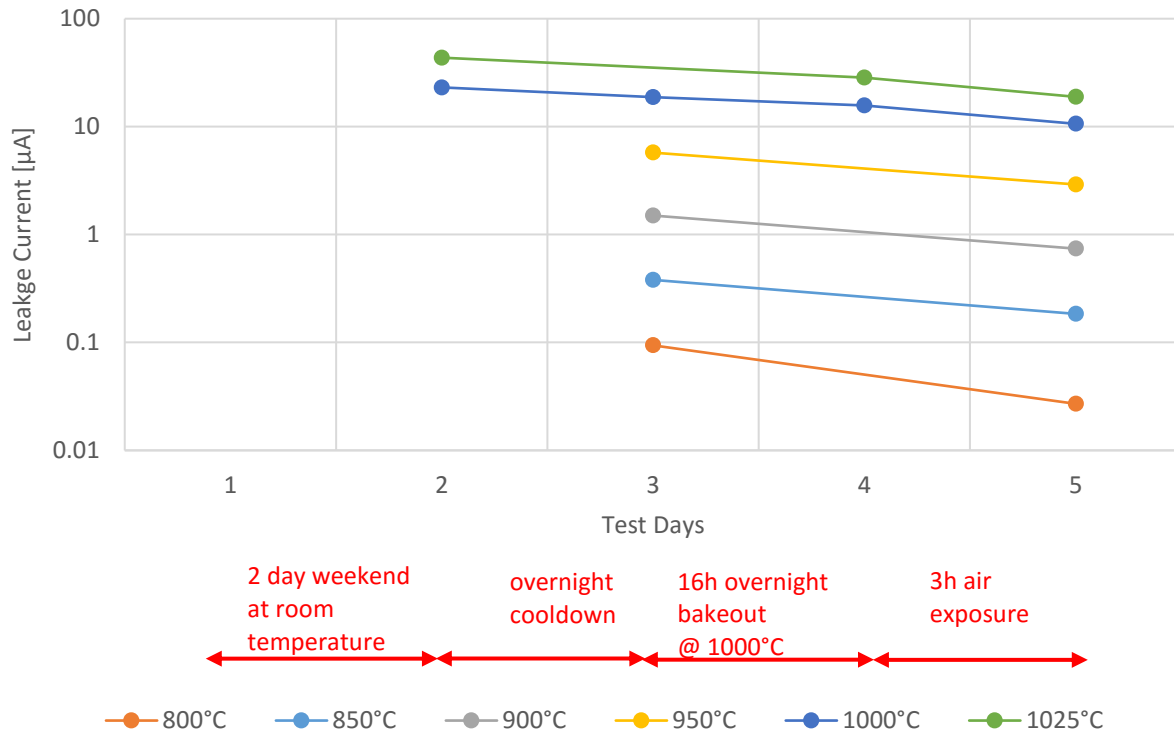


Figure 3.3-4 Reduction of leakage current over multiple days of bake out, anode voltage +200 V



at 1000°C was performed between test day 3 and 4. Although the leakage currents decreased by only one third at high temperatures, the resulting currents at lower temperatures became much smaller.

To test if the level of the leakage current would remain small after the test setup had been exposed to air, the vacuum chamber was vented after test day 4. The setup was exposed to ambient pressure for 3 hours and the vacuum chamber was evacuated again. As it can be seen from both Figures below, the current levels were in general even much lower. Most progress can be seen by comparing the leakage current at 800°C from test day 1 and 5, the current at +20 V has reduced from 1.8 μ A to just 10 nA.

By comparing the graphs of Figure 3.3-3 and Figure 3.3-4, it becomes obvious that the leakage currents do not increase linearly with the applied voltage. In fact, they are only roughly twice as large at ten times the voltage and do not significantly increase for higher voltages. As a conclusion from these observations, it might be necessary to heat the setup to even higher temperatures (above 1025°C) to sufficiently reduce the leakage currents.

The bake out procedure just described was done for any new configuration from this point on, in order to get better readings during our actual tests campaigns.

3.4 Tests with Material Samples

3.4.1 Emission Tests during the first year of the project

Three different Specimen were tested, all made of pure C12A7 electrider. For the first and second specimen, a silver contacting paste was used to attach it to the substrate holder and ensure electrical connectivity. However, the low pressure point of silver lead to high evaporation rates of the paste and a corresponding coating all over the setup. Furthermore, the samples had a green glimmer after dismounting them from the setup, indicating some kind of degradation. Still, for both samples, the current curves were well above the initial zero measurements, indicating some kind of electron emission during the test!

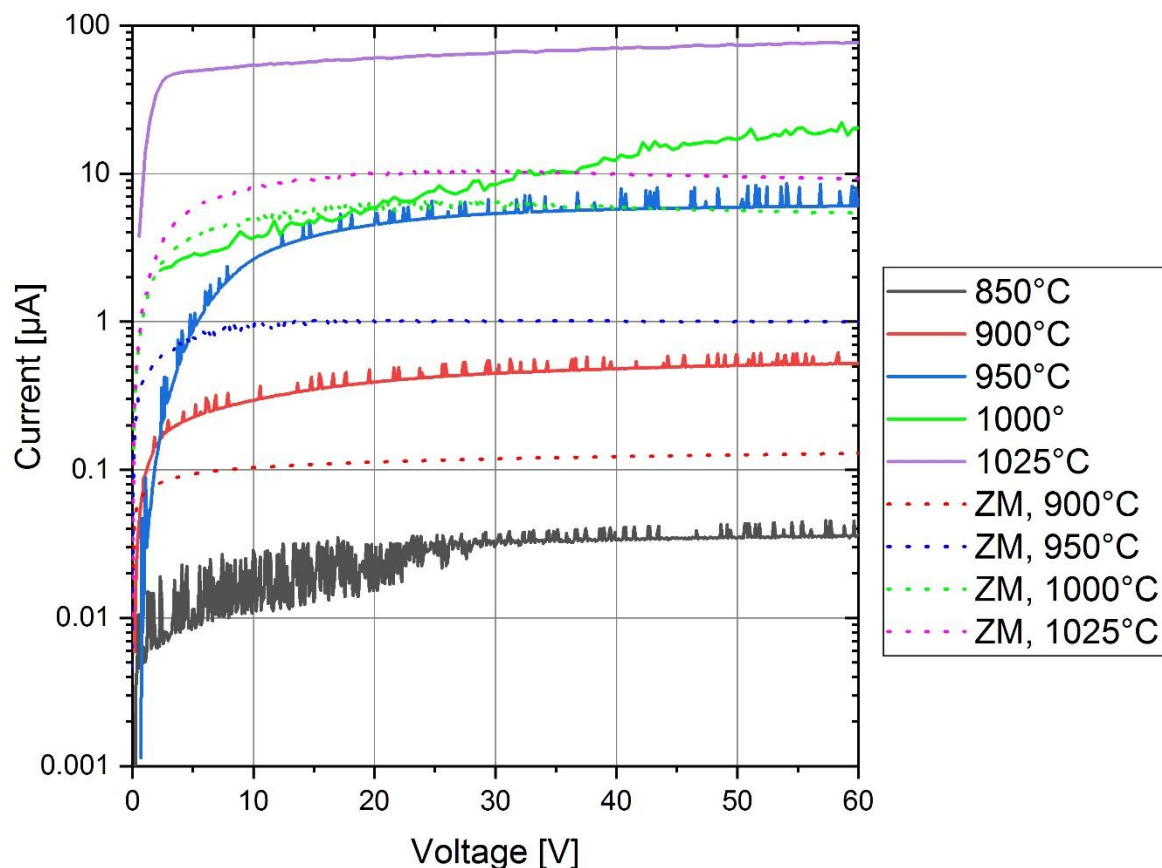


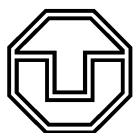
Figure 3.4-1 Current – Voltage – Characteristic for specimen 3 with logarithmic axis. ZM indicates zero measurement.

The best test at this campaign was done with a carbon paste as conductor between the specimen and the substrate holder. The paste itself withstands temperature up to 2000°C and is advertised as an alternative to silver paste for electron spectroscopy. Unfortunately, the paste is based on a water solvent. Because the C12A7 electrified is not supposed to be in contact with water (it will convert back to the normal ceramic), the use of this paste had to be with cautiousness. After assembly, the sample was rested in vacuum for about 60 hours, befor slowly heated with 0.1°C/s to 90°C and rested at this temperature for about two hours. Then it was heated to 260°C and rested again for two hours. This is to get rid of all the solvent of the paste.

The Current – Voltage – Characteristic as well as the corresponding zero measurement can be seen in Figure 3.4-1. This time, the currents were significant larger than in any other experiment before. The emission current reached about 80 μA at 1025°C heater core temperature, which equals about 900°C SH surface temperature. Overall, the emission currents reported have been significantly higher than the leakage currents, with at least one order of magnitude difference. This indicates, that thermionic emission from the C12A7 electrified has been measured. Having verified the closed diode setup suitable for measuring emission currents and therefore the work function of the material, we can now start to testify the actual samples.



Figure 3.4-2 Specimen 3 after operation. Again, a metallic shine is detected and green areas are observed.



After removing the setup from the vacuum chamber, the specimen again showed a slight green coloring at the top surface area (Figure 3.4-2). However, the general condition was better compared with the two previous experiments. Having such high emission currents probably indicates the improved electrical connection between the specimen and the substrate holder. The slight metallic shine on the top surface of the specimen is still some silver residue. Therefore, the setup was cleaned again thoroughly, to resolve this contamination problem in future tests.

3.4.2 Emission Tests during the second year of the project

After the first year underlined the importance of the contacting of the specimen, the focus in the second year was at the performance of the doped material. In particular the added molybdenum and titanium.

Due to the drawback of the contacting pastes in the first year (see Table 3.4-1), another carbon based paste was chosen: *Aremco`s Graphi-Bond 551-RN*. This contact paste showed signs of outgassing in vacuum, making it necessary to slow the heating process to keep the vacuum pressure in the 1E-8 mbar range. Otherwise, it worked fine and bonded with the material samples and the substrate holder. To keep the bonding intact up to 1000°C, the heat and cooling rate was set to just 0.1°C/s.

Table 3.4-1 : Overview of different contacting pastes

#	Name	Constitution	Remarks	Pros and Cons
1	Silver-based Paste	internal recipe	by Fraunhofer IKTS	+ successfully used to bond insert to hollow cathode - silver evaporates at high temperatures in vacuum and contaminates samples and setup
2	PELCO High temperature carbon paste	Dispersion of carbon flakes in an inorganic silicate	High temperature adhesive	+ no evaporation - contains aqueous constituents that might contaminate/decompose samples

		aqueous solution		
3	Aremco Graphi-Bond 551-RN	Single-parted, phenolic bonded, graphite and fiber-reinforced	High temperature adhesive	+ successfully used to bond insert to hollow cathode - signs of degassing in vacuum up to 700°C - once not bonded during heat up or broken during cool down in vacuum

Pure C12A7 electride sample

Several specimen were tested in this test campaign, the first being a pure C12A7 electride sample. The sample was integrated and slowly heated. The sample showed significant current emission at temperature above 750°C. The IV-traces that were recorded at different temperatures are shown in Figure 3.4-3. Because at some temperatures a significant current drop occurred when the anode voltage reached 60 V, the IV-traces were limited to 100 V. At 800°C, the current stayed below the values of the previous temperature step at 775°C.

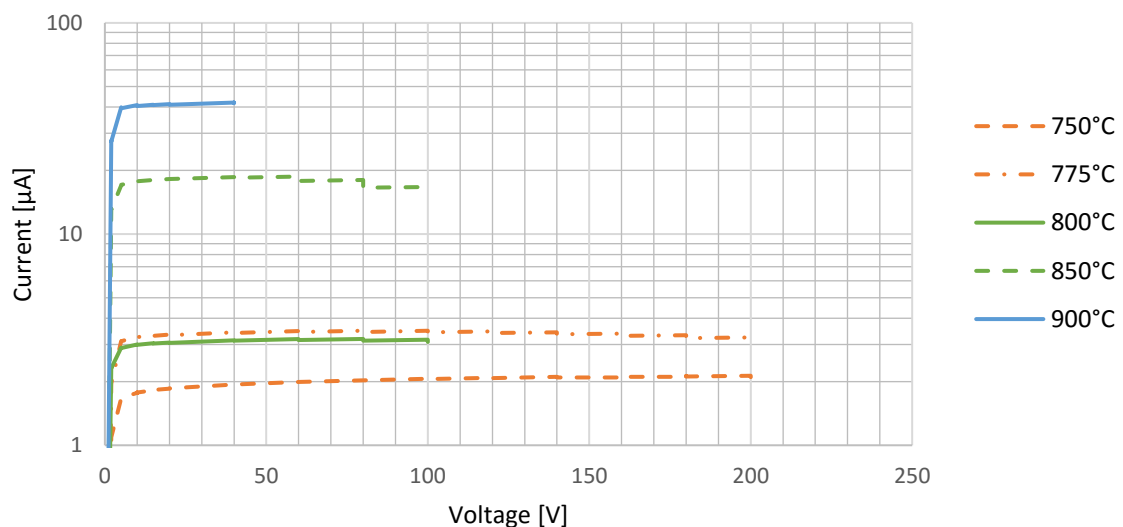


Figure 3.4-3 IV-Characteristics of different temperatures. The potential difference between the anode and the sample was sometimes not increased beyond 100 V because the current started to drop significantly at higher voltages.

As it can be seen in Figure 3.4-3, the current increases with higher temperatures up to $42\ \mu\text{A}$ at 900°C . However, when the heater temperature was further increased, the current did not but either stagnated or even became smaller. It was unclear if this was a result of material decomposition at high temperatures, either caused solely by the high temperatures or maybe by a contamination effect or if the bonding with the carbon contact paste was insufficient to supply larger currents. Therefore, the specimen was left to cool down over night in vacuum.

On the next day, the sample was heated again. This time, the emission started around $700^\circ\text{C}/660^\circ\text{C}$, but was small with just about $1\ \text{nA}$. At $875^\circ\text{C}/830^\circ\text{C}$, the maximum current was just $16\ \mu\text{A}$ and below the value expected from the first measurement process. The voltage was only increased to $60\ \text{V}$, because the saturation current was already reached at these low voltages.

The sample showed a slightly greenish gloss after the test, as shown in Figure 3.4-4. This might be an indicator for a partial decomposition of the material on the surface. During the removal process, it became clear that the contact paste was quite brittle, and the specimen could easily be removed. However, this might have been an indicator for an insufficient electrical contact. The color of the backside of

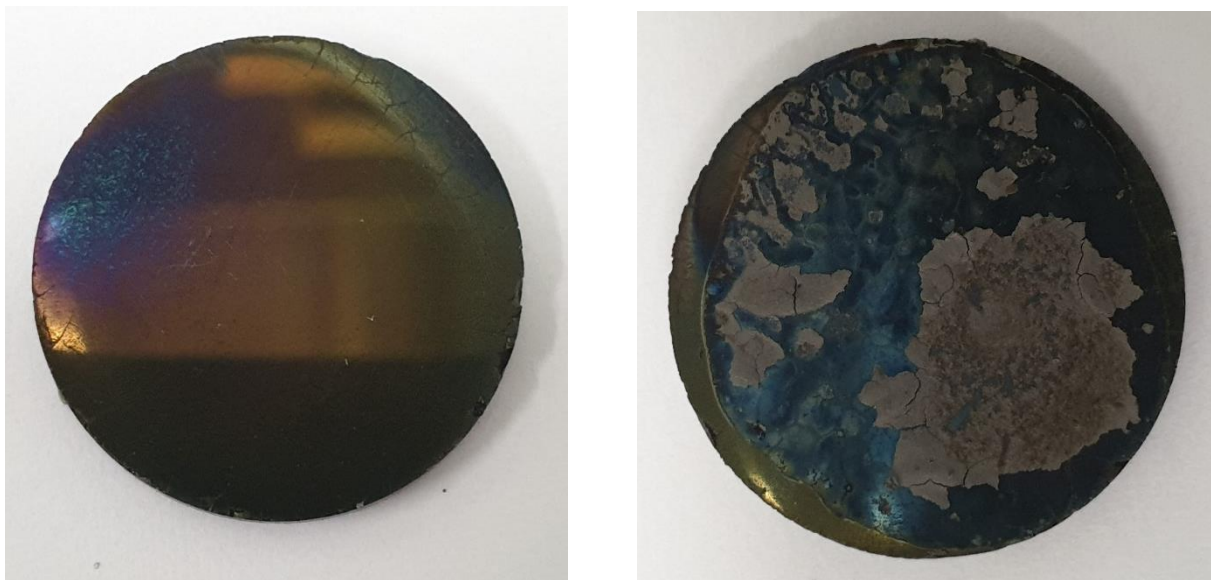


Figure 3.4-4 Pictures of the front (left) and back side (right) of the pure C12A7 electride sample after the tests. Although the front side has remained its glossy finish, it has turned slightly green and blue. The back side which has still some residuals of the contact paste attached to it has taken a blue color tone.

the sample had turned to a blue tone, indicating the creation of molybdenum carbides (MoC) with the contact paste.

The Richardson plot of the first heating procedure is shown in Figure 3.4-5. It can clearly be seen that there is a discontinuity between two lower temperature points and three higher ones. Therefore, two estimates of the work function were made: One concerning the complete range and one involving the upper temperature points only. These values are 2.08 eV (complete) and 2.62 eV for the 800°C to 900°C range. However, especially concerning the partial range three values are not enough to get a good estimate of the work function value.

Therefore, during the second heat up more temperatures were considered in steps of 25°C from 700°C to 875°C. The results are depicted in Figure 3.4-6. This time the data points show a very good alignment. However, the work function calculated from the slope of the fitting function is 4.36 eV.

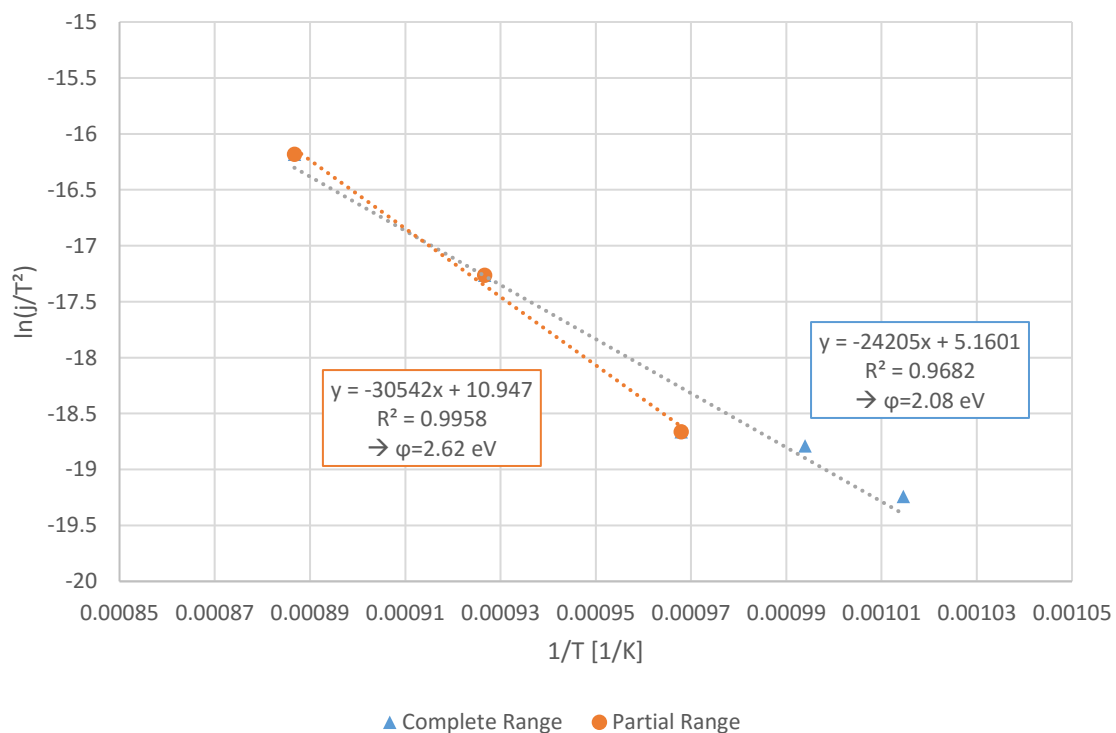


Figure 3.4-5 Richardson plot of the first heat up with the pure C12A7 electride sample. A discontinuity between the upper three points and the lower two points can be seen.

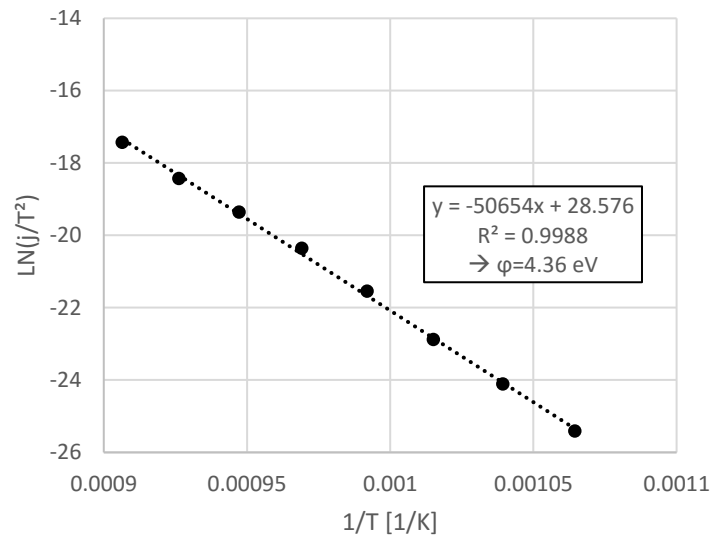


Figure 3.4-6 Richardson plot of the second heat up of the specimen.

Molybdenum additive

The second measurement was conducted with a specimen with molybdenum as additive (20 Vol-% molybdenum). Because the surface of the material is conductive, it was decided to test it at first without any contact paste. Emission started around 750°C/684°C and was observed until 950°C/875°C. It was not increased further with the intention to use the specimen in a second test run.

The IV characteristics are shown in Figure 3.4-7. The emission current density remained a little bit smaller compared to the pure C12A7 electride specimen.

The test was then repeated with the same specimen and the graphite contact paste. This time the emission was detected at higher temperatures (775°C/712°C). Although the currents seemed to be on the same order of magnitude (see Figure 3.4-7), they were generally smaller compared to the first measurement without contact paste. After the test, the sample showed no sign of degradation.

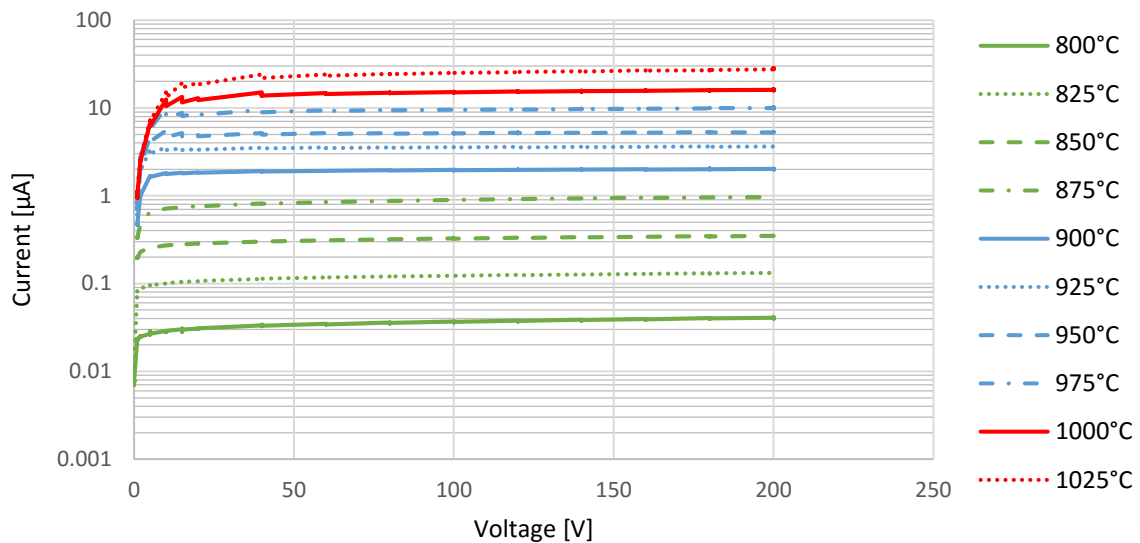


Figure 3.4-7 IV traces measured with molybdenum specimen (with graphite paste).

The same test was done with a second specimen with the same additive, with the same results. Figure 3.4-8 depicts one of the samples after the test. The backside as residues of the brittle carbon paste. Also a slight blue discoloration, where the Formation of MoC is expected.

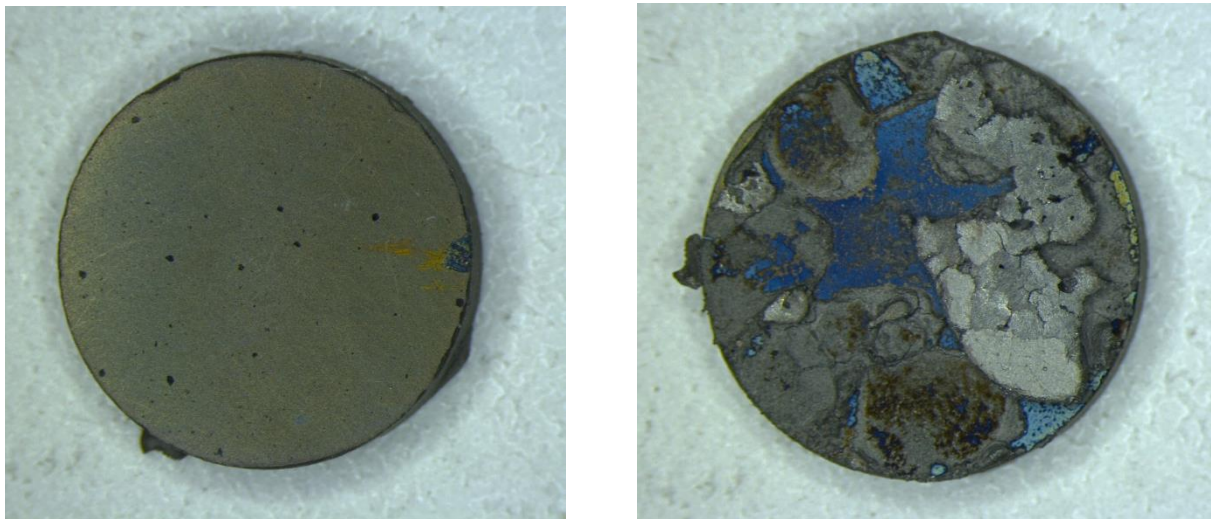


Figure 3.4-8 Pictures of the front (left) and back side (right) of the 1st molybdenum specimen after the tests.

Titanium Additives

The final material sample to be tested was a specimen with 30 vol.-% of titanium, with a diameter of 20 mm and a height of 1 mm. The measurements taken with this material sample were in some respect very different from the previous measurements. This can be seen from the IV-traces displayed in Figure 3.4-9.

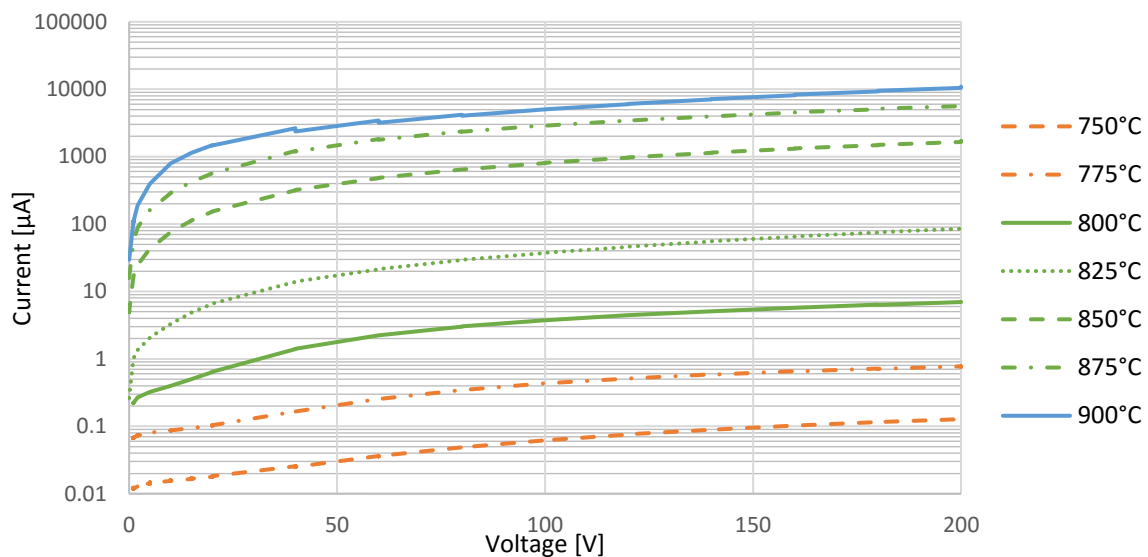


Figure 3.4-9 IV trace of the first experiment with the titanium specimen.

In contrast to earlier measurements, the currents did not saturate at voltages around 20 V to 60 V but instead increased nearly linearly with the increasing voltage. This was a problem, because the voltage could not be increased beyond 200 V with the Keithley 2450 Picoammeter. This was the first measurement where the current increased beyond 1 mA and reached a peak value of 10.92 mA at 200 V and 900°C/826°C. Swapping to the Keithley 6487 device with a maximum output voltage of 500 V was not possible because the current limit is 2 mA.

Although these large current values were very encouraging, two problems were inherent: Such a behavior was very different from the first tests and because the currents do not saturate, it is difficult to obtain reliable values to determine the work function. The test was repeated after some changes had been applied to the setup. Some parts of the heat shield were realigned to ensure that they did not

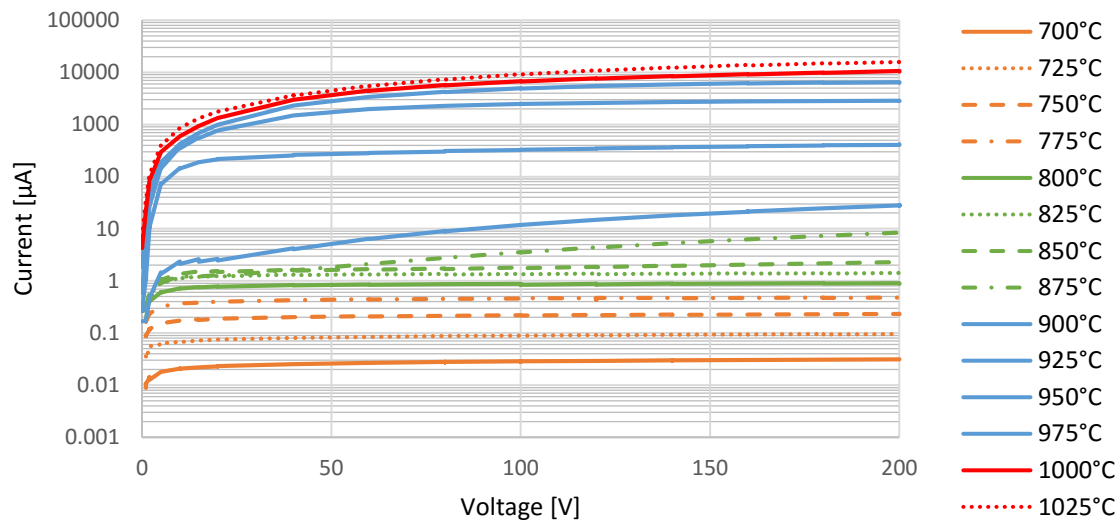


Figure 3.4-10 IV traces of the second experiment with the titanium sample.

cause these unusual current characteristics. The anode-sample distance was increased from approximately 5 mm to 8 mm. The second set of IV-traces is shown in Figure 3.4-10. The currents are smaller compared to the first measurement. The current of 1 mA is only reached at 950°C/850°C and therefore the required temperature was about 100°C higher than in the first test. By looking at Figure 3.4-10 it can be pointed out, that the currents between 900°C/830°C and 925°C/850°C increase by over one order of magnitude. After this, the growth of the current with increasing temperatures is reduced again. Under the influence of temperatures of 875°C/810°C and 900°C/830°C, the missing current saturation of the emission current at high voltages is most pronounced but is less significant for higher temperatures and even smaller at lower temperatures. This can only partially be explained by the increased distance between the anode and the sample.

Due to the irregular behavior of the currents, it was not possible to deviate a useful Richardson plot for the work function analysis.

The post-inspection of the specimen and the setup showed that the specimen was nearly unchanged, but especially the anode was covered by presumably evaporated material. This is shown in Figure 3.4-11 and Figure 3.4-12. This had not been observed when the specimen had been heated to approximately 820°C during the

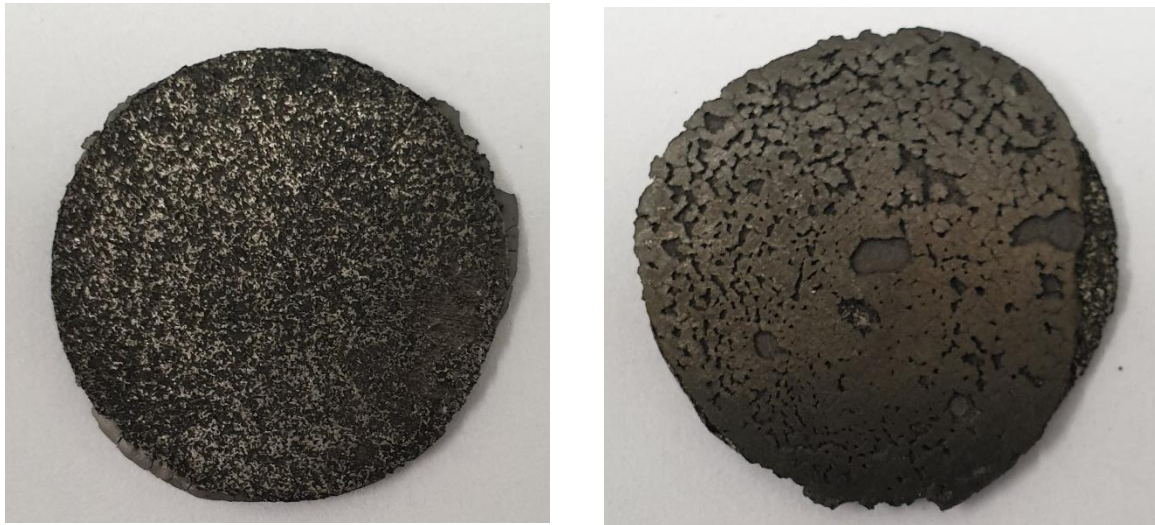


Figure 3.4-11 Front left) and back side (right) of the specimen with titanium. The sample has not visually changed by the test. The pore structure in the contact paste attached to the back of the sample indicates that the material might be prone to outgassing in vacuum.

first test. An EDX-analysis of the covered surface will be conducted as soon as possible. An evaporation process could most likely also have disturbed the emission process.



Figure 3.4-12 Picture of the front side of the anode (faced towards the specimen) after the test run at 1025°C/942°C.



3.4.3 Evaluation of work function values from current density measurements

The goal of measuring the thermionic emission was to evaluation of the work function of the C12A7 electride, due to its significant influence at the hollow cathode operation.

However, the tests showed significant lower current to be emitted at the samples in the thermionic setup, compared to any experiments with the in parallel developed heaterless electride hollow cathode. It is obvious, that there need to be significant effect at work that alter the effective work function of the material in a plasma environment.

Furthermore, the evaluation of work function values was rather inconsistent. On the one hand, no clear linear line could be drawn through the measurement point in order to evaluate the work function from the current density. Whether one would take single measurement points, in particular at lower temperature, had severe influence on the calculated value, as seen in Figure 3.4-5. The degradation is too unstable and effects like degradation as well as coatings from residues like reported with the silver coatings make it difficult, to find any reasonable value. Finally, not only the work function would be of great interest, but also the Richardson-Dushman constant. These values varied even more so than the work function, in rather non-realistic ranges nonetheless.

The work function values, that have been calculated, are most often in the range of 2.4 eV and 2.8 eV and therefore in line with the most recent literature. The focus was not any more on the work function value, but on the current density drawn from the sample itself.

3.4.4 Tests during the zero-cost extension

Due to the great results of the specimen with titanium additive, further tests have been conducted to get a better understanding of this behavior. Two bulk samples of C12A7 electrified with 30 vol.% titanium were tested.

The previous experiments had shown that the contacting past is a critical part of the setup. The best results had been achieved with the carbon paste with water solvent, which was not to be used further. The performance of the second carbon based paste was not ideal, as it was brittle after being heated.

Consequently, the setup was adjusted in a way that the samples are now pressed onto the heater directly. The same kind of heater made of SiN is used, but no substrate holder is necessary any more. A faceplate is attached to a counterpart with some screws and pushes the specimen onto the heater. Such a setup does not need the substrate holder, reducing the temperature gradient at this part. The specimen is electrically contacted at the faceplate. A graphite fold is placed between the C12A7 electrified ceramic and the metallic parts, to have some softer areas to adjust different thermal expansion coefficients. A sectional view of such a setup can be seen in Figure 3.4-13.

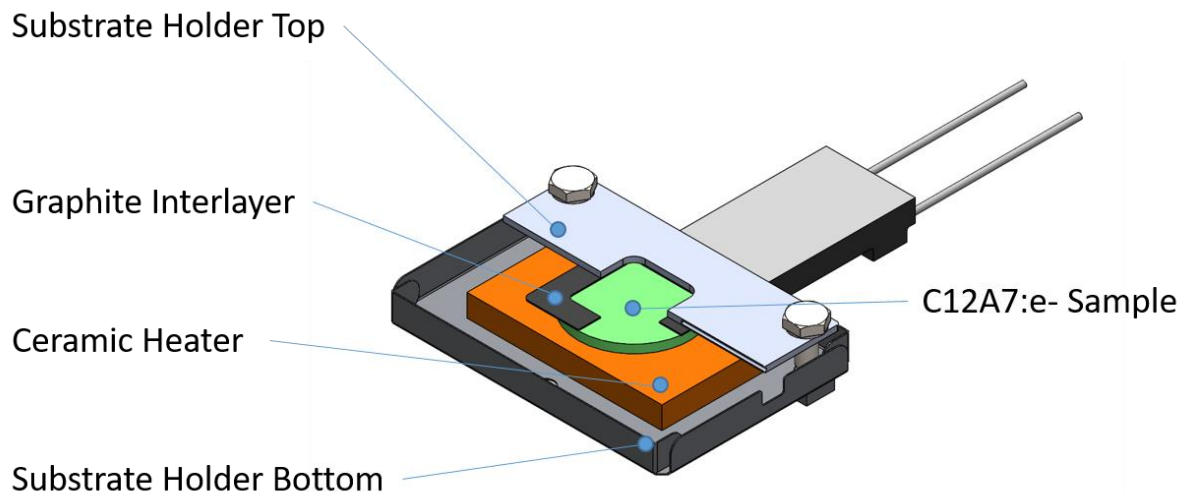


Figure 3.4-13 Sectional view of thermionic Diode setup with sample clamped directly onto the heater.

With the first sample, the following observations were made:

- During the first heating, the emission started at around 700°C. It kept increasing for over 70 hours.
- The IV-curves were nearly linear instead of showing the expected saturation current. Even with a field strength of 300 V/mm it was not possible to achieve saturation and Schottky or field effects might have played a role during the emission from the rough surface
- A maximum current of 100 mA/cm² was extracted at 825°C. This was the highest emission current measured with a C12A7:e- sample at TUD. However, the high current density seemed to lead to self-heating of the sample and was not stable over time. Evaporated titanium and calcium was found with an EDX analysis on the anode and other parts of the thermionic diode.

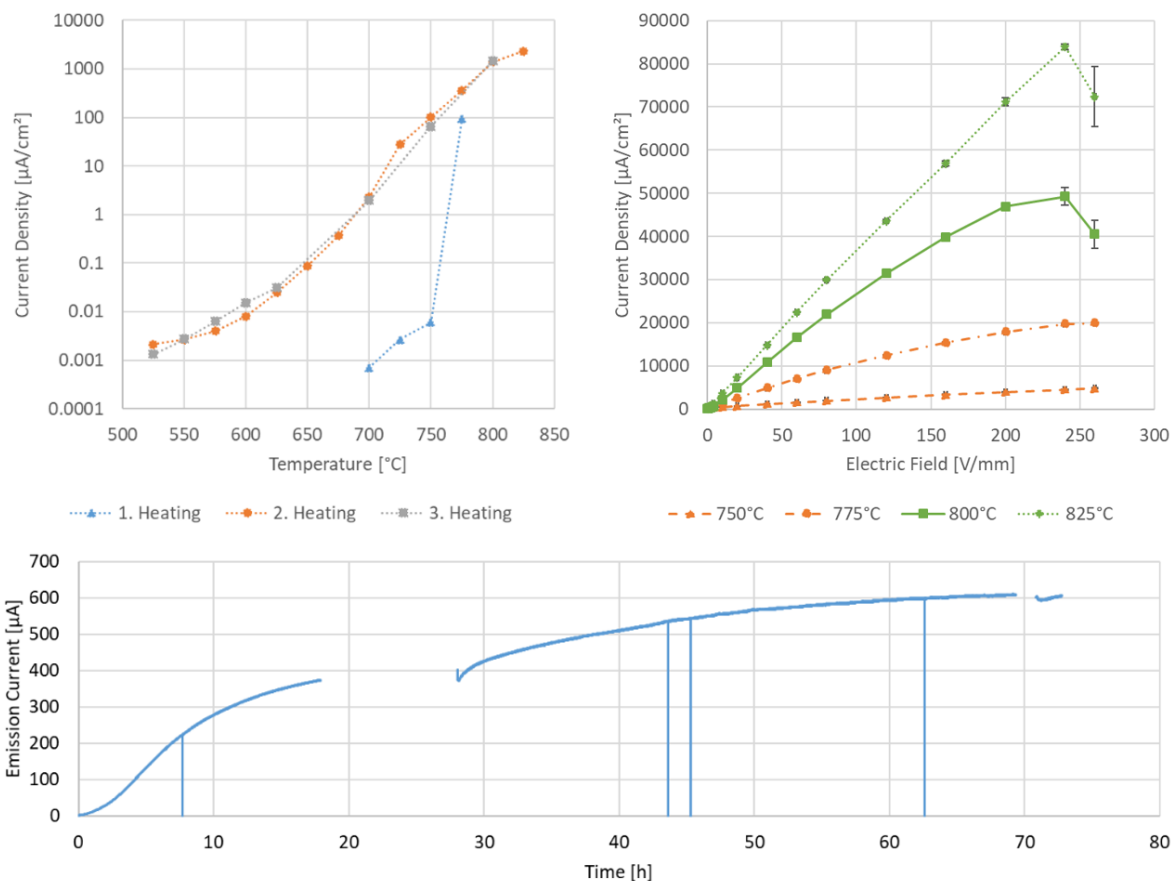


Figure 3.4-14 Top left: Current measurement during the heating cycles; Top right: I-V Traces during the 3rd heating cycle; Bottom: Slow current increase during 1st heating cycle at 750 $^{\circ}\text{C}$ over 3 days.

- After the initial heating procedure currents occurred at lower temperatures down to 525°C and were reproducible

The reproducibility of the results was shown with a second bulk sample of the same composition. At around 750°C the emission current of the sample increased from a few nA to more than 5 mA/cm² over the course of 110 h and the limit was not even reached, see Figure 3.4-15. Due to time constraints, the test had to be concluded and measurements were conducted at higher temperatures. To prevent the overheating of the sample the temperature was only increased to 800°C. An emission current of nearly 35 mA/cm² was detected at an electric field of 120 V/mm. Figure 3.4-15 shows that significant currents were also detected subsequently at lower temperatures.

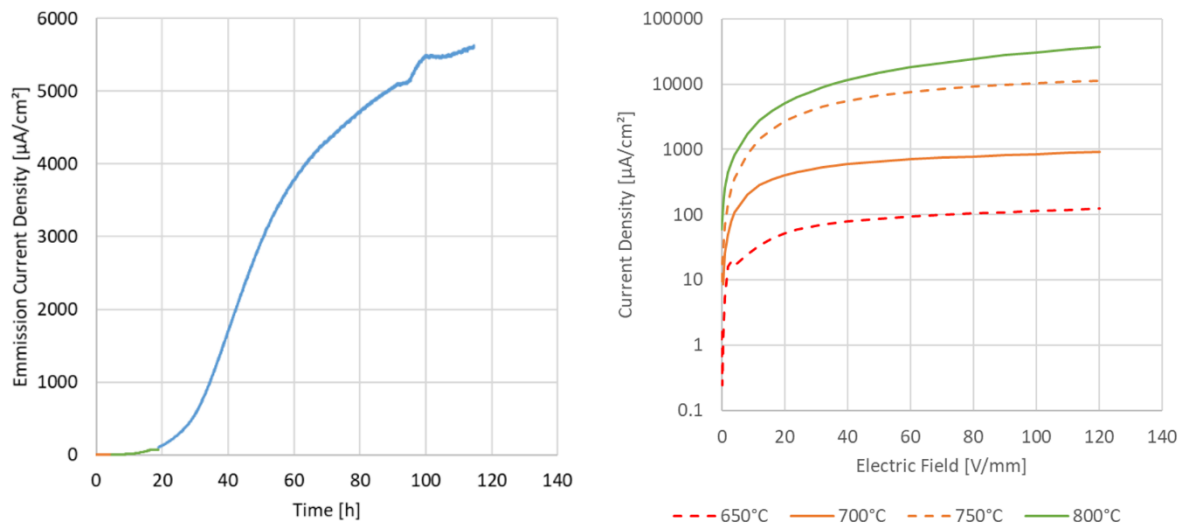


Figure 3.4-15 Left: Temperature increase of titanium sample over 110 hours at 750°C during the first heating; Right: I-V Traces of titanium sample

The samples showed no severe degradation after testing. Only some slight discoloration can be detected between the exposed and the covered area of the sample, as seen in Figure 3.4-16.



Figure 3.4-16 Titanium sample after thermionic emission test. Exposed / Emitting area can be seen clearly.

Overall, these experiments showed the best current density performance of any sample measured during the course of the project. As discussed in the previous section no work function has been evaluated for this particular setup. For this campaign even more so, as the measured curves were highly unstable! The high emission currents lead to a significant power dissipation into the sample and the anode, and consequently to an additional heating of the specimen. This was observed by an increasing current over time, while reduction of heating power in an originally equilibrium temperature state. The system was not able to control any constant power, which led to a chaotic oscillation of emission current, specimen temperature and heating power.

Eventually, even though the performance is again an order of magnitude higher than anything reported before, the performance still lacks behind any characteristic observed in the hollow cathode discharge.



3.5 Plasma Cleaning Processes

As stated several times in the previous chapters, there seems to be still a vast difference in the performance of the C12A7 electride with the thermionic diode and with the hollow cathode. The primary difference in the operation would be the appearance of the plasma in the hollow cathode, compared to the thermionic diode. The exact processes are not clear, yet.

Still, the exposure of the sample to an (abrasive) plasma could be beneficial concerning the performance of the electride in the thermionic diode setup. Therefore, an RF-generator was acquired to ignite an RF-discharge with an inert gas between the anode and the substrate holder to clean the surface of the specimen by sputtering.

It was anticipated from data found in the literature and a discussion with the manufacturer of the RF generator that the ignition of the RF plasma would be difficult for pressures below 1E-2 mbar. Due to safety precautions, the pressure inside the chamber can only be increased up to 1E-3 mbar (with the cryogenic pump operational). For higher pressure, the cryogenic pump needs to be shut off, only having the roughing pump operational. This would however imply that no direct test from the operation to plasma cleaning and operation again would be possible in the current test.

To prevent damage to the thermionic diode setup during the initial tests with the RF generator, a test rig was built to test the ignition behavior of the RF generator. The test rig consisted of two parallel sheets of molybdenum (0.2 mm thickness) with an area of 60 x 60 mm² each, resembling the rough dimensions of the thermionic diode. POM was used as spacer material to keep the plates at a distance of 10 mm or 25 mm. A tungsten wire with a diameter of 150 Microns was installed between the plates with the intention to assist the RF discharge by electrons emitted from the hot wire and reduce the required ignition pressure. This attempt was unfruitful, and it was not possible to ignite a discharge. Instead, a stable discharge was only observed at higher pressures (1E-2 mbar to 1 mbar) with the active backing pump. This is shown in Figure 3.5-1.

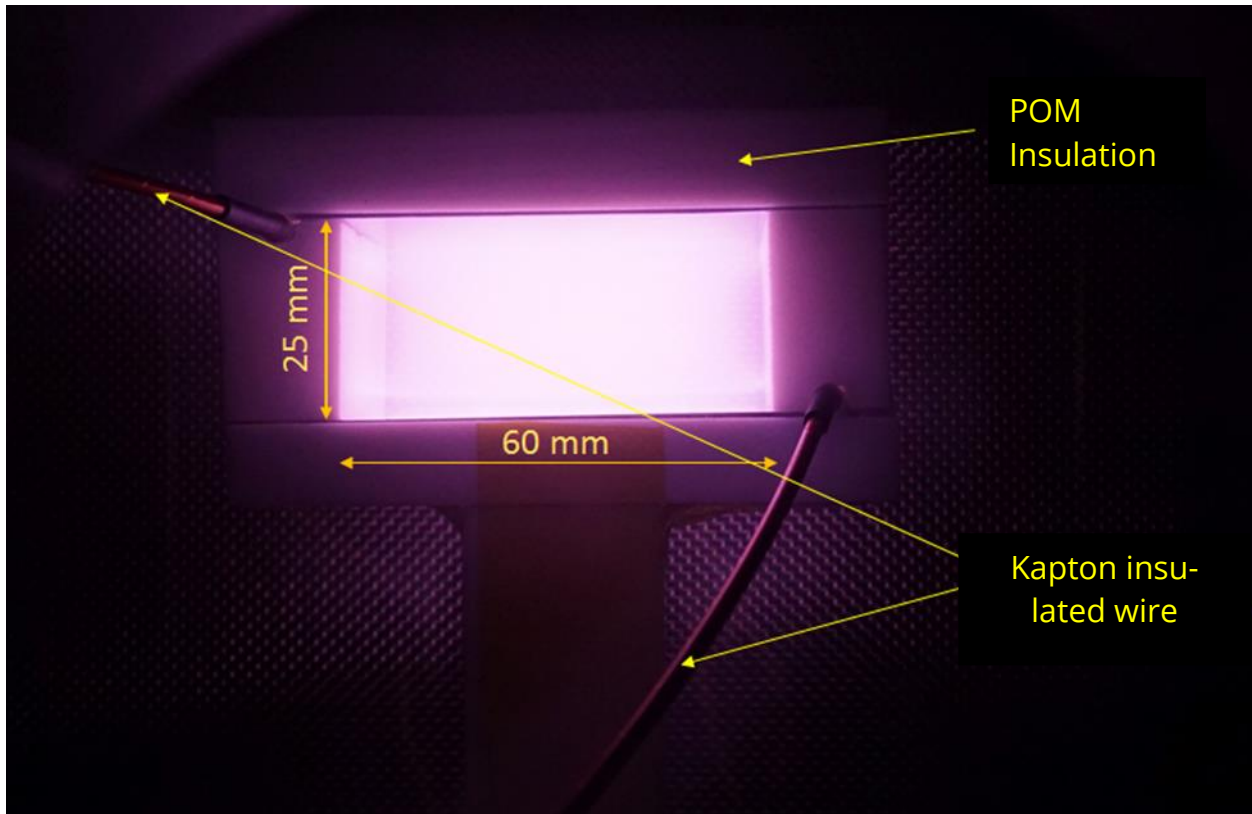


Figure 3.5-1 RF argon plasma discharge at approx. $1\text{E-}1$ mbar.

Due to the operational constraints with the ignition of the plasma inside the setup, the approach of cleaning due to RF-plasma sputtering was currently not approach further.

Table 3.5-1 : Parameters of RF-generator of type Diener LFG1000

Property	Value
Frequency	100 kHz
Current Mode	1 A to 4 A
Power Mode	200 W to 1000 W
Max. output voltage	1200 VAC
Pulse-width	100 μs to 100 ms (burst mode)
Pulse-delay	100 μs to 100 ms (burst mode)
Cooling	Air-cooled



3.6 Conclusion WP2

During the course of the setup, much insight was won into the development and optimization of a thermionic diode setup to measure thermionic electron emission of specimen. Several iterations lead to a steady improvement of the measured data. Many causes of errors have been identified and irradiated. Still, the process is very complex and time consuming!

Numerous samples have been tested in our setup. This led to a significant improvement of the performance of the material. Furthermore, significant information about the capabilities but also limitations of the material have been reported and analyzed. Overall, our material is in range of most recent literature sources concerning the work function of the material, being in the range of 2.4 eV and 2.8 eV. The best performance was achieved and verified using C12A7 electrified with 30 vol.% titanium added, reaching close to 100 mA/cm². Furthermore, the general functionality of the material being doped with molybdenum to improve the thermal and electrical conductivity internally as well as at the surface, has been confirmed, which was to the best of our knowledge not yet reported in literature.

Critical is still the overall low current density of the material, which is in steep contrast to the performance inside the hollow cathode. Unfortunately, the attempts of the in-situ RF-plasma cleaning processes have not been successful. This could be a task for future work!

- Design of a modular setup for the evaluation of work function of C12A7 electrified samples using thermionic emission → done
- Assembly of said setup → done
- Characterization of the work function measurement setup → done
- Work function measurements of C12A7 electrified samples → done
- Evaluation of the influence from surface contamination, implementation of a plasma cleaning mechanism → not concluded



4 WP3/WP4/WP5 – HOLLOW CATHODE DESIGN AND CHARACTERIZATION AND OPTIMIZATION

The Design, characterization and optimization of the hollow cathode goes hand in hand. Therefore, all three work packages will be discussed together along the iterations of the cathode over the course of the project. Overall, four iterations can be distinguished. An initial overview of the iteration is given in Table 4-1.

Table 4-1 Result of testing different contacting pastes.

Iteration	Geometry	Tests / Results
AFRL 1.0	Hollow cylinder	- 300h test with partial anode discharge at low currents - Plasma degradation
AFRL 2.0	Hollow cylinder	- Advanced temperature measurement - Bias Operation - Melting / Degradation of Electride
AFRL 3.0	Tablet	- First tests with tablet shaped insert
AFRL 4.0	Tablet	- Planar hollow cathode - Mounting and contacting pastes - Influence of electronics - Multi-orifice operation - Endurance Operation (950h) at 2A

4.1 Design AFRL_1.0

Generally, the idea of the Design is to decrease the temperature at the insert region. In previous experiments, the C12A7 electride material often seemed to be melting, resulting in a failure of the hollow cathode operation itself.

Therefore, the cathode base and tube (which will then hold the insert) are made of copper, because of its great thermal conductivity. Furthermore, rather large diameters as well as short distances were chosen, in order to increase the heat flux along the material to the backside of the cathode. At the backside of the cathode, a radiator is positioned in order to decrease the temperature of the cathode itself

and therefore allow a decrease of temperature at the insert. A sectional view of the 3D model to the described design can be seen in Figure 4.1-1.

A type-K thermocouple is mounted at the backside of the copper housing. Although the position seems not ideal for an exact temperature measurement at the tip of the cathode, it should be sufficient for an approximate estimation. Due to the high thermal conductivity of copper and to the large cross section, no major temperature gradient between the tip of the cathode as well as the back of the housing is to be expected.

The insert, that was supposed to be used with this kind of setup, is of cylindrical geometry with 4.2 mm outer diameter, 0.8 mm inner diameter and a length of about 20 mm. To improve the thermal connection between the insert and the copper mantle, sheets of carbon foil are used (25 μm and 0.5 mm). To improve the electrical conductivity of the C12A7 electride to the surrounding materials, a silver-palladium paste (AgPd) was used.

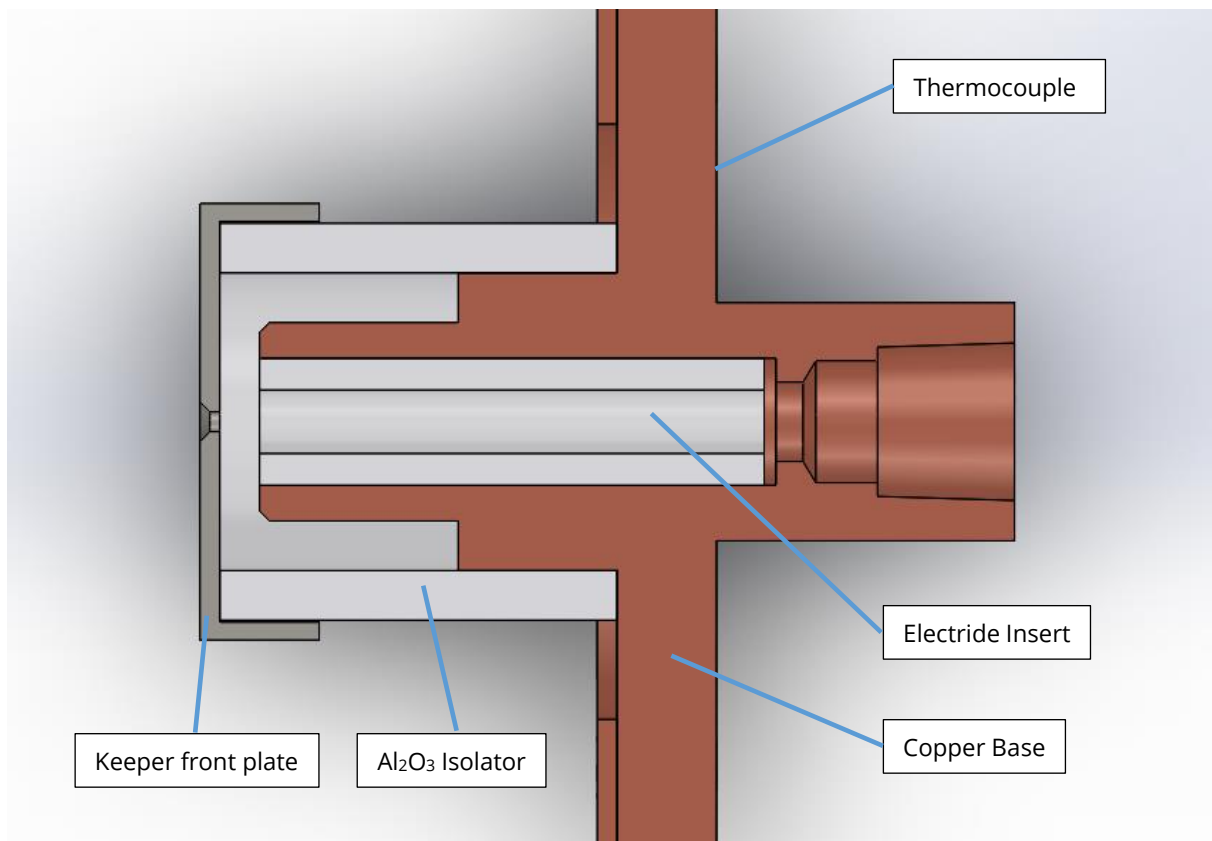


Figure 4.1-1 CAD Modell in Sectional View of Hollow Cathode Design AFRL_1.0



The keeper is fully enclosed and isolated using an Al_2O_3 -tube. The keeper orifice diameter is reduced to about 1.0 mm, while the molybdenum orifice at the cathode itself has been removed. Previous tests showed better ignition behavior with a greater cathode orifice diameter. It is theorized, that without the cathode orifice plate there will be a better penetration of the electric field from the keeper potential to the inside of the insert, in order to ignite the cathode discharge.

For an anode, a hollow cylinder made of stainless steel was used. The diameter was in the order of 35 mm and with a length of about 10 cm. The anode was positioned a few centimeters in front of the cathode.

A pre-resistor is used to improve and stabilize the ignition process of the hollow cathode. The resulting voltage drop from the resistor is removed from the presented measurement data.

The testing of the hollow cathode was performed in the same vacuum chamber as the thermionic emission. The base pressure without mass flow was in the range of $2\text{E-}8$ mbar and with 4 sccm argon mass flow in the order of $1\text{E-}6$ mbar. Keeper and anode were both operated with Delta Elektronika SM660-AR-11 power supplies.

4.1.1 Operational Results

With the setup just presented, ignition was easily achieved. We operated at low current limits, moderate mass flow rates and were in no need of any kind of additional ignition help like an electron source (filament). Overall, more than 300 hours of operation with one single insert have been achieved. At this time and to the best of our knowledge, this was by far the longest operation of a C12A7 electride hollow cathode reported in literature.

4.1.2 Ignition

Figure 4.1-2 shows the characteristic keeper voltage and cathode temperature over time of operation. For this test, the current limit at the keeper was set to 0.1 A. The voltage ranged between 80 V and 160 V. For about the first 100 hours the mass flow rate was set to 10 sccm and was later set down to 3 sccm. This resulted in a

pressure in the order of $2.1\text{E-}5$ mbar and $4.5\text{E-}6$ mbar respectively. The temperature measured during this test can be seen in Figure 4.1-2 and ranged between 75°C and 150°C .

During the test, the cathode was shut down several times. In some cases even taken out of the chamber. The situations and the time being out of the chamber is marked in Figure 4.1-2 as arrows at the x-axis. The time in air ranged from some hours up to 3 days. During this time, the materials was exposed to normal air humidity as well as oxygen. Re-ignition of the cathode was achieved reliably. The only distinction that has to be made, are two different plasma modes that occurred (discussed later on).

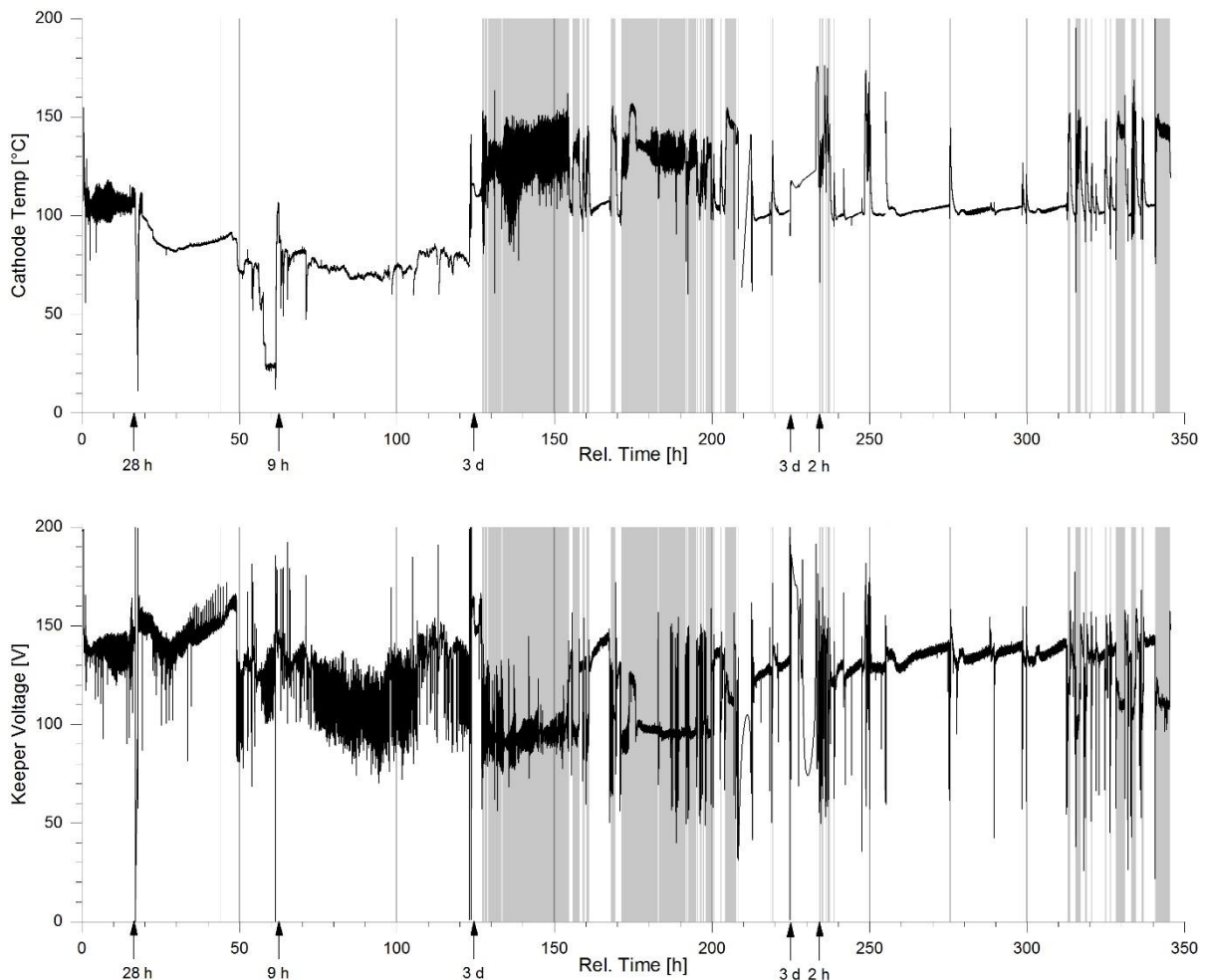


Figure 4.1-2 Voltage and Temperature Characteristic for the long duration test. Grey is the anode operation and on the x-axis are the times of air exposure with duration marked.

4.1.3 Anode Operations

During the time of operation, a discharge towards the anode was attempted several times. Therefore, 600 V with a current limit of 0.1 A was applied to the anode. Ignition to the anode was not instantaneous and did not occur all the time. Most often, a current to the anode was only recognized several minutes (if not hours) after applying the voltage. The corresponding times when a discharge to the anode was recorded are marked grey in Figure 4.1-2. The measured anode voltage during discharge was in the range of 120 V to 170 V. The voltage at the keeper dropped by about 25 V during an anode discharge. Furthermore, the increase in temperature but also in the noise level can be clearly seen. In the best case, the discharge to the anode was continuously stable for about 25 hours. Overall, about 60 hours of anode discharges were logged.

To stabilize the anode discharge, several parameters have been varied. A slightly higher mass flow rate, higher discharge current limits at keeper and anode and a shorter distance between anode and cathode were tested, but without any clear improvement. There was no clear indication apparent, how the discharge could be improved. This will be one of the major points on the agenda for the next upcoming tests.

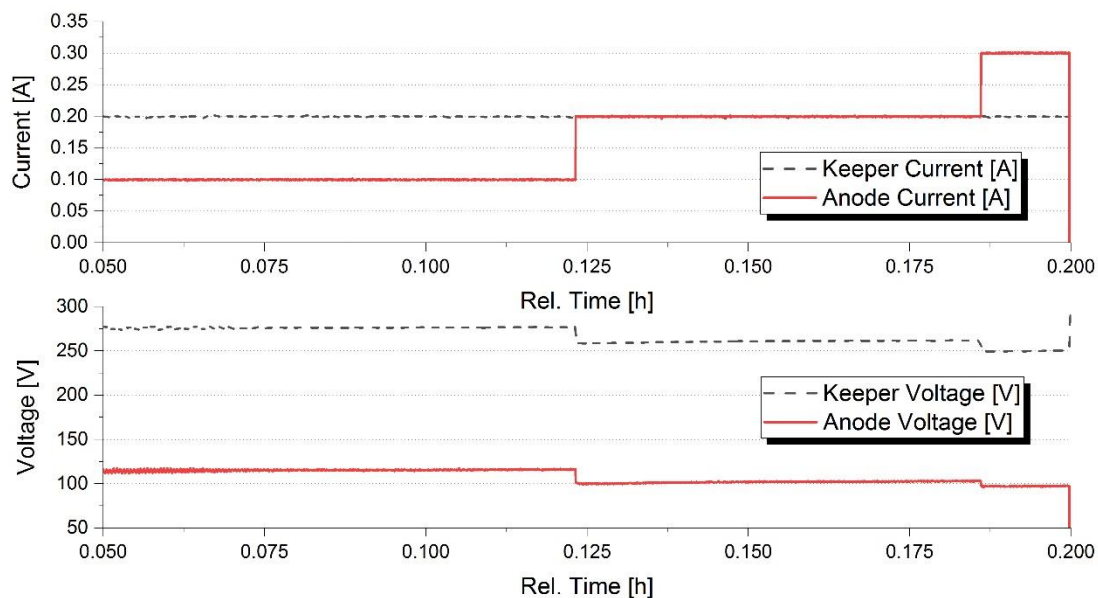


Figure 4.1-3 Current and Voltage at Anode during discharge.

During the endurance test, the current limit at the anode was set to only 0.1 A. In addition to that, the anode was also tested with higher current limits. As shown in Figure 4.1-3, the discharge current was increased up to 0.3 A. As expected, the voltage at keeper and anode dropped here. It is expected, that a further increase in discharge current lead to a decrease in discharge voltage, therefore keeping the discharge power at a similar level.

Unfortunately, during this time, the temperature reading did highly fluctuate between around 200°C and 0°C (Figure 4.1-4). We assume that there was some kind of grounding problem with the measurement during anode discharge. After some time of operation and shut down of the anode, the temperature did read about 140°C.

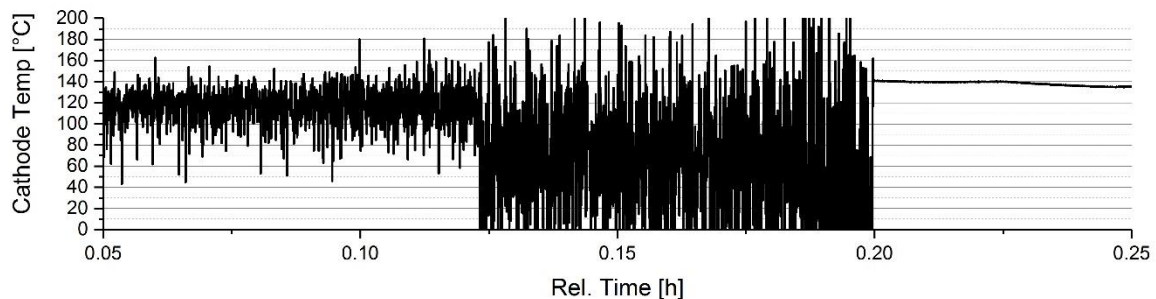


Figure 4.1-4 Noise of temperature reading during cathode operation. Increasing from 0.1A to 0.3A and then shutdown.

4.1.4 Plasma modes

During testing, two distinct plasma conditions were identified. The first is best described as “low power” mode under normal operation conditions with discharge currents at the limits and voltages between 50 V and 150 V. The plasma seemed to be light in color and there was a small plume emerging from the orifice. Long-time exposure pictures showed a somewhat white plasma inside the cathode, as shown in Figure 4.1-5 a).

In the second condition, the appearance of the plasma was not as intense and showed a purple color, as pictured in Figure 4.1-5 b). But more importantly, the voltage in this condition was much higher, sometimes even at the limit of 600 V. This led to a much higher operational temperature in this mode, of up to 180°C. Therefore, this mode is referred to as “high power” mode.

Naturally, the mode with lower heating power and therefore lower temperature would be the desired mode for operation. Furthermore, an anode discharge was achieved only in the low power mode. It could well be, that the high power mode is some kind of indication towards a conditioning of the insert, as it seemed to be apparent when the insert had been exposed to air for some time. However, no clear indication of the time or the temperature could be found, when the transition between the modes appeared. On the contrary, random changes of parameters provoked a change from the high power into the low power mode, without any clear indication of what caused it, yet. This will be one of the important topics to cover in upcoming tests, too.

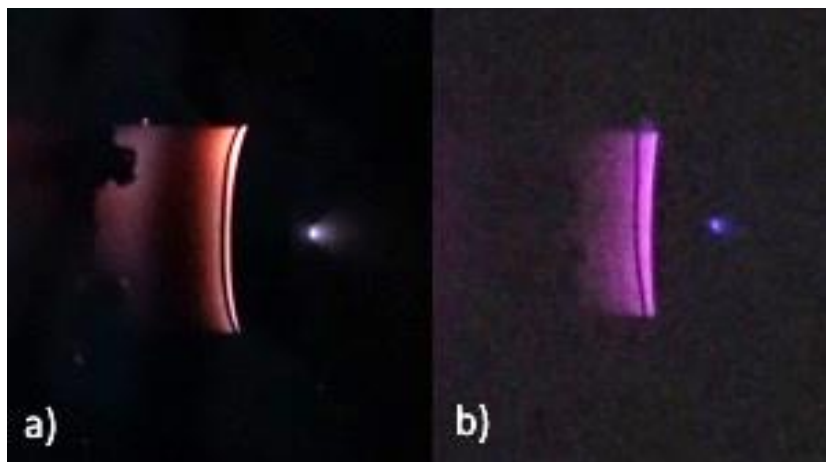


Figure 4.1-5 Plasma modes during operation. a) Low Power mode with white plasma. b) High power mode with dim purple plasma.

4.1.5 Degradation

To get a better understanding of the emitter material in order to be able to evaluate the long time operation potential, regular checks of the insert surface quality have to be done. Therefore, whenever the cathode was removed from the vacuum chamber and dismantled, the front surface of the insert was documented. The pictures after 24 hours, 100 hours and 300 hours of operation can be seen in Figure 4.1-6.

Clearly, there are indications of emission and higher temperatures. However, overall, the condition of the insert material is quite decent. Only after about 300 hours of operation (Figure 4.1-6 c)) we see some kind of wear of the material. The surface

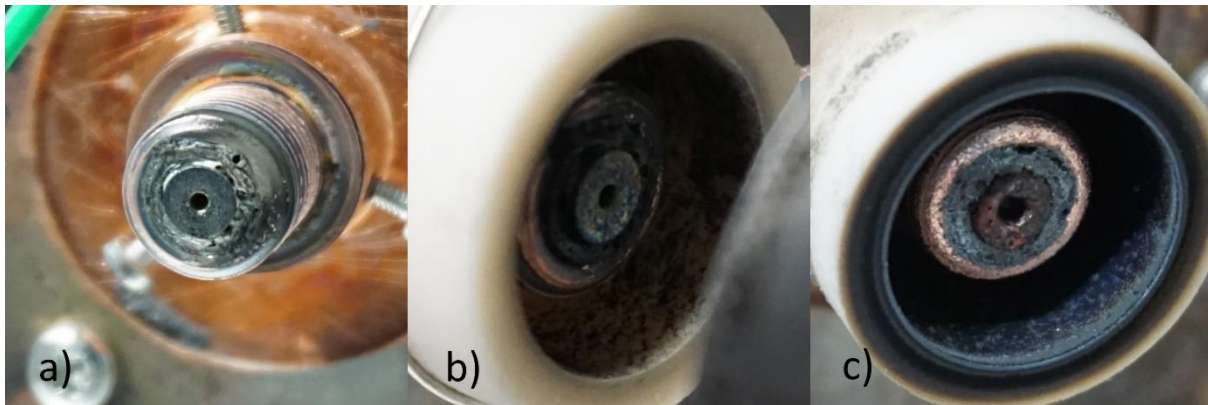


Figure 4.1-6 Degradation of insert at several points of operation. a) 24 hours, b) 100 hours, c) 300 hours.

looked rough and had a reddish color. By comparing the insert with the adjacent copper, it must be assumed that some kind of sputtering had appeared and that therefore some copper material was depleted onto the C12A7 electrode material.

4.1.6 Analysis

Operating the cathode for several hundreds of hours showed great improvement. As far as we know, this is the longest operation of a C12A7 electrode hollow cathode so far. Furthermore, 3 sccm to 10 sccm argon mass flow indicate the possibility towards a small and low mass flow rate hollow cathode. Still, there are several things to improve and adapt.

The results presented do imply that the design of the cathode is functional after all. Either way, a number of adjustments can be made and are presented in a later section, which deals with the analysis and improvement of the design in particular (see chapter 4.4).

The first thing to discuss would be the C12A7 insert. Having no insert, the ignition of a plasma in the inside of the cathode was rather reliable. Although, having two distinct plasma modes indicates some kind of conditioning of the insert. Analyzing the order of degradation shown in Figure 4.1-6, we can see that no intense burn out of material was apparent. This would be great in terms of long-term operation of such a material. However, the Pictures also show that the insert has to be protected from sputtering of materials. Figure 4.1-6 c) clearly shows the depletion of material at the front surface, which will result in a change of properties of the material. A solution has to be found to protect the insert from such depositions



but also allow for a good penetration of the keeper potential to the insert for the startup process.

The geometry of the Insert seemed to be suitable for low current operations. The small inside diameter allowed low enough mass flow rates and the wall thickness is strong enough, to withstand the thermal stress during operation. However, it has to be examined whether these dimensions are still suitable for larger emission currents, as higher temperatures and temperature gradients would be expected.

The cathode has been operated for more than 300 hours at 0.1 A keeper current and anode current respectively. For the joint operation with electric propulsion systems, emission currents in the order of at least 1 A anode current would be needed. Figure 4.1-3 shows the operation of the cathode with higher anode currents. Test like this will be stressed in future test, having resolved the problem with the temperature reading.

Either way, the characteristics show a significant drop in discharge voltages with the increase in discharge currents. It has to be expected, that the discharge voltage will drop even lower for increased current limits. Having a discharge voltage in the order of 50 V at a discharge current of 1 A would result in an insert heating in the order of 50 W. Comparing these 50 Watts with thermal calculations in previous iterations of the cathode indicate a serious increase in operational temperature. And obviously, this would be the amount of heat that has to be removed from the insert area. Studies, whether an increase or decrease in removed thermal energy would be more beneficial (concerning the power balance) have to be made.

Having an unreliable discharge to the anode is rather inconvenient. Obviously, the discharge to an outside potential is one of the key factors of a cathode. The current challenges with the anode discharge have to be analyzed and resolved. Because the 25 hours of continuous discharge seem to indicate, that it should be generally possible. Although changes in mass flow rate, anode distance and applied voltages did not seem to have any significant effect, further parameters have to be varied to get to a more reliable discharge to an external potential.

The measured temperature at the cathode was just in the order of 120°C. Although the temperature was measured at the backside of the cathode, which means that there was a higher temperature at the tip of the cathode in the emis-



sion area of the insert, these values indicate a rather low overall operational temperature. One has to consider, that the design is in particular using high conductivity materials as well as short distances and great cross sections. Either way, the temperature distribution as well as the cooling of the cathode could potentially be another challenge for the implementation of such a cathode in an actual flight system. Either way, more detailed temperature measurements have to be done to get a better understanding of the behavior of the insert itself.

4.2 Design AFRL_2.0

Two major aspects were approached with this design iteration of the cathode: First, the design and especially the contacting of the keeper and second, the availability of the temperature measurement. Furthermore, the design was arranged in a way to improve and simplify the manufacturing and assembly of the cathode.

The design of the cathode that has been developed can be seen in Figure 4.2-1. The main part is made of copper, allowing the drain of excess heat from the insert to the radiator. Insulators made of the machinable ceramic *Rescor 902* [9] are used

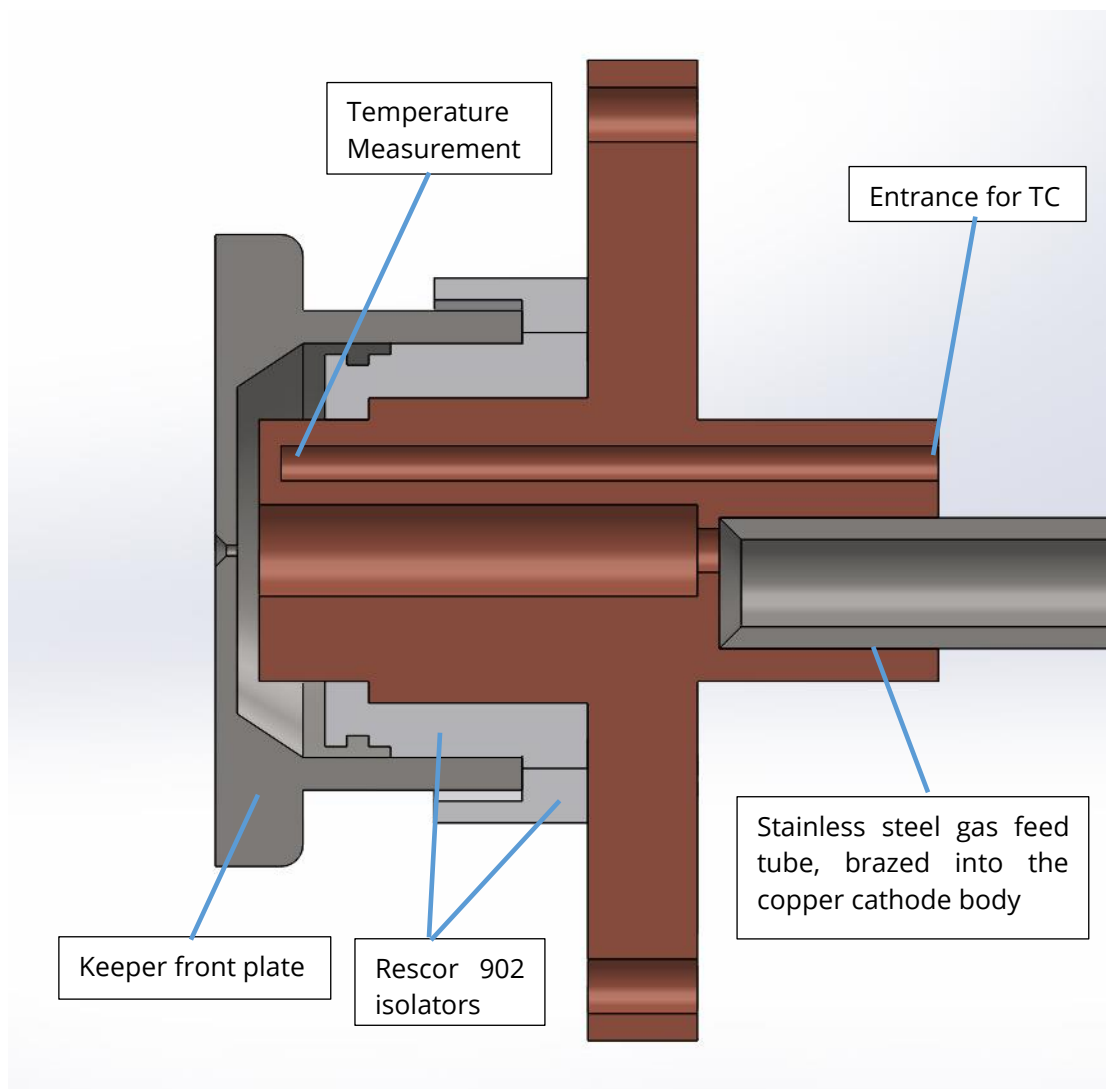


Figure 4.2-1 3D Model of the Design AFRL_2.0 in Sectional View

to hold the keeper front plate made of stainless steel. The insulators are designed in a way, to create undercuts when assembled. This will prevent the buildup of electrical pathways between the cathode bias and the keeper potential.

To connect the isolators with respect to each other as well as to the cathode base and the keeper front plate, fine threads are used. They guarantee a tight fit and a better gaseous seal. To improve the contacting of the keeper, a small thread on the outside of the keeper plate will be added which can be used to attach a cable using a cable lug.

In order to get a better temperature reading close to the tip of the insert of the cathode, a hole was drilled from the backside of the cathode base, close to the front of the cathode. There, a sheathed thermocouple could be inserted, allowing the measurement of the temperature at the tip of the cathode. As the thermocouple in this hole would collide with the Swagelok-adapter from the feed line, a smaller setup for the feedline was implemented. The stainless steel gas feed tube is blazed directly into the copper body, being slightly of axis allowing for enough space for the thermocouple to be inserted.

The Cathode with the improved design can be seen in Figure 4.4-2.

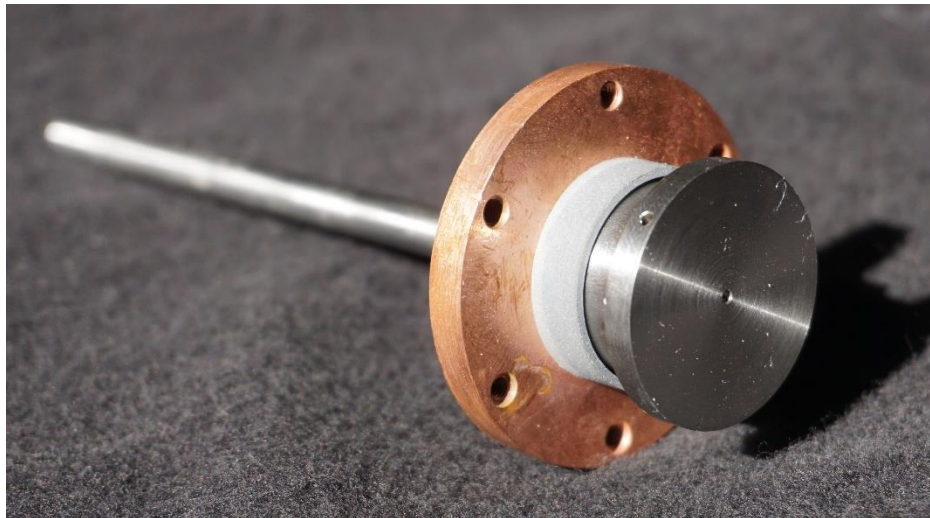


Figure 4.2-2 New Cathode Design AFRL_2.0 assembled after manufacture.

4.2.1 Electrical Setup

One of the major changes for the operational characteristic was the electrical setup of the system. Therefore, the different designs will be presented here in principle. For details, why one or the other setup was used and why the setup was changed at all, see the upcoming chapters with operational conditions of the cathode.

In general, there are two different electrical setups. They will be denoted "direct setup" and "bias setup". The power supplies used are identical for both setups, Delta Elektronika SM660-AR-11.

4.2.1.1 Direct Setup

A schematic of the electrical setup can be seen in Figure 4.4-3. The setup is in triode configuration, meaning that there are three electrode potentials: The emitter insert, the keeper as well as the anode. This is the most common test configuration for hollow cathodes with respect to testing the plasma thruster operation.

The insert itself is attached directly to a common zero volt potential, which itself is disconnected from the facility ground. At the keeper as well as the anode, a power supply is positioned. For each power supply, the negative connection of the power

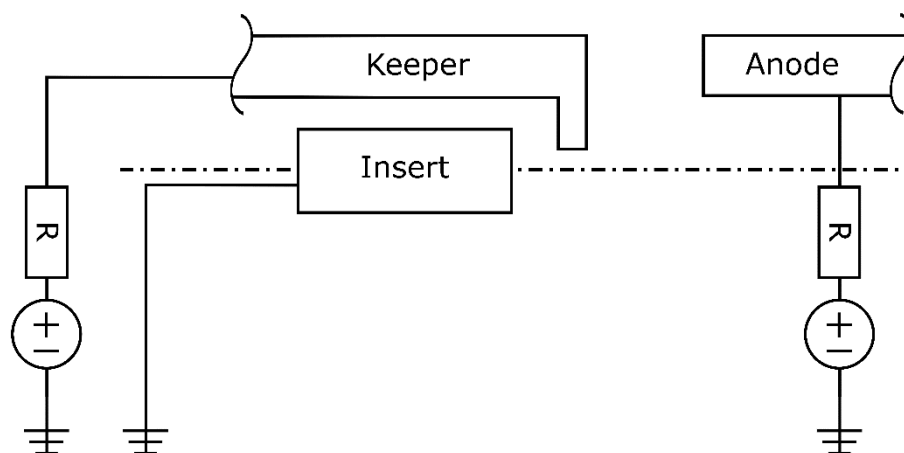


Figure 4.2-3 Schematic for the direct setup of the hollow cathode test stand in triode configuration.

supply is connected to the zero volt potential, and the positive connection to the respective electrode. Therefore, a positive potential can be applied at each electrode independently with respect to the potential to the insert.

Between the power supplies and the electrodes, pre-resistors are added, which proved to be beneficial for the ignition of a stable plasma discharge. Not shown in the schematic are capacities between the pre-resistor and the electrodes towards the zero potential. These are also added for the stabilization of the plasma ignition process, but were left out because of the insignificance for the discussion at hand.

4.2.1.2 Bias Setup

A schematic of the electrical setup can be seen in Figure 4.2-4. The major difference would be the additional power supply at the emitter insert as well as the usage of pre-resistors.

For the bias setup, an additional power supply is added at the emitter insert. Contrary to the power supplies at the keeper and anode, this supply is positioned in a way that the positive connection is attached to the zero volt potential, and the negative to the insert. This allows setting the insert at a negative potential with respect to the zero volt potential.

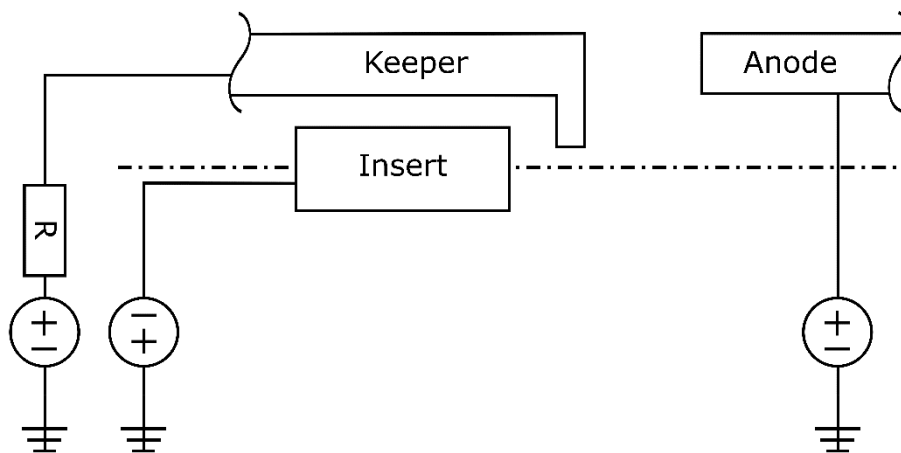


Figure 4.2-4 Schematic for the ***bias*** setup of the hollow cathode test stand in triode configuration.

For the keeper and anode, the connections of the power supply is the same as with the direct setup. Only the pre-resistor at the anode is removed, which proved to be beneficial for the characteristic of the system, as plasma stability at ignition and operation was not the main concern anymore at that point.

4.2.2 First tests with AFRL_2.0

The setup was assembled and equipped with a new pure C12A7 electrified insert, wrapped in carbon foil for better thermal and electrical connection to the copper cathode body. Such a setup can be seen in Figure 4.2-5. For the electronics, the direct setup was used. Krypton was used as propellant.

For ignition, a mass flow rate between 1 sccm and 5 sccm was set through the cathode. At 0.1 A current limit at the keeper, a voltage of 400 V was applied, which resulted in an immediate ignition of a discharge. Shortly after, the ignition at the anode was achieved with 400 V at 0.1 A limit. A typical discharge characteristic can be seen in Figure 4.2-6. There we can see that even though the both keeper and anode immediately ignite, there is a significant noise in the voltages, especially at the keeper. While operating in the current limit, the voltage fluctuates between 50 V and 250 V.



Figure 4.2-5 Fresh Insert in the Hollow Cathode setup AFRL_2.0. Insert is fitted tightly using electrically and thermally conducting carbon foil.

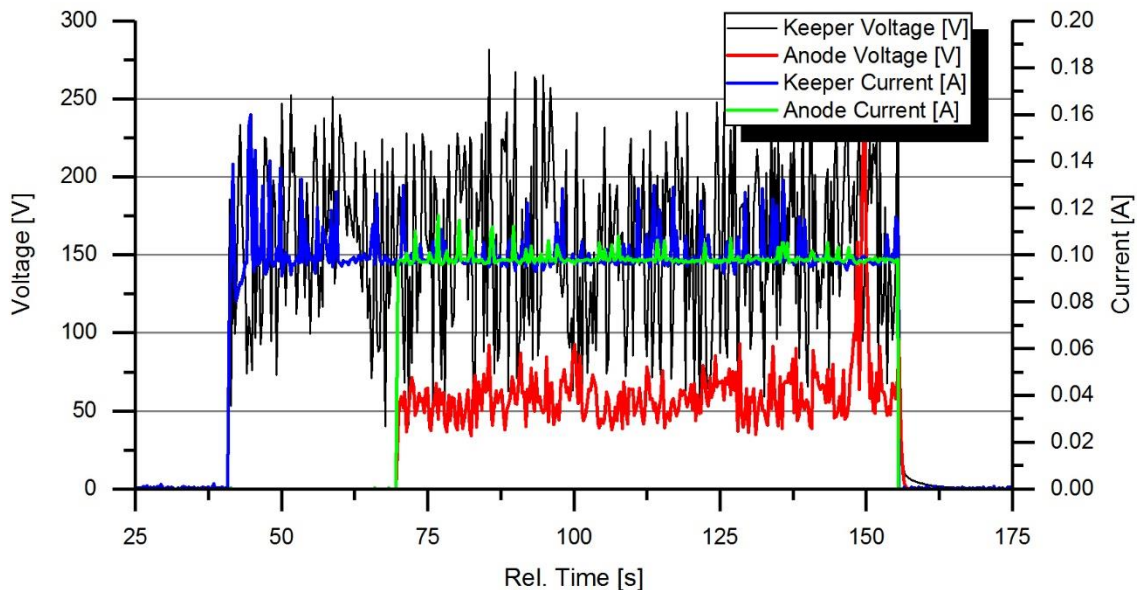


Figure 4.2-6 Current and voltage characteristic at keeper and anode with the new setup. Even though the plasma ignites immediately, the noise in the voltage is much too high.

Characteristics similar to Figure 4.2-6 could be reported several times, sometimes even with much more stable discharge voltages. Either way, after disassembling the cathode the tip of the insert appeared melted, suggesting a great amount of thermal stress into the insert, probably because of the enormous fluctuations in the discharge voltage.

After cleaning the insert, further tests with similar results were achieved. This time, also with more prolonged stable conditions, as can be seen in Figure 4.2-7. Therefore, the cathode was left operational overnight and over the weekend, resulting in about 80 hours of operation in total. Just then, a short between the keeper and the cathode body prevented further operation.

After disassembling the system it was noticed, that the insert was melted again at the tip. There was a red residue between the keeper and the insert, apparently being responsible for the short. This buildup can be seen in Figure 4.2-8.

The insert itself was fit very tight in the cathode body. It needed significant force to remove it, and did broke in this process. The appearance of the insert at this

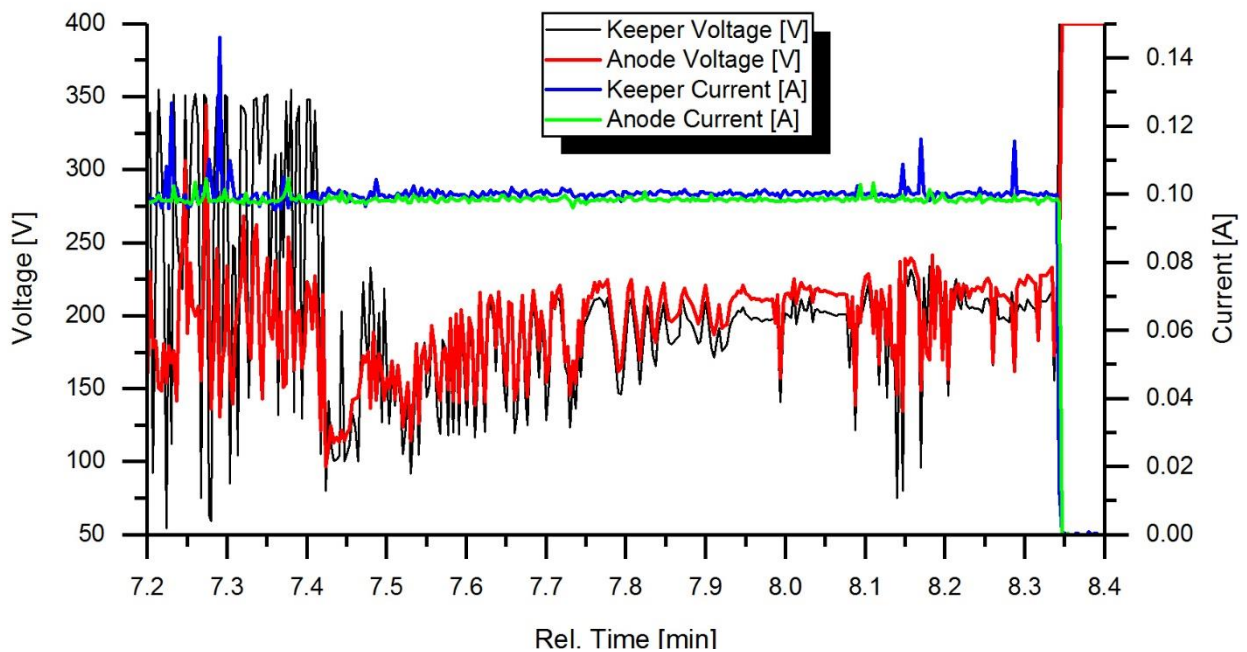


Figure 4.2-7 Current and voltage characteristic at keeper and anode. After significant noise in the first part of the operation, the voltage become much more stable at one point, indicating a change in discharge conditions.

point can be seen in Figure 4.2-9. Clearly, the insert is discolored in the inner surface area. There, it is of white color before changing first to green and then to



Figure 4.2-8 Red burnout residue from the insert, responsible for the electrical short to the keeper.

black the farther it gets out over the diameter. At the backside of the emitter insert, the surface of the material appeared black.

The white color of the material indicates that C12A7 electride was transformed in the oxide state. The gradient in color is typical for the change in electron density, being an indicator for the state of the material. Here, black hosts the most free electrons, marking the material as electride [3]. One possible explanation could be that the innermost areas of the emitter did overheat during operation, resulting in a change of material properties. This was obviously something that had to be prevented in up-coming tests.

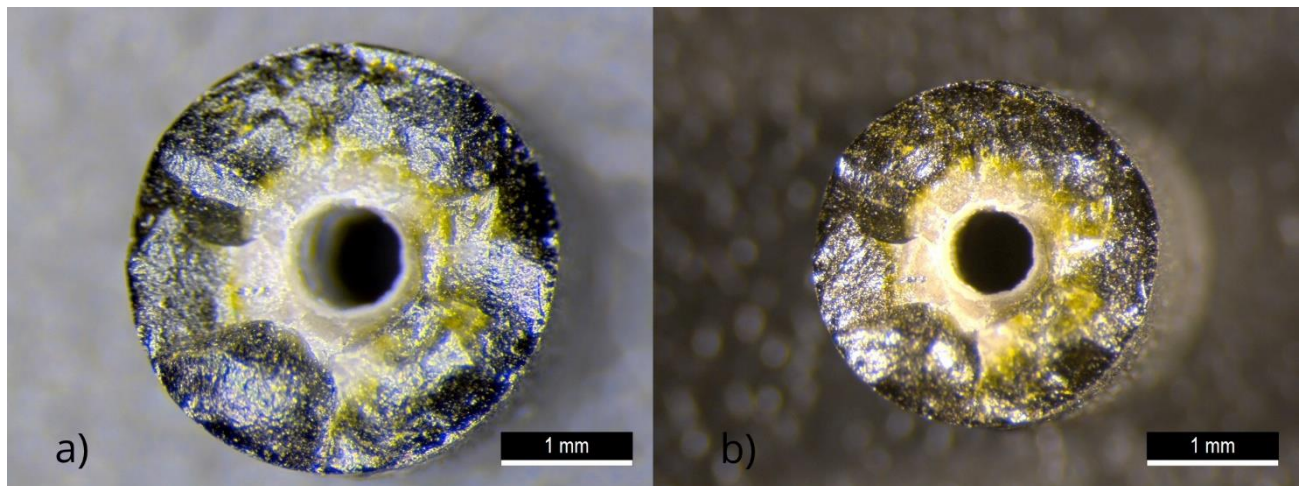


Figure 4.2-9 Coloring of insert after continuous operation. At the inner surface, the electride material is exchanged. The green phase indicates a stepwise increase in electron density towards the black outside material.

4.2.3 Characterization of the Discharge using an Oscilloscope

After first initial results with the new setup, measurements with an oscilloscope were planned in order to better understand the plasma behavior of the discharge as well as the enormous oscillations in the keeper and anode voltages respectively. Therefore, a new insert was fit into the cathode body.

In order to measure the plasma oscillations during the plasma discharge, an oscilloscope did measure the voltage drop over one of the pre-resistors at keeper and anode respectively. This value is in direct correlation to the emission current and therefore the plasma condition during discharge. A differential probe was used to protect the oscilloscope from potential voltage peaks and therefore damages.

Again, the ignition of the plasma discharge was absolutely reliable, resulting into stable current emission at the DC power supply but again with significant voltage oscillations. To our surprise, the signal at the oscilloscope was not stable at all. Rather, it was a flat line at 0 V with very short but very high peaks. After all, these peaks were in the order of 300 V, being short below the set voltage limit for operation. A typical characteristic of such behavior can be seen in Figure 4.2-10.

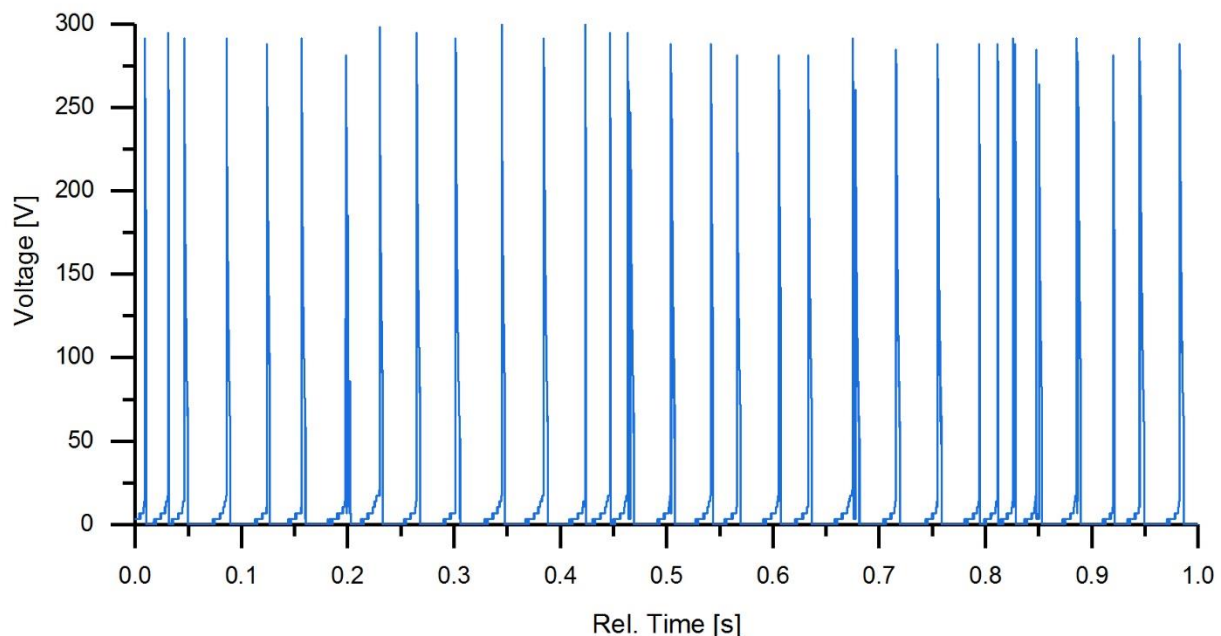


Figure 4.2-10 Signal measured with oscilloscope at keeper pre-resistor. Zero volt level of signal with a number of high peaks. Mean DC-Value fits the expected voltage drop at resistor for the set current limit at the power supply.

The frequency of these peaks correlated with the set emission current at the corresponding electrode. The higher the current limit, the higher the frequency of the peaks. This behavior indicates more of an On / Off behavior of the plasma, rather than a continuous discharge, even though the DC power supply still showed a DC current flowing. In addition to that, the calculated mean DC values at the oscilloscope did fit with the set current limit.

Interpreting this behavior leads to the assumption, that the cathode plasma does ignite and extinguish repeatedly. At ignition, the current is at such a high level, that the power supplies will overdrive the voltages and extinguish the cathode like that. This process repeats itself, indicating on the one hand a great ignition behavior of the system with the current setup, but on the other hand a poor operational behavior. Obviously, such a state of operation should be avoided, as it will lead to high erosion of the emitter material and therefore to low lifetimes of the cathode.

Nevertheless, plasma conditions with much more stable voltage characteristics have also been achieved and been stable for more than one hour, as can be seen in Figure 4.2-11. The Oscillations were decently low at $75 \text{ mV} \pm 5 \text{ mV}$ (original signal

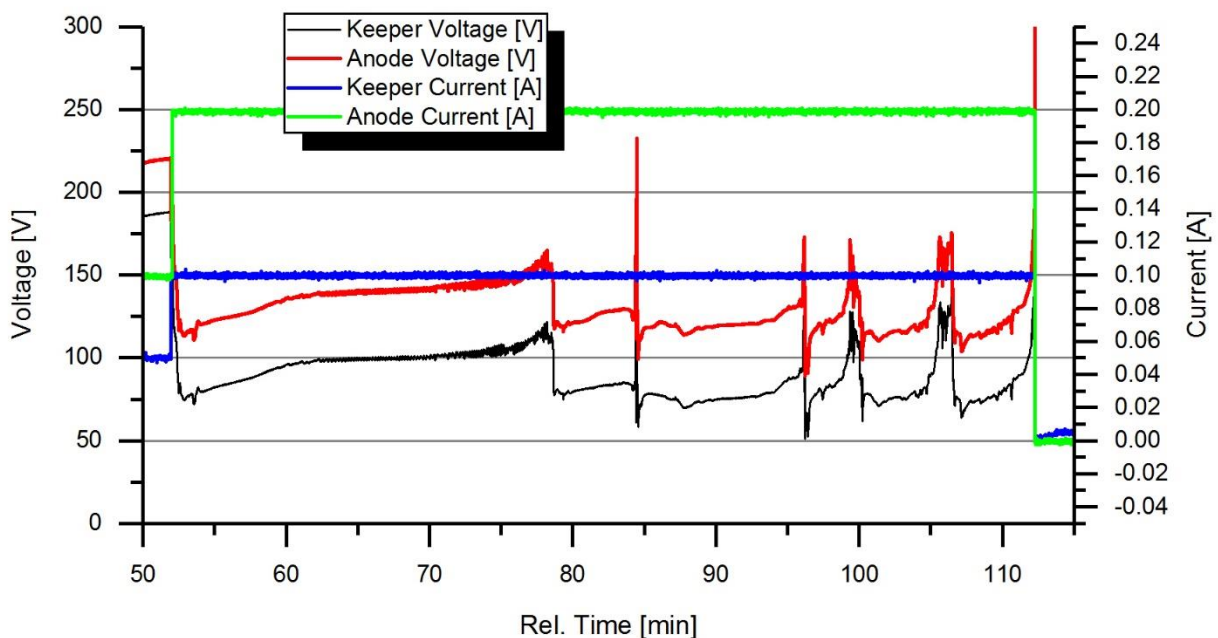


Figure 4.2-11 More stable voltage characteristic at keeper and anode during discharge. Operation for more than 1 hour.

with differential probe – no peaks anymore!). The Temperature did pan around slightly above 100°C.

When analyzing the insert it got apparent, that the tip of the insert did melt again. Obviously, the thermal stress is too high. With the impressions from the oscillating behavior of the discharge, it was decided to change the electrical setup towards the “bias setup”, as the power supplies are not able to control the discharge voltage adequately. The idea was, to set a negative bias at the electron emitter to prevent the cathode from extinguishing over again. Stable discharges that were achieved previously indicate that voltages in the order of 50 V to 80 V would be sufficient for operation.

The insert with the melted tip was still used for testing, this time with the “bias setup”. First, the keeper and anode were ignited and operated noisy as expected. After that, a negative bias potential was applied. Both keeper and anode voltage dropped straight to 0 V while the bias potential was constant at around 40 V. Such

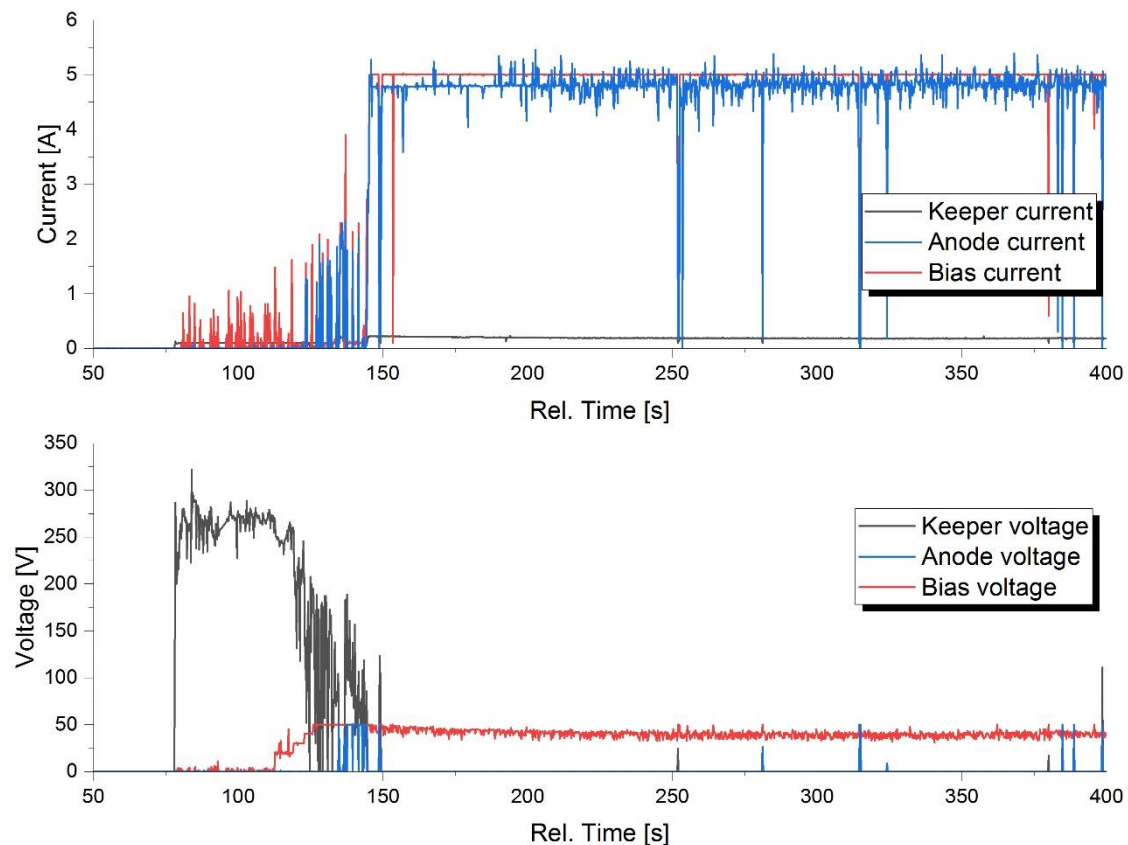


Figure 4.2-12 Characteristic for prove of concept of bias electrical setup.



a characteristic can be seen in Figure 4.2-12. At the meantime, the oscillation at the pre-resistor did decrease significantly, being constant at the expected voltage level correspondent to the set current limit.

The current flowing at keeper and anode was only dependent on two things. First, the value of the pre-resistor towards ground. Second, the current limit set at the bias power supply. For the case of the operation shown in Figure 4.2-12, the current limit at the bias was set at 5 A, with 0.1 A at the keeper and 0.2 A at the anode. Either way, the actual currents at anode and keeper were much higher, as the corresponding power supplies are not able to set a negative potential and therefore force this limit. Only the bias power supply can regulate the bias potential and therefore the total emission current.

Even though the keeper is much closer to the plasma, the current at the anode is much higher at the same potential for both electrodes. The reason would simply be the high resistance at the keeper and the lack of thereof at the anode. For the characteristic shown in Figure 4.2-12, no pre-resistor was built in at the anode. Following the simple ohms law and assuming a low resistance in the plasma itself, leads to the understanding of the high anode currents. Therefore, the simple control of the pre-resistors will be sufficient to control the efficiency of the cathode. Minimizing the power loss at the keeper can easily be achieved by the increase of the pre-resistor at the keeper. In addition, this would also improve the stability of the plasma ignition process.

Emission currents up to 5 A have been achieved in stable operation, which is one of the major goals of the development of the project. However, after about six minutes of operation at 5 A, the anode started to glow, indicating an overheating of this part of the system. No overheating was recognized at the cathode itself (visually or by measurement). At this point, the emission current was decreased to 2 A, which reduced the thermal stress at the anode significantly. For future tests, the setup of the anode has to be improved, in order to test such discharge current ranges.

In general, this test proved the possibility to operate the cathode much more reliable stable with a small change in the electrical setup. Using the additional supply at the bias will allow to get much better current readings at the pre-resistors and therefore allow the frequency analysis (FFT) of the signal and with that the classification of the discharge itself. Furthermore, this test motivates the testing of a



tablet cathode setup, as apparently no hollow cylinder is needed for a stable operation of the cathode.



4.3 Tablet Design AFRL_3.0

After seeing the operational principle of the cathode with the melted insert, it was decided to test the cathode with a tablet insert. The reason for that is twofold. First, tablets are much easier to manufacture and to handle than inserts in cylindrical shape. This will make the manufacturing of the material easier. Also, there is a better comparability of the samples to the work function tests. Second, no great temperature gradient is expected for the tablet emitter, as for the hollow cylinder insert. As this seemed to be the reason for damages at the probe for several times already. At the same time, the area of equal temperature could increase, therefore also increasing the active electron emitting area of the emitter insert. This could lead to better operational conditions. In addition to that, reports in recent literature showed good results on cathodes using a tablet / disk as emitter [10].

A schematic of a sectional view of the cathode can be seen in Figure 4.3-1. In general, the basic principle of the design is a combination of the two previous designs. This stems from the availability of cathode bodies made for tablet inserts from a design similar to AFRL_1.0. These bodies were adjusted accordingly, to fit the keeper and insulation from the most recent design AFRL_2.0.

The general idea of the design is, to have a mass flow through the central stem of the cathode body, which will then be directed around the emitter insert to flow through the keeper orifice. The keeper orifice will increase the pressure of the propellant close to the insert, what will lead to easy ignition and operation of the system.

Because of the usage of older cathode bodies, there is no temperature measurement at the tip of the cathode anymore. But, as there was no significant difference in the operational temperature reported for the measurement at the back of the cathode and for the tip of the cathode, measurements at the back should still be sufficient.

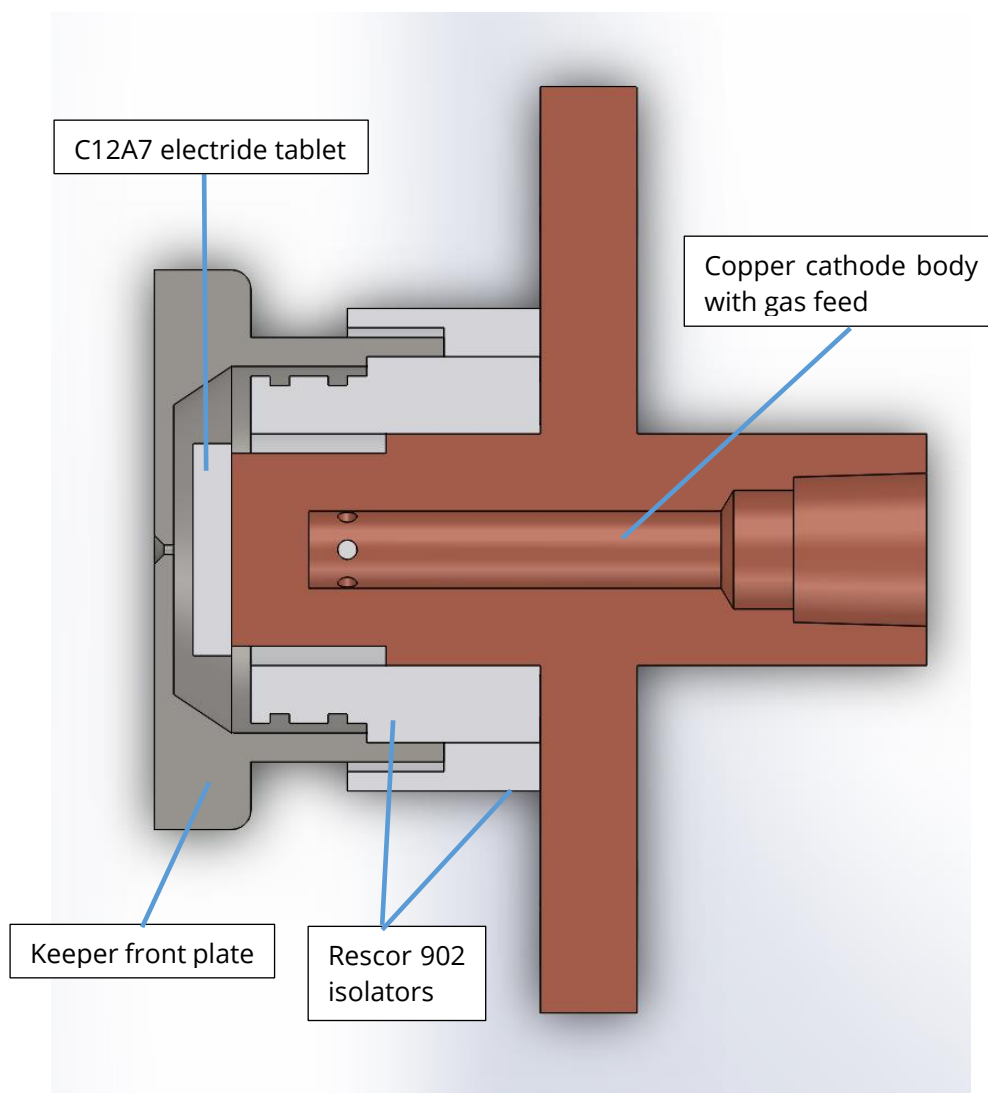


Figure 4.3-1 3D Model of the Design AFRL_3.0 for a tablet insert in Sectional View

4.3.1 Operation and Characteristic of Tablet Cathode

First tests were made using a tablet of 10mm diameter with 10 vol.% molybdenum added. Initial, 5 sccm krypton were used for operation. The bias setup was used for ignition and operation. The current limit at the bias power supply was set at 1 A.

Igniting the Keeper as well as the anode was successful, but the voltage did oscillate as expected. After applying 80 V at the bias, the discharge was immediately stable. Both keeper and anode voltage did drop to 0 V. The discharge itself does extinguish from time to time by itself, but reignites shortly after. A typical characteristic can be seen in Figure 4.3-2.

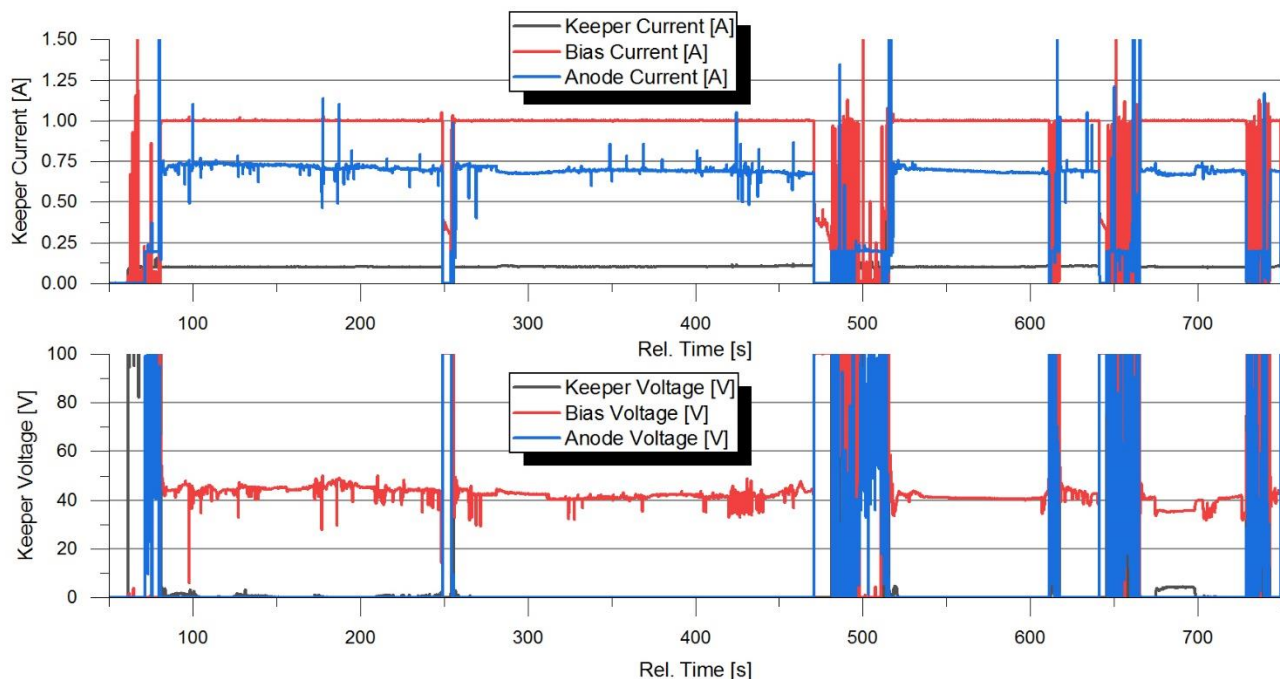


Figure 4.3-2 Characteristic of first operation with tablet.

Because of the disruptions in the operation of the cathode, the mass flow rate was increased to 20 sccm for further tests. Even though 5 sccm seem to be sufficient for the operation in the current setup, we wanted to be sure that the system can operate stable for as long as possible, without pushing any limits. Indeed, the cathode operated longer stable with the increased mass flow rate. At 1A bias current limit, the discharge was operated continuously for more than 2 hours. Here, an

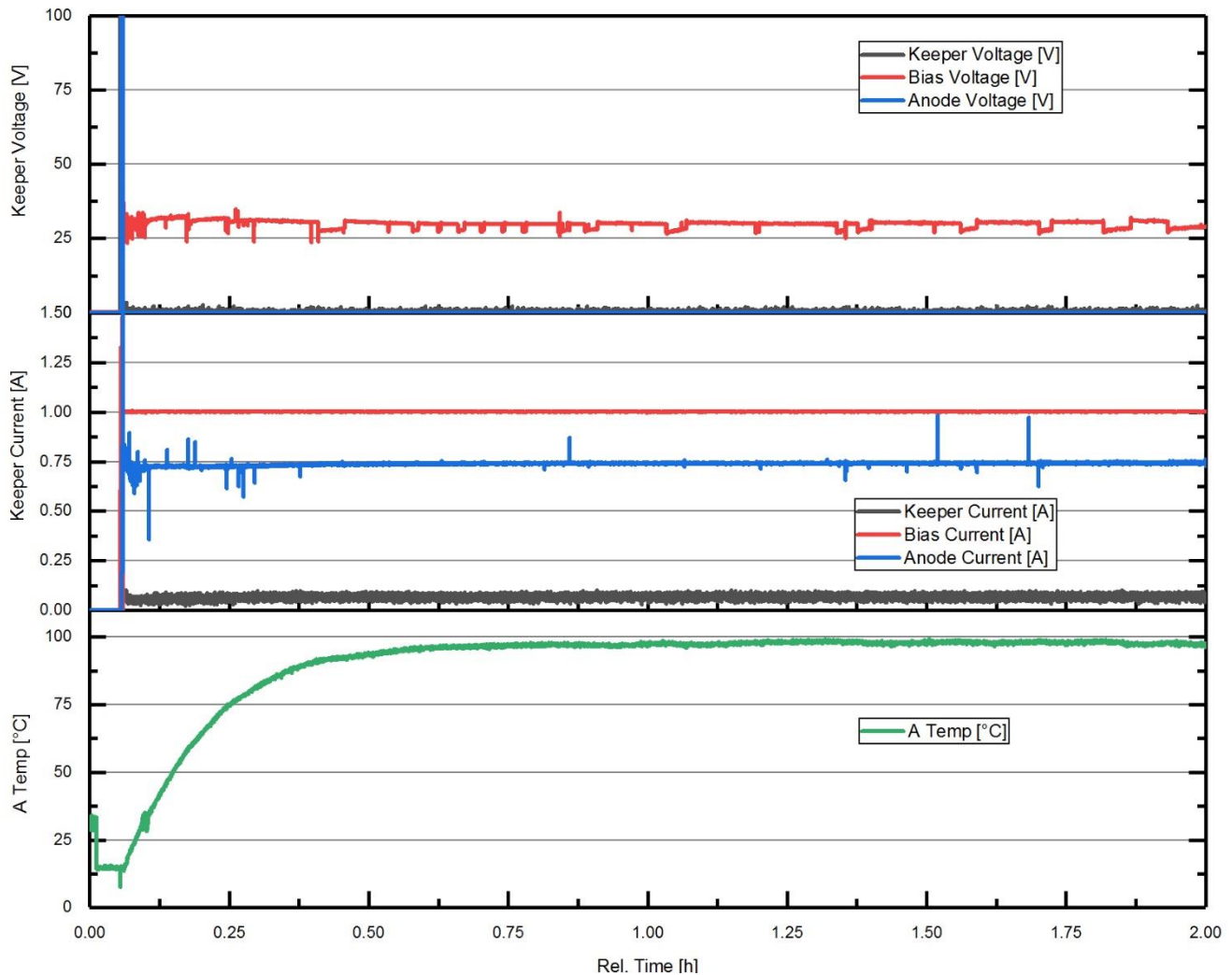


Figure 4.3-3 Temperature at the back of cathode during 2h continuous operation.

equilibrium temperature in the order of 100°C was reached, as can be seen in Figure 4.4-6. Even though the temperature was now again measured at the backside of the copper body, this is a promising result.

During operations, two distinct plasma conditions were observed. The first, with slight oscillations in the pre-resistor voltage (about 2 V oscillations), with a small plume right at the keeper. The second with nearly no oscillations anymore and nearly no visible plasma plume in front of the keeper anymore. Unfortunately, the second mode is not as consistent as needed for a secure analysis of this state. It can be theorized, that this could be the change between spot and plume mode in operation.

4.4 Design AFRL_4.0 Cathode planar

The idea of the new design was to get a design as simple as possible, but also to allow many easy variations that could be manufactured easily and quickly. The result of this approach was the planar setup, as it is shown in Figure 4.4-1.

The general approach is still to have the copper body to get rid of any excessive heat during operation. The Isolation of the keeper as well of the gas feed line is made of the machinable ceramic *Rescor902*. The keeper itself can be manufactured (laser cut) from a sheet, allowing very easy and quick manufacturing and exchange. Therefore, parameter studies concerning the keeper orifice diameter and design can be achieved. The contacting of the keeper will be at the backside

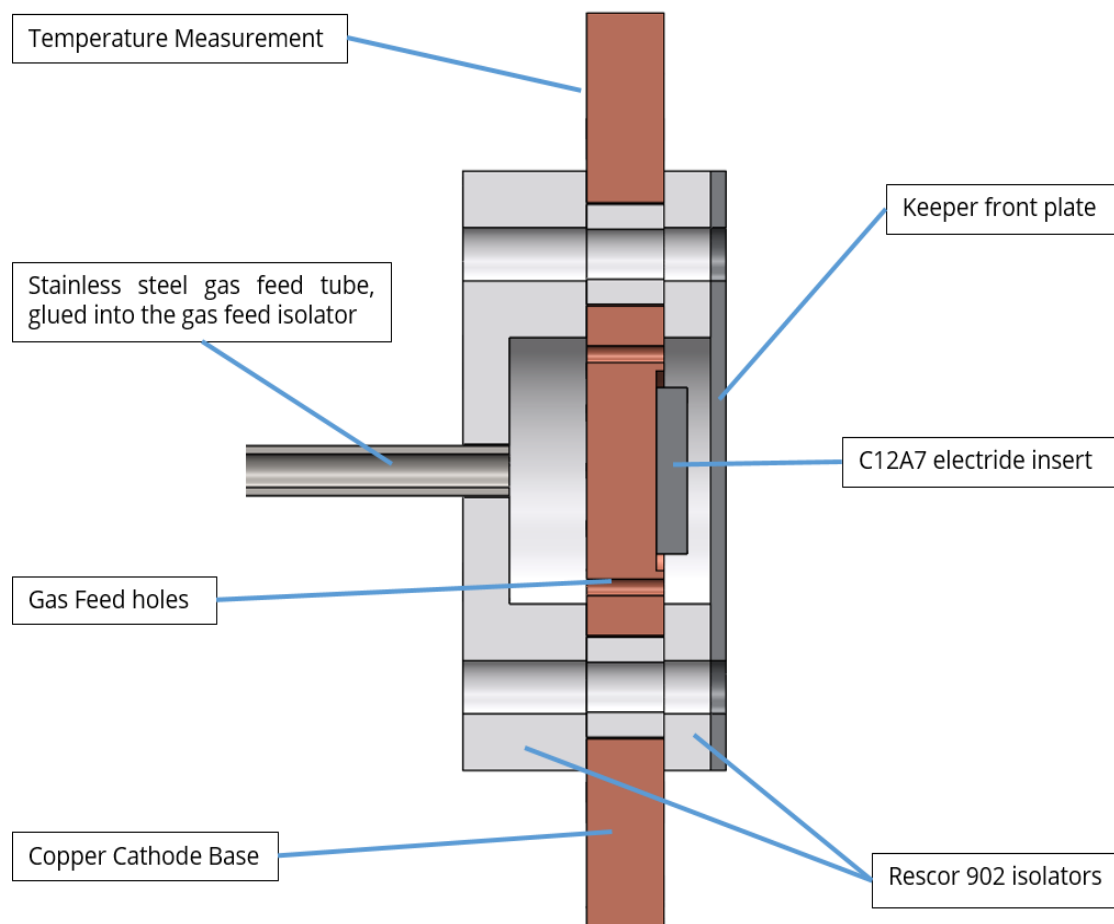


Figure 4.4-1 3D Model of the Design AFRL_4.0 in Sectional View

of the cathode using the screws that are holding the components together. Similar for the potential of the electron emitter.

The Cathode will be mounted on a bended sheet of stainless steel mounted on four ceramic standoffs, assuring electrical isolation of the setup towards ground. The gas feed line is connected to the chamber feedthrough using a non-conducting tubing.

In the inside of the cathode, the gas will be guided to the front of the cathode through twelve small holes symmetric around the electride insert. The C12A7 electride insert is attached to the copper body using the adhesive properties of the contacting paste. The plasma shall be ignited between the tabular electride insert and the keeper plate. The orifice shall be dimensioned in a way to easily ignite the cathode at low mass flow rates but also allow for sufficient current flowing to the anode positioned in front of the cathode.

The modular setup will allow the addition of variations in the keeper orifice design. For instance, a sheet of the insulating Rescor902 ceramic could be positioned between the already used insulating ceramic and the keeper plate, allowing the addition of a small ceramic orifice. A number of various ideas will be tested to verify,

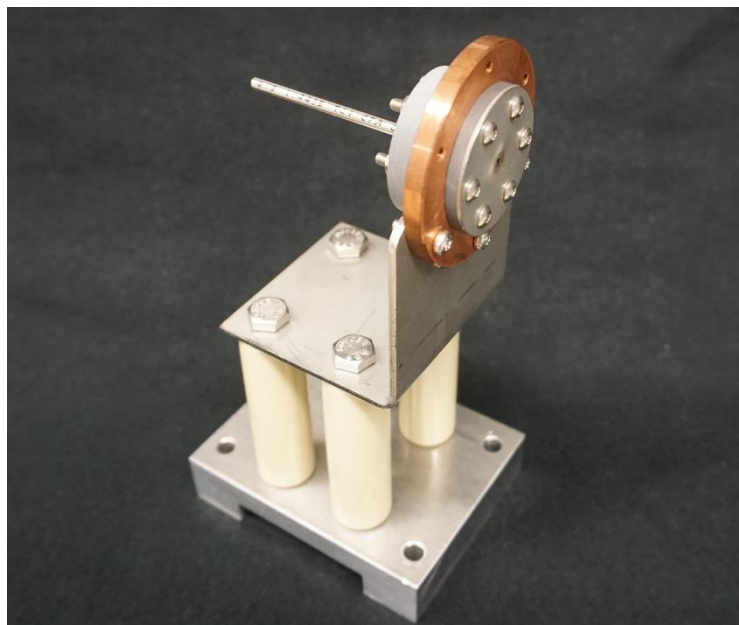


Figure 4.4-2 New Cathode Design AFRL_4.0 assembled after manufacture.

if the discharge behavior could be increased (e.g. lower mass flow rate for operation, better ignition behavior, lower discharge voltage).

Finally, the open area at the gas feed can be used to add any kind of resistance for the gas feed if necessary. As it is a common problem to have plasma appearances in the feedline of thruster systems, this area can be used to add features to prevent the plasma to reach further into the feed line.

The final assembly of the cathode is depicted in Figure 4.4-2.

4.4.1 Hollow Cathode Diode Setup

Previously, it was observed that for high discharge currents (observed at 5A) the anode did overheat (started to glow). Furthermore, findings in literature suggest, that an increase in anode size would be beneficial for the discharge characteristics of the cathode [11].

Therefore, the size of the cathode was increased significantly and is now made of copper to improve the thermal conductivity and electrical conductivity at the sur-

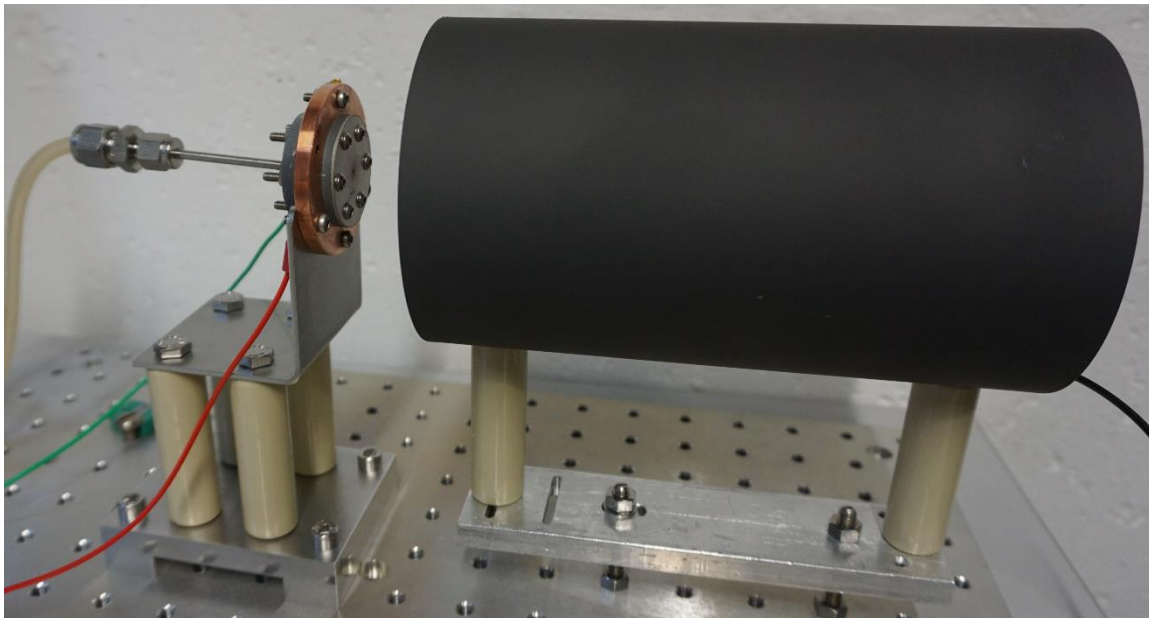


Figure 4.4-3 Final setup of the AFRL4.0 planar hollow cathode diode setup with optimized anode.



face. The outer surface was coated with a carbon spray to increase in thermal radiation during operation. The carbon surface is black and should have an emissivity in the order of 0.8 to 0.9. In addition to that, the surface still has a good electrical contact ensuring no problems during the plasma discharge.

In the meantime, standoffs were added to improve the mounting of the anode. Furthermore, the electrical connection of the anode has been improved. Overall, the setup of the anode should be easier to assemble and more stable for testing.

4.4.2 Current Measurement System

In order to determine the plasma stability, we observe the current stability using an oscilloscope at a resistor in line of the power supply and the corresponding electrode. Based on the given resistance of the resistor, the voltage detected is direct proportional to the current flowing.

To improve our capability to measure the current at different places of the setup simultaneously, the electronics for four differential channels with the necessary voltage rating but also the desired resolution have been designed and tested. The setup allows us, to easily measure at up to four resistors the current simultaneously and therefore have a quick and easy access to the plasma stability.

To determine the plasma mode of the cathode based on the current measurement, the ratio of the noise of the signal to its mean level is analyzed. As reported in literature [12][13], the ratio should be below 9% in order to be classified as spot mode. A ratio above 9% would be classified as plume mode. Obviously, spot mode would be highly preferred, as it has lower voltage characteristics but also much less wear at the emitter material.

Figure 4.4-4 shows an exemplary behavior of the electronics. First, there is the signal of the Oscilloscope itself. Then there is the signal of the Oscilloscope with the electronics attached. Finally, there is the signal as it is measured during spot mode operation (without the DC component). Clearly, we see that at this point a major influence originates from the electronics setup. However, the expected DC component for a representative discharge current would be in the order of volts, which would be well above the noise of the signal.

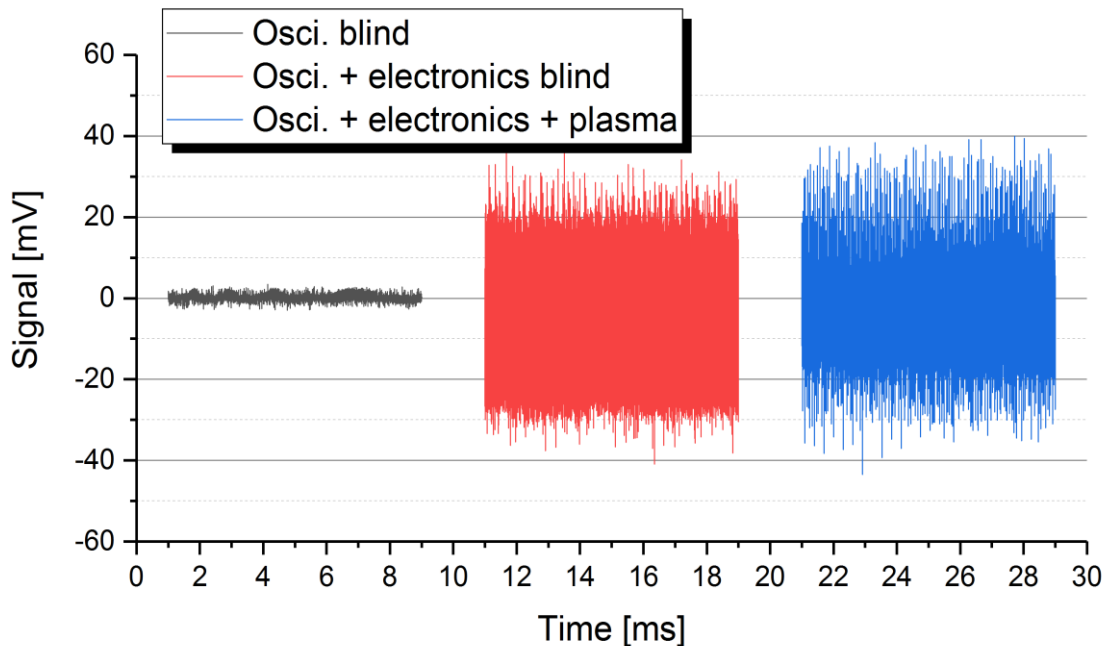


Figure 4.4-4 Signal noise measured with oscilloscope for different options. For any current expected at the endurance test (2 A), the electronics are sufficiently accurate. Challenges may arise for low current operations.

For any discharge current above 2 A this measurement should be sophisticated. However, for discharge currents below 1 A this will become critical, as the noise of the electronics will be in the range of the level of noise of the plasma that needs to be observed (see the 9% criteria).

The measurement of the voltage is done by a digital oscilloscope *Picoscope 5000 Series* with 4 parallel channels and a resolution of 14 bits. This allows a sophisticated measurement of the current with the desired frequency's up to 500 kHz.

4.4.3 Emitter mounting and contacting paste

The contacting paste is an elemental part of the current design, as it on the one hand side holds the emitter disk onto the cathode body, and on the other hand electrically connects the emitter material to the cathode body. A good electrical contact guarantees continuous operation, as obviously electrons have to be continuously provided to the emitter material in order to emit them.

The method of contacting has been a pressing topic for the entire duration of the project. Initially, we used a silver-palladium (AgPd) paste to contact the pure C12A7 electrified to the cathode body. However, especially during the work function tests we observed a silver coating all over the sample and the test setup. We supposed that the low evaporation pressure at elevated temperatures for silver would be the problem, and tried to avoid using any contacting paste using silver from that on.

After all, we used a graphite based contacting paste, that is also being used and recommended from others in literature [14]. Overall, we have observed good results with the carbon-based paste *Aremco Graphi-Bond 551-RN* [15]. However, during our tests with elevated discharge currents, we repeatedly had problems with the probe just falling off the cathode body. Furthermore, the graphite seemed to be reacting with the plasma. On the one hand, the surface of the graphite glue had a typically sputtered surface. On the other hand, a black coating especially at the insulator and the keeper plate were observed, which is suspected to be carbon based (Figure 4.4-5). Therefore, we wanted to find a better alternative to the state of the art system.

Although the silver-based paste was a problem with the work function tests, no such severe problems have been observed using it with the hollow cathode. One possible explanation could be the higher pressure in the cathode when heated

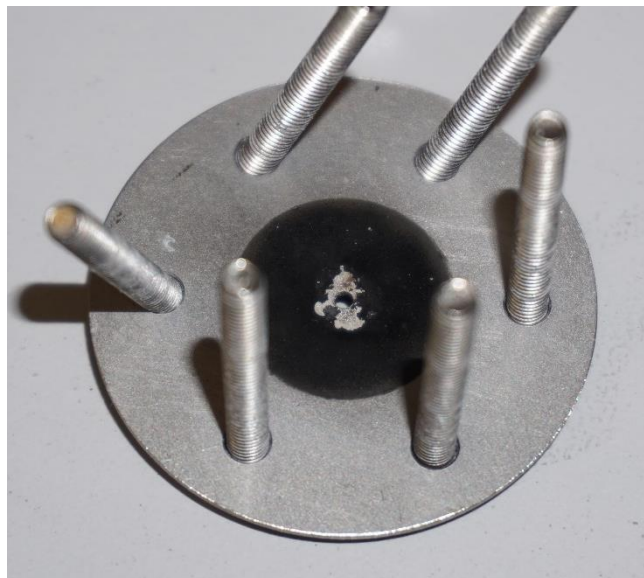


Figure 4.4-5 Plasma residue at the inner side of the keeper plate after operation. Analysis suggest a high carbon concentration.



and therefore a lower evaporation rate. Therefore, we tried to use a minimum of contacting paste, that no material would be exposed and in direct contact to the plasma. A number of pastes have been tested.

The overall results (discharge behavior) using different silver pastes have been good. However, similar with the carbon paste, after about one hour of operation, the samples did repeatedly fall off from the cathode body, resulting in a failure of operation. Apparently, either the thermal stress is too high for these pastes, or the overall strength when dried is not high enough.

Only for one tested paste the emitter disk did not fall off. It was the silver-doped epoxy. With this paste, the endurance test was successfully conducted. Although the maximum operation temperature is just in the order of 150 °C, it has great operational conditions and a good long-time stability of holding the sample to the cathode body.

Still, these tests showed that the adhesive mounting of the emitter is not ideal. Especially considering the increased mechanical requirements for any space mission. Therefore, we designed and manufactured a hold down mechanism to mechanically mount the emitter disk on the cathode body. A molybdenum sheet was laser cut in a way to be able to hold down the emitter to the cathode body without

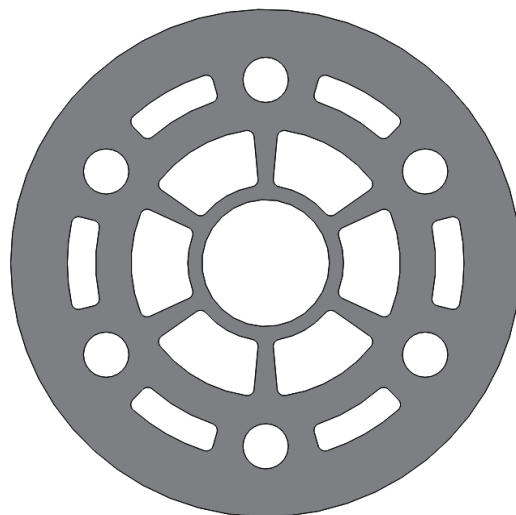


Figure 4.4-6 Hold down mechanism to be tested to support the contacting paste. The pattern has been laser cut from a molybdenum sheet.



any other significant changes (due to the modular setup of the cathode design). The hold down mechanism is shown in Figure 4.4-6.

However, due to the successful endurance test using the epoxy adhesive, the hold down mechanism has not been tested, yet. Overall, it should provide a more reliable mounting of the insert. Furthermore, the electrical connectivity by the contact paste could be improved, as the requirements (mounting) would be reduced.

4.4.4 Influence of passive electronics

As often observed, the stability of the discharge is highly dependent on the control capabilities of the power supplies. As changing the power supplies is not always an option, we need to find out how other electrical components can guide a stable discharge. Ideally with passive components that do not need any control. Furthermore, they should be without any power losses, as this would minimize the efficiency of the system.

Simple resistors in line of the electronics repeatedly showed great advantages for achieving stable operation. However, the power losses cannot be accepted. Since only a resistance during the ignition process is required, at which point we have a high gradient in the current, coils may be an option. However, we only observed a damping in the ignition oscillation (lower but longer Peak), but not improvement in the stable discharge. Finally, to dampen the oscillations, different kind of capacities have been added to the electronics: Here we actually observed higher oscillations and even increased oscillations until shutoff of the discharge. The optimization of the electronics seems to be non-trivial and thorough effort has to be taken to develop a dedicated electronics.

4.4.5 Multi Orifice

One major innovation at the 2019 IEPC was the introduction of a multi orifice keeper plate [16]. A theoretical approach as well as first results have been presented. Advantages include the decrease of mass flow rate for a given discharge characteristic.

With the modular setup of the cathode design, this change could be easily implemented for a first test. A keeper orifice plate with 91 holes each 0.1 mm in diameter was manufactured and assembled. A microscopic view of the keeper orifices can be seen in Figure 4.4-7.

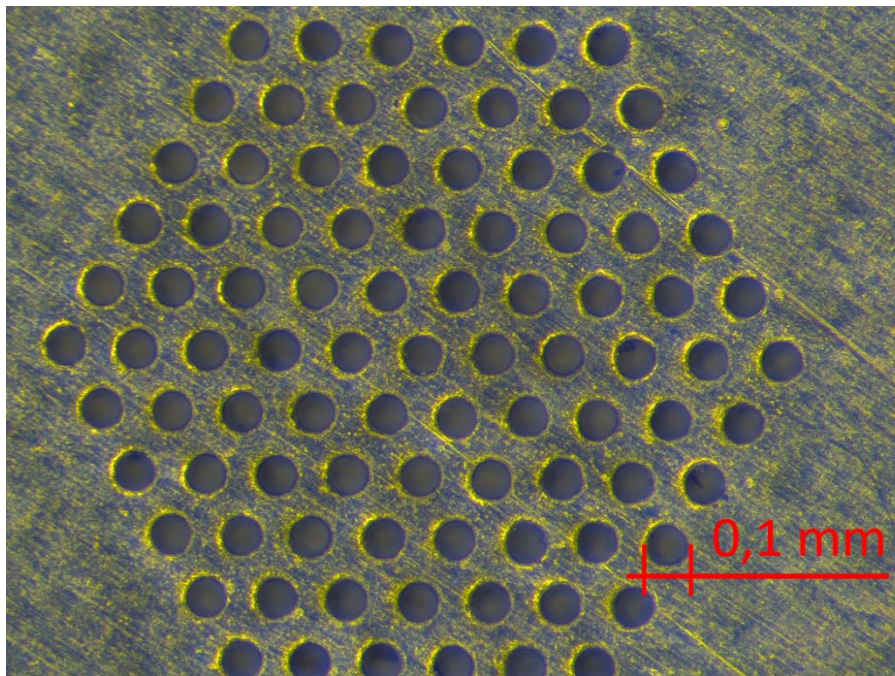


Figure 4.4-7 Microscopic view of one multi orifice plate manufactured. For this case, 91 holes drilled with 0.1 mm diameter in stainless steel.

Overall, the discharge of the cathode with the multi orifice plate was very successful. After all, a much more detailed characteristic needs to be done. However, some lessons learned shall already be mentioned:



Figure 4.4-8 Cathode with Multi-orifice during operation.

1. Stable discharge can easily be achieved. However, the plasma cone as seen in Figure 4.4-8 sometimes seemed to “jump between the active orifices”. From outside the chamber, a repositioning of the plume could be clearly identified. This repositioning was also synchronized with a very short instability in the currents, as observed by the oscilloscope.
2. The system is rather sensitive about the size, number and distance of the orifices. Just two configurations have been tested, however it seem to be indicating that a wider arrangement of the orifices would be beneficial. In addition, the number of orifices was probably too high, and should be tested with fewer.
3. The Cathode can be operated at lower mass flow rates. With a single orifice of comparable cross section, the minimum mass flow rate was in the order of 15 sccm. With the multi orifices, discharge was achieved at 3 sccm, and a characteristic was made at 5 sccm already.
4. However, for the keeper plate at hand, the mass flow rate did increase with time. As depicted in Figure 4.4-9, the thermal stress into the plate seemed to be too high, resulting in a deforming of the plate material and therefore generating leakages at the sides. A thicker plate could already be sufficient to get rid of this effect.
5. Abrasion at the surface of the multi orifice as well as at the small orifices itself could be a limiting factor for the long time operation of the cathode. This needs to be evaluated and tested accordingly.

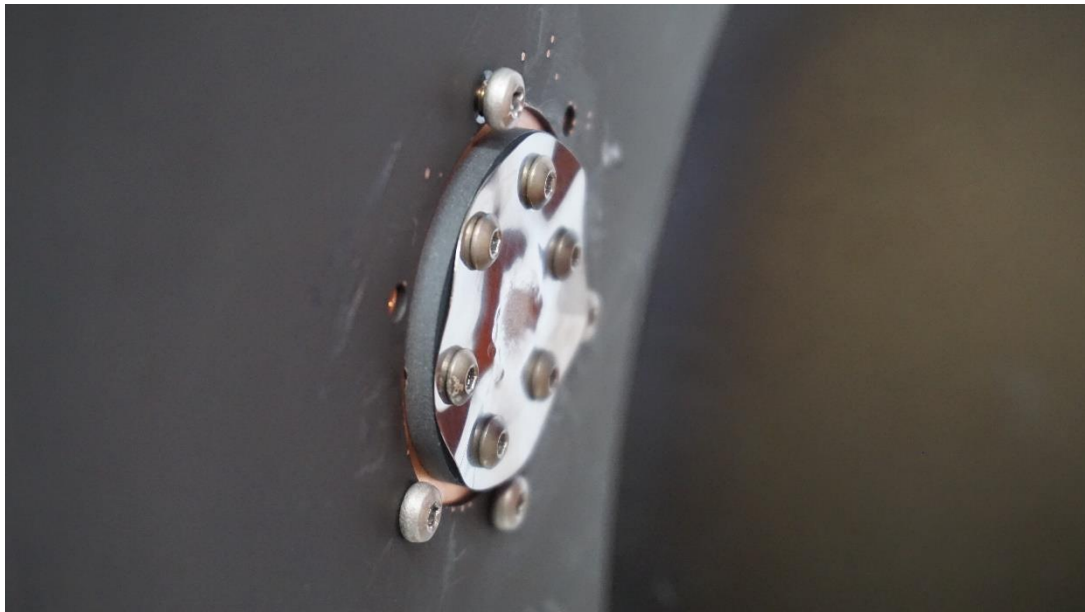


Figure 4.4-9 Thermal stress during operation results in the deformation of the keeper front plate, resulting in severe leakages.

Figure 4.4-10 shows the total discharge voltage over the discharge current. For this characteristic, the keeper was set floating. The total discharge voltage is the sum of the negative emitter potential and the positive anode potential. The discharge current is the total current reaching the anode.

As expected, the discharge voltage does increase significantly for lower discharge currents. For higher discharge currents, the fit is nearly constant. Unfortunately, the Characteristic was only done up to 1A. Overall, the discharge voltage seems to be in the range of the observed characteristics with single orifice cathodes. If so, the offset is minimal.

Overall, the multi orifice configuration seems to be quite promising. After improving the first basic findings with such a setup, we feel confident that it could be quite beneficial for the overall characteristics of the cathode. More tests will be conducted soon, with variations in the number of orifices, the size of the orifices and the thickness and type of the keeper plate material.

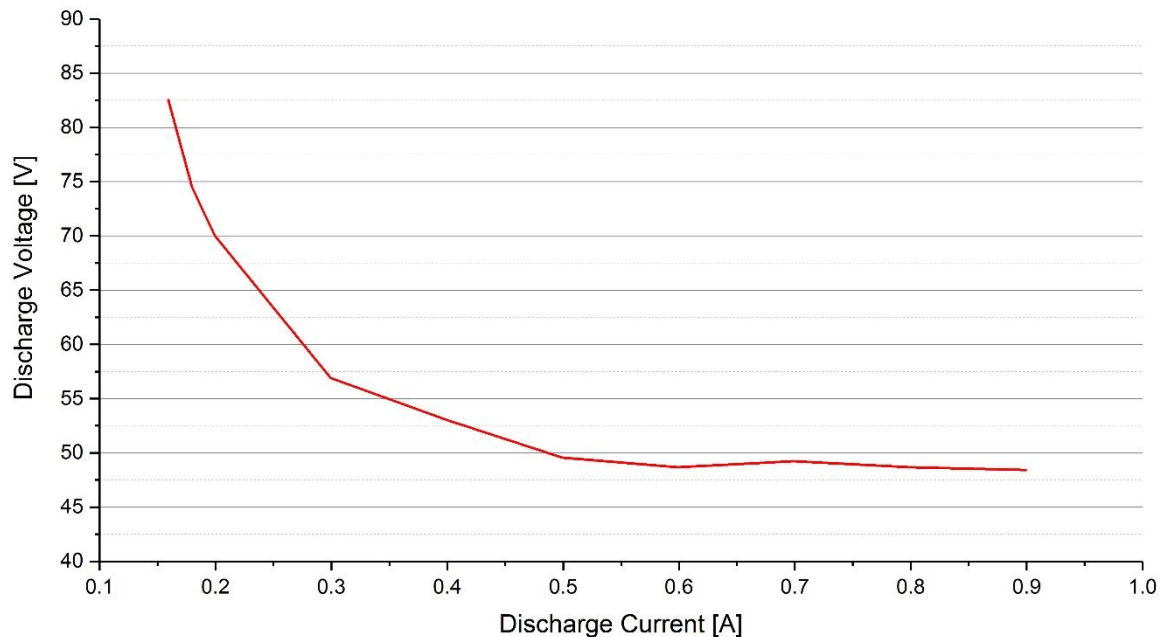


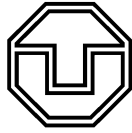
Figure 4.4-10 Current-Voltage Characteristics for the multi orifice discharge at 8 sccm.

4.5 Conclusion WP3/WP4/WP5

The Design of the heaterless hollow cathode changed significantly over the course of the project, and so did its performance. Overall, great improvements have been achieved, with several new “firsts” and “highs” compared to literature. The electrode material confirmed its great potential as alternative emitter material for hollow cathode operations.

With the introduction of the planar cathode design, a very simple and modular design was achieved that allowed easy and fast adjustments. Manufacturing times have been reduced significantly and especially the flat keeper plate allowed the manufacturing of numerous keeper designs with smallest diameters.

Significant insight was gained analyzing the influence of electronics onto the discharge. This may be a great starting point for the further development of the hollow cathode, since there seems to be great potential for optimization.



The temperature readouts during operation have been for all iterations extraordinary low. Although direct measurements at the emission surface of the emitter have not been achieved, the measurements at the cathode base allowed a decent evaluation of the overall temperature.

Comparing the results from the hollow cylinder and the disk shaped insert, the electrified disk emitters seem to be much better suited for the discharge. However, the high mass flow rates needed for operation are still a severe problem. The multi orifice did improve these conditions, but more detailed experiments need to be done, especially concerning the durability of such a setup.

- Design of heaterless hollow cathode → done
- Setup of cathode with temperature stable design → done
- Optimization of cathode design → done
- Repeated starting of cathode without any help → done
- Operation of cathode after exposure to air → done
- Long time operation of cathode → done (~1000 hours)
- Operation at low flow rates → done (3 sccm)
- Operation of cathode at 1 A anode discharge → done
- Operation of cathode at 5 A anode discharge → done
- Material response to plasma exposure → done



5 WP6 – CATHODE LONG DURATION TEST

One of the most anticipated tests is an endurance test of the C12A7 electride hollow cathode. The initial goal was to achieve operation for 1000 hours continuously at an elevated current level.

Previously, the cathode operated at 0.1 Keeper current and mostly 0.1 A anode current during the endurance test. Overall, 300 hours of total operation had been added up with one insert. The insert was exposed to air in between several times and restarted. The voltage during operation was significantly oscillating in the range of 80 V to 160 V. The maximum temperature has been in the order of 150°C.

Later on, the cathode was repeatedly operated at discharge currents in the order of 1 A to 2 A for up to a few minutes. Operation even at 5 A discharge current were successfully achieved and reported. However, the discharge times here have been rather low, in the order of a few minutes. Obviously, the cathode would need to be operated for many hours at the elevated current limits to be able to observe any kind of change in the discharge characteristics and stability, in order to assess the potential of the electride as emitter material for a hollow cathode.

Therefore, a dedicated test campaign for endurance operation at elevated current levels was planned and conducted. One major challenge during this campaign was the mounting of the sample onto the cathode body, as the electride disk did fall off repeatedly. Therefore, a number of different contacting pastes was tested and the endurance test was conducted with one that had sufficient bonding.

Unfortunately, the krypton did run short during the endurance test, and supply was delayed. We did not reach the 1000 hours but got close, with 950 hours of operational time at 2 A discharge current. At this point, we decided to end the endurance to start the post processing. To our knowledge, this is (again) the longest operation of an electride hollow cathode reported in literature.

The following chapter will describe the endurance test in detail. After presenting the setup and general remarks to the test, we describe in detail into several specific phases of the test.

5.1 Setup

The endurance test was conducted at a vacuum chamber at the Institute of aerospace engineering at TUD. The chamber is cuboid with a width of 1.2m, a height of 1.5 m and a length of 2.5 m. Mounted on top is a Leybold Cryo COOLVAC 10.000 iCL with a nominal pumping capability of 10.000 l/s for nitrogen.

For the power supply, three Delta Elektronika SM660-AR-11 were used. In addition to that, pre-resistors are positioned in line between the power supply and the keeper the anode electrode respectively. In addition to these power resistors, 1 Ω resistors are positioned in line for each electrode (keeper, emitter and anode) to act as shunt-resistors to measure the current flowing and its stability. The current is measured using the electronics described in section 4.4.2. The schematic of the electrical setup can be seen in Figure 5.1-2. In addition, Figure 5.1-1 shows the chamber with the additional electronics (minus the power supplies) used for the test.



Figure 5.1-1 Vacuum chamber with electronics setup for endurance test.

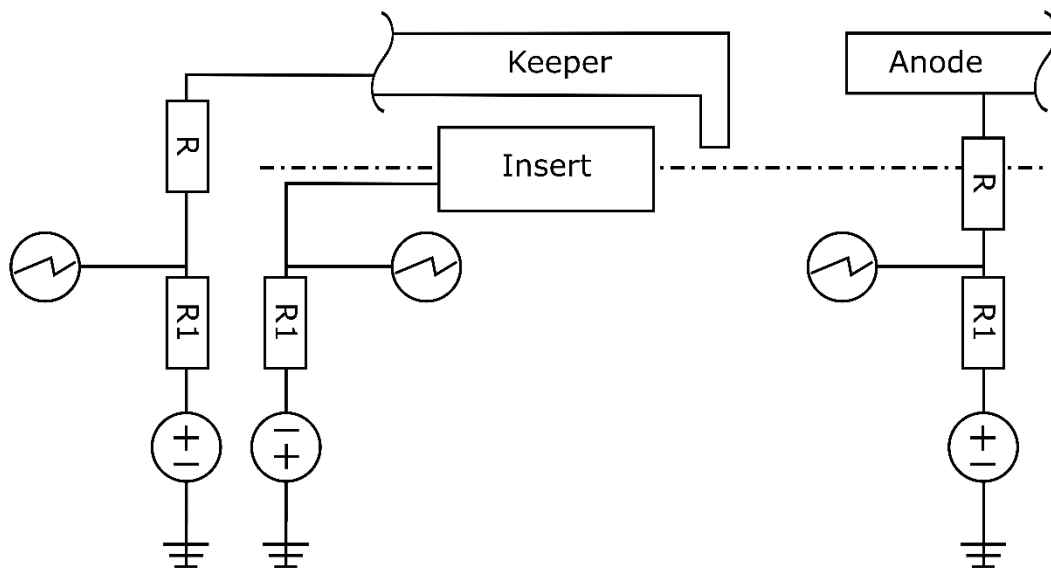


Figure 5.1-2 Electrical Setup for the endurance test.

Figure 5.1-3 shows the setup of the cathode in the inside of the chamber. As pre-

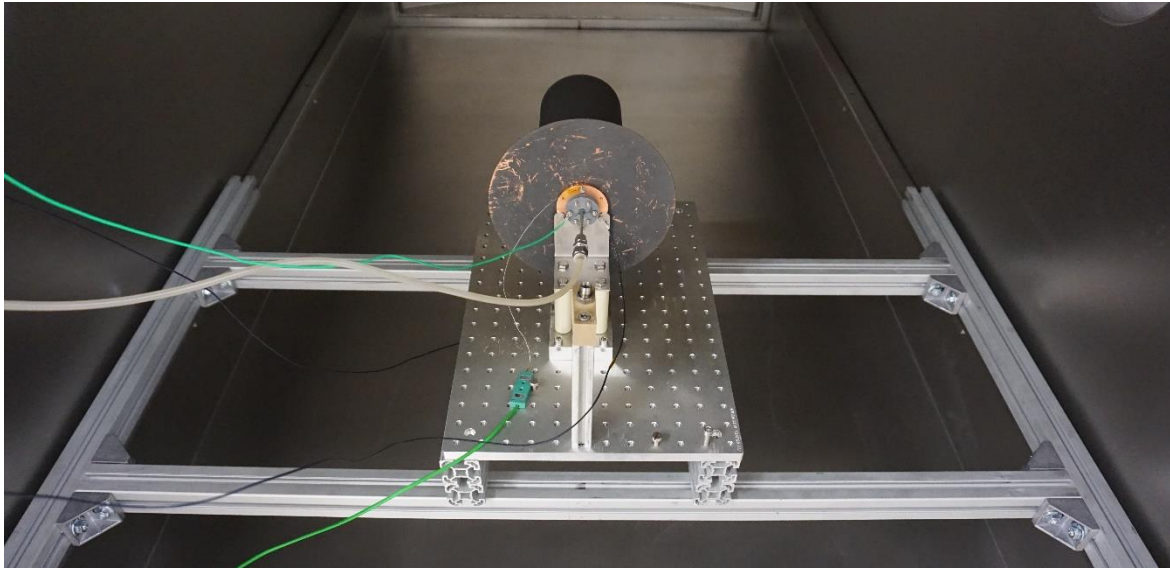


Figure 5.1-3 Electride hollow cathode setup in vacuum chamber (backside view).

viously described, the setup is electrically insulated using ceramic standoffs. The anode is positioned about 2 cm in front of the cathode. A thermocouple is mounted at the backside of the cathode copper body.



For the cathode itself, the silver-doped epoxy was used for mounting and electrical connection of the electride sample to the cathode body (see section 4.4.3). The keeper plate was mounted about 1mm in front of the emitter tablet. For the keeper orifice, a single 1 mm hole has been used. At the backside of the cathode, three layers of filter material have been used to reduce the backslash of plasma into the feedline. The electride material sample itself was doped with 20 Vol.-% Molybdenum and at a Diameter of 10 mm with a height of 2 mm.

5.2 General Remarks

The initial test during ignition was to verify the mounting capability of the contacting paste used for this particular setup. Therefore, some slight variations in the discharge parameters were conducted during the first hour of operation. Variations in mass flow rate and discharge currents have been made. The process of finding the parameters, that were used for the rest of the endurance test, will be describes in chapter 5.3.

Once the mounting of the sample was confirmed, to focus was set on endurance operation at constant parameters. In the end, this resulted into an 800-hour stint of continuous operation at 2A anode current without any interruption of the discharge what so ever. During that time, the discharge did change significantly, finally, to a very stable discharge condition. The details will be describes in chapter 5.4.

After the about 800 hours, it was clear that we most probably would not be able to reach 1000 hours with the krypton stored available. Therefore, we decided to do some rudimentary cathode characteristic at this point, to be sure to have some more information. During this characteristic, the discharge did extinguish a few times. However, re-ignition was not a problem at all. Details will be described in chapter 5.5.

After that, the discharge was started again to get as many hours as possible until the krypton did run out. Another 150 hours of operation were reported, until the mass flow rate did fall off resulting in the end of the endurance test.



At this point, we decided to stop the test and start the post-processing of the cathode. The first results and documentation will be presented in chapter 5.9. We decided against waiting for the krypton or the operation with another gas (argon), as this would not be in time for the deadline of the report and we thought that an initial post-analysis would be much more beneficial.

Overall, the discharge has been quite stable. However, we decided to leave the pre-resistor at the anode. At 2 A anode current, this resulted into a significant power loss close to the limit of the resistor. At 5 A it would have been well beyond the stated limit. We could have tried to remove the resistor during discharge, but failed attempts at similar tests previously made us cautious. Again, we wanted to be sure to have as many operational hours as possible, without playing too much with the electride sample mounted and possibly damaging it. In the end, we deemed 2 A as sufficient and decided not to go for the 5 A for the endurance operation.

5.3 First Ignition Phase

The initial discharge of the samples was done with ignition voltages of 400 V and current limits of 0.1 A and 2 A respectively. The Anode was set to 50V at 2.2 A current limit. For convenience, the discharge voltage is defined as sum of anode voltage and bias voltage. The discharge voltage is defined as anode current.

The discharge ignited perfectly well, as show in Figure 5.3-1. The keeper was set to 0V right after ignition, which improved the stability quite significantly as known from previous tests. The oscilloscope did show some different conditions changing with time, some more stable than others. However, at short to 1 hour of operation, the discharge did extinguish by itself.

Re-ignition was without any problems. At this point, operation at 15 sccm was tested, which was successful. However, when decreasing the flow rate to 10 sccm the discharge did extinguish. During the next 1.5 hours, the cathode was ignited

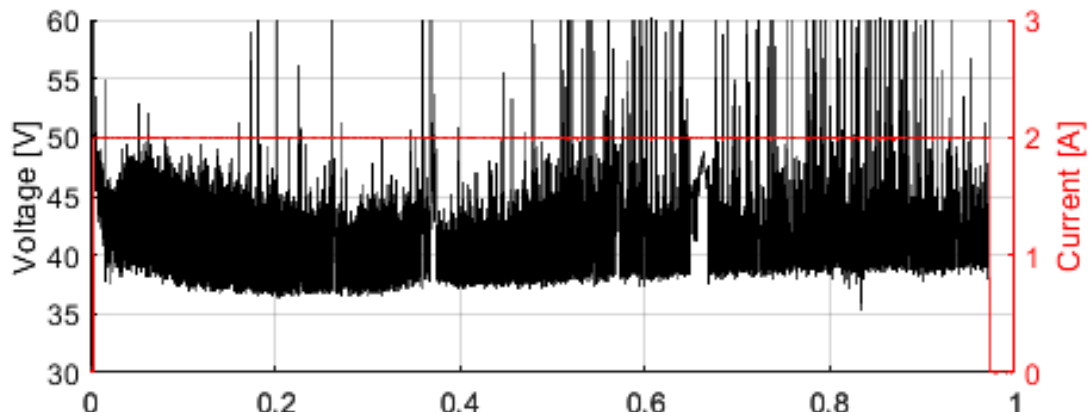


Figure 5.3-1 First Discharge of sample for about 1 hour of operation. Ignition without any problems, extinguished by itself.

several times. The discharge current was slightly decreased and increased, without any changes in the ignition behavior (still great) or the fact that it did shut down after some time. After some time, the discharge stable and stayed so for the next 800 hours.

Why the cathode has initially problems with continuous operation is not clear. No indicators in the characteristics of the discharge or the current observation with the oscilloscope have been identified. It is assumed, that there could be some kind of conditioning of the insert happening. However due to the great ignition behavior, this challenge can easily be dealt with the automatically (script based) ignition of the discharge.

5.4 First 800 hours

During the first 800 hours of the endurance test, the cathode did operate continuously without any interruption and was only shut down for the sake of the I-V characteristic at that point. The keeper was set floating during the entire time. Due to the high pre-resistor, a voltage potential in the order of a 10 V to 20 V will set at the keeper electrode itself.

The current and voltage characteristic over time can be seen in Figure 5.4-1. The signal was logged with 2 Hz. The voltage seems to be rather noisy. However, these are distinct discharge levels will be discussed later. The overall discharge potential increases during the first 75 hours from 45 V to 50 V. At this point, the potential drops down to about 40 V and stays there for the rest of the time. During this first 75 hours, the plasma changes significantly as depicted in Figure 5.4-1. First, the plasma was a distinct and defined plume of purple color, as seen in Figure 5.4-2a). During the increasing part of the discharge, the plasma plume did vanish and there was only a diffuse purple glow between the cathode and the anode as well an intense yellowish glow of the keeper orifice, as seen in Figure 5.4-2b). Finally, during the steady state condition, the diffuse plasma did vanish and only the glow in the orifice remained, as seen in Figure 5.4-2c).

Comparing the plasma appearances with the oscilloscope measurements, we can correlate a much lower noise in the signal for the plasma condition without any

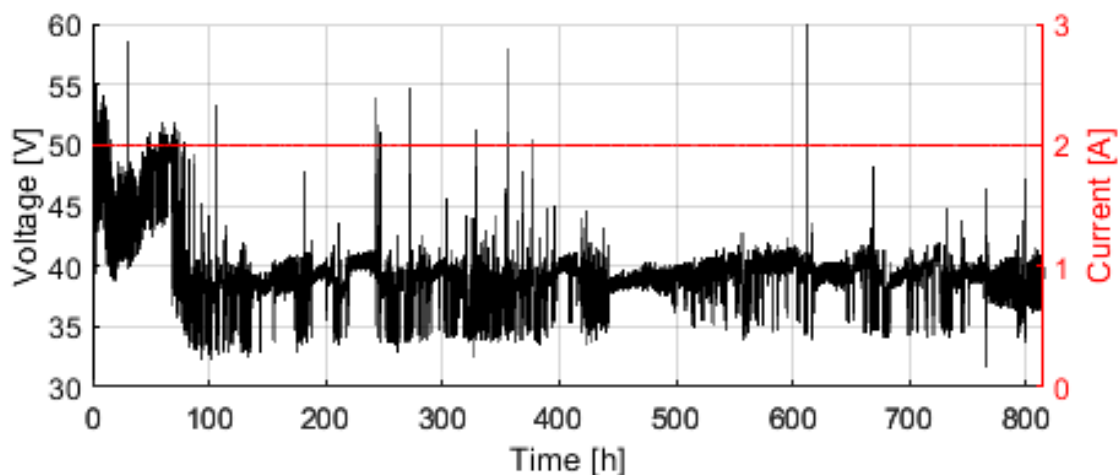


Figure 5.4-1 Current and voltage over time for the first 800 hours of operation.

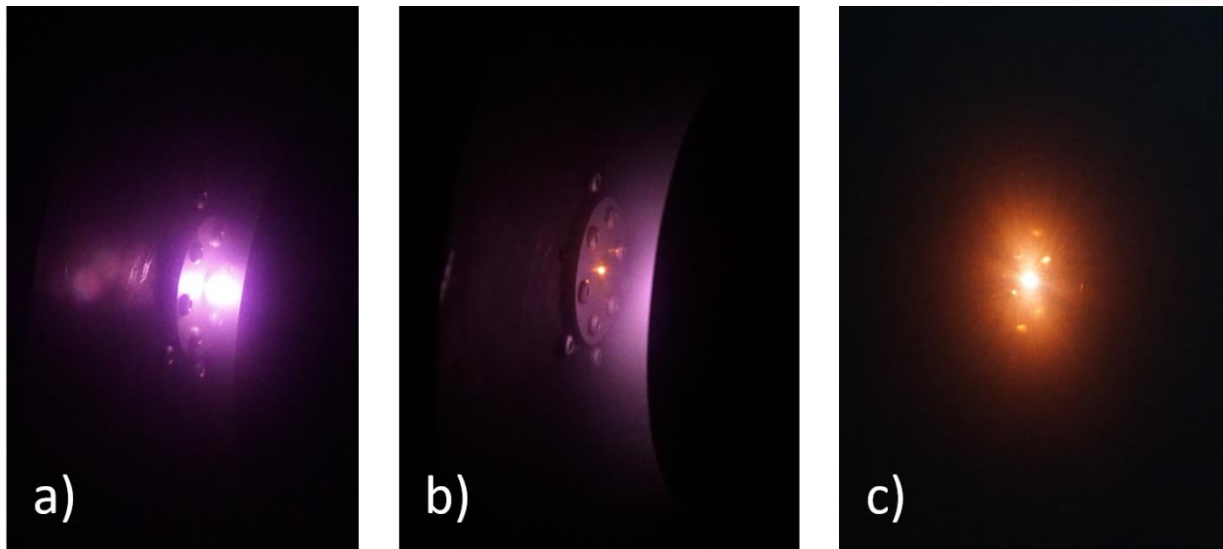


Figure 5.4-2 Different plasma appearances during endurance test. a) Defined purple plasma cone. b) Yellowish glow of orifice and diffuse plasma between electrodes. c) Orange glow of orifice without any other plasma.

kind of diffuse plasma. Figure 5.4-3 shows the measured signal during the distinct phases.

As already mentioned the signal looks noisy and seems to be peaking from 40V down to 35V. However, a closer look as in Figure 5.4-4 shows, that these are no peaks, but rather distinct plasma states. At the 35V level, the discharge seems to

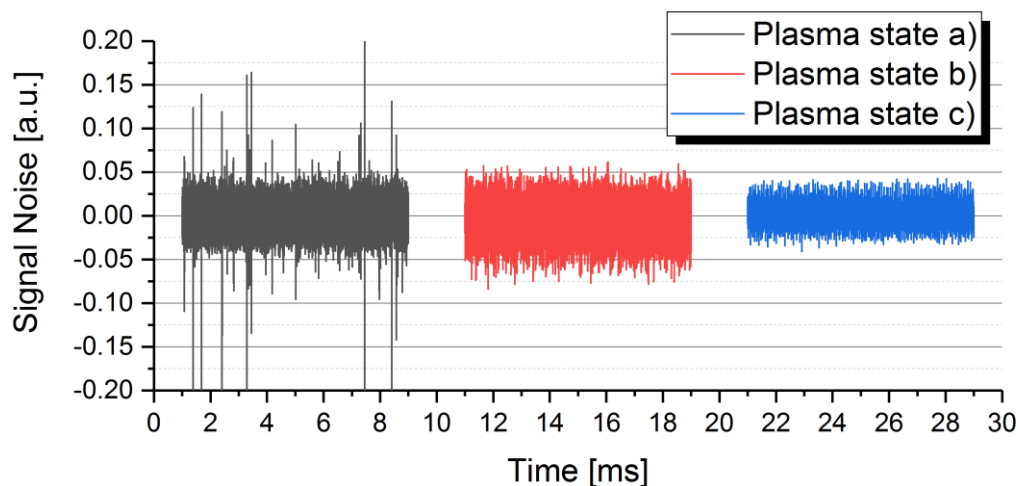


Figure 5.4-3 Plasma stability at different Phases of discharge, correlating with the plasma appearances from Figure 5.4-2.

be a bit noisier. Unfortunately, no significant differences between the two states could be observed, neither in appearance nor in plasma stability by the oscilloscope.

As stated above, the discharge voltage is defined as the sum of anode potential and bias potential. The plot of the voltage components (also Figure 5.4-4) suggests that the discharge to the anode is quite stable, only the potential of the emitter varies. As the bias current limit is set slightly above the anode current limit, there is a current of 0.2 A emitted that does not reach the anode, but any other electrode in the chamber. It is safe to assume, that this is any ground potential (for instance the chamber itself) and therefore a leakage current per definition. Why this discharge would be unstable is not clear.

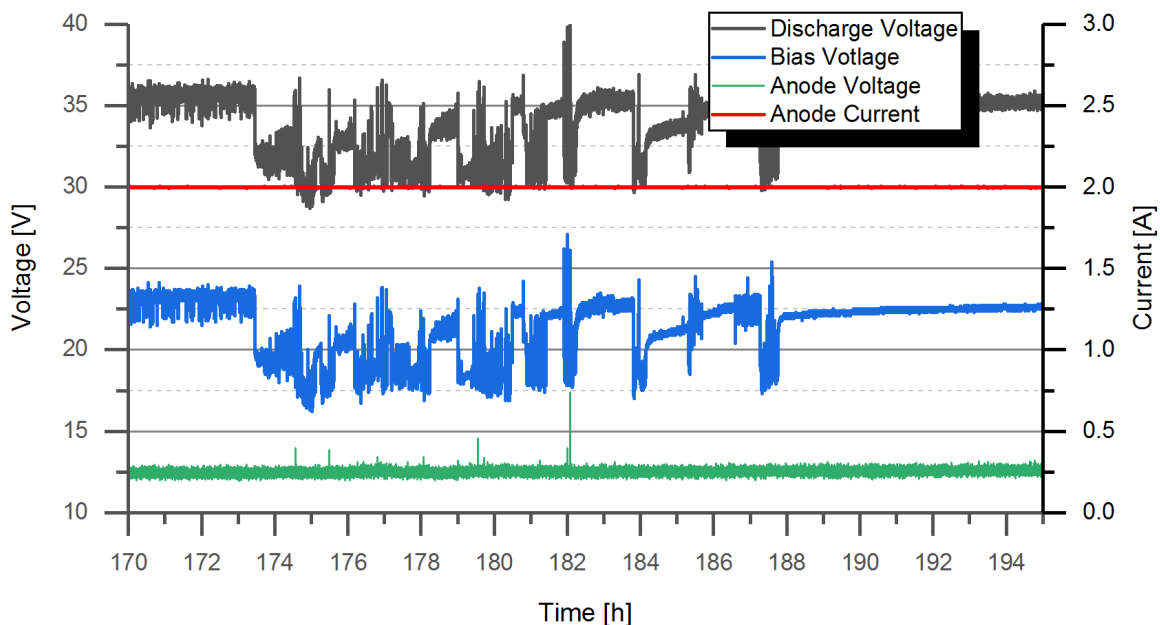
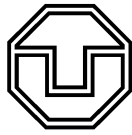


Figure 5.4-4 Different levels of discharge voltage during endurance testing. 40 V seems to be the norm, with 35 V being a prolonged condition (not just a peak) but with higher noise.



5.5 Cathode Characteristic

When it became clear, that the endurance test would most probably not reach the 1000 hours of continuous operation, due to the lack of krypton expellant, we decided to pause the continuous operation to get a characteristic of the cathode discharge. However, we decided to only go for a brief test series, as the focus was still on the endurance testing of the cathode. We did not want to stress the emitter material with repeated re-ignition and unfavorable discharge regimes, as we wanted to have a sound analysis of the emitter material degradation due to continued operation, rather than due to a characteristic. The following chapter will describe the findings of the cathode discharge characteristic.

In general, two major parameters were supposed to be varied. On the one hand, the discharge current and on the other hand the mass flow rate. The mass flow rate in particular to check, if operation at significant lower mass flow rates could be feasible. When changing one parameter, the other was supposed to be left constant for that time. If the cathode did extinguish or get into an unstable condition, we went back to the standard operation of 2 A at 20 sccm. Changing these parameters in particular, we did change the plasma stability of the discharge several times, i.e. changing between spot mode and plume mode as observed visually as well as with oscilloscope measurements.

Bias Potential

First, the influence of the bias potential was evaluated, as shown in Figure 5.5-1. During the first 800 hours of operation, the Bias potential was set at 30 V at a current limit of 2.2 A, which was 0.2 A above the anode current limit. During operation the anode current limit as well as the bias current limit were reached, meaning that there were about 200 mA of leakage current, most probably to the chamber walls. Furthermore, the bias potential did jump between 23 V and 18 V, as reported in the previous section.

When setting the voltage limit below the voltage that did set at the current limit, the current did fall back to the level of the anode (so no leakage current anymore) and the potential of the anode increased slightly. The further decrease of the bias potential directly added to the anode potential. In the meantime, the overall discharge potential (sum of bias potential and anode potential) is constant.

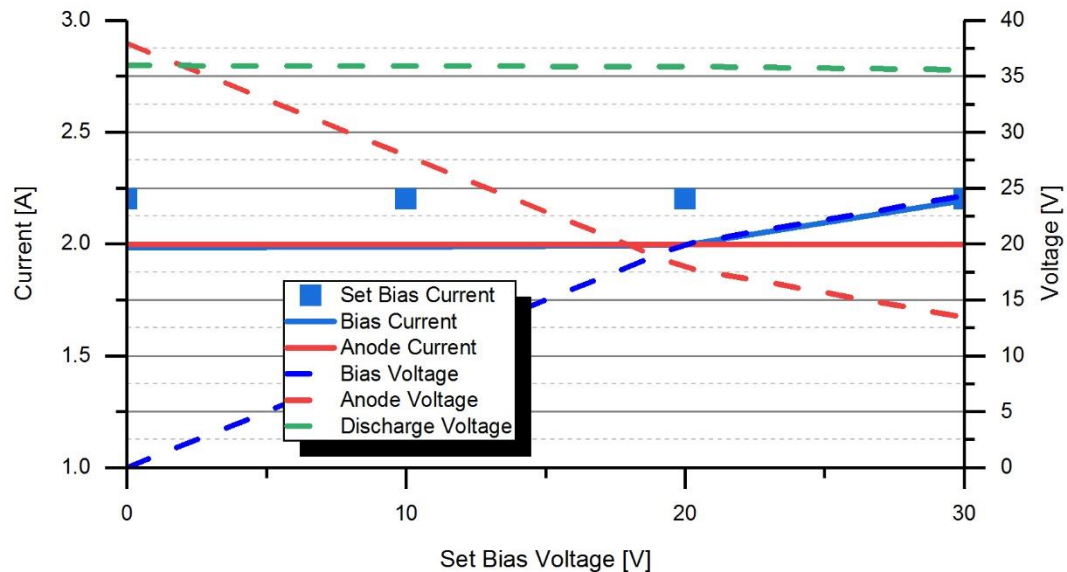


Figure 5.5-1 influence of Bias potential on the discharge characteristic.

The bias potential was initially added, as it did improve the discharge stability as reported at last year's report. The results presented here suggest, that for the test at hand no bias potential would be needed anymore, as the discharge is stable by itself. Therefore, the bias potential was set to 0 V for the remainder of the characteristic as well as the remainder of the endurance test.

I-V Characteristic

Next, the influence on the discharge potential at a constant mass flow rate was observed. Figure 5.5-2 shows the corresponding characteristic for 20 sccm mass flow rate and 16 sccm mass flow rate. The discharge current was varied in the range of 1 A and 3 A.

For both mass flow rates, we clearly see the change between the different plasma conditions spot mode and plume mode. For 20 sccm at 2.0 A and for 16 sccm at 1.8 A. Decreasing the current limit leads to a decrease in discharge voltage at a constant mass flow rate. When reaching the critical mass flow rate, the discharge changes its state, which includes a potential increase of about 6 V. The change in the plasma state was confirmed with the oscilloscope measurements at the shunt resistor.

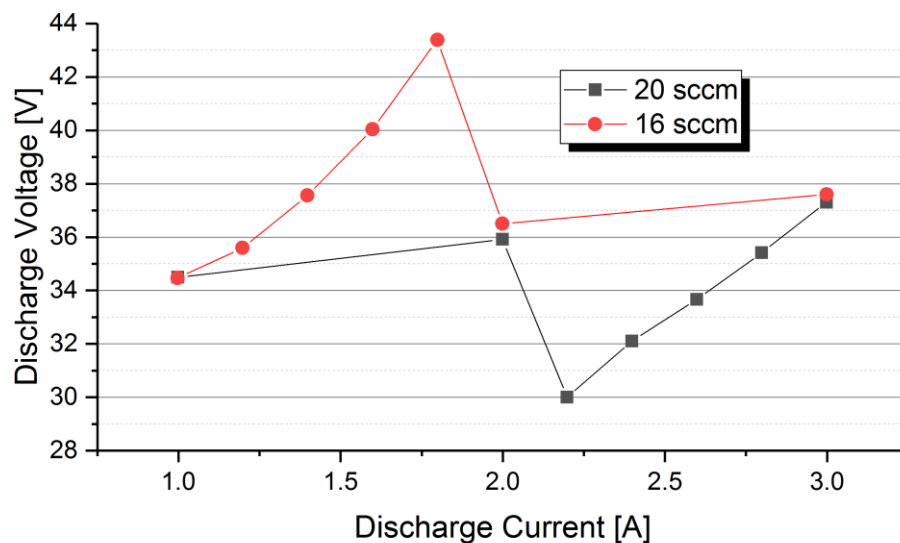


Figure 5.5-2 Discharge voltage over discharge current at constant mass flow rates of 16 sccm and 20 sccm. Clear plasma mode transition observed.

This graph indicates that the discharge potential increases with decreased mass flow rate. Furthermore, it suggests that at 2 A discharge current and 20 sccm mass flow rate, the discharge would be in plume mode. However, as reported during the long duration testing, the discharge was clearly in the more stable spot mode. This indicates that the discharge seems to be right at the verge between these two plasma modes. This could also explain the plume mode to spot mode transition after about 75 hours of operational time as previously reported. In addition to that, a similar behavior will be discussed in the following section. For the current setup (combination of orifice size), the 20 sccm therefore seem to be the ideal value at this point.

Constant discharge current

Finally, the discharge potential over the mass flow rate at constant discharge current was observed and is depicted in Figure 5.5-3. For the currents of 1 A and 3 A the mass flow rate was only varied to the point, where the plasma switches states. For the 1 A current, this was at an increase of mass flow rate to 22 sccm the case. For the 3 A current this was at a mass flow rate decrease to 12 sccm. For the 2 A current, the mass flow rate was decreased to the point, where it went off (at 6 sccm).

The graph indicates that the plasma mode transition will happen at lower mass flow rate for higher discharge currents, which is to be expected from plasma physics. Furthermore, in this series the plasma was in spot mode for the 2 A and 20 sccm operational state, which stands against the values reported in the previous paragraph. This means, that we will need to do a more prolonged and dedicated campaign for the definitive characteristics of the cathode. The operational times at one set point need to be much longer, to have really steady state operation and to be able to eliminate any side effects of the discharge.

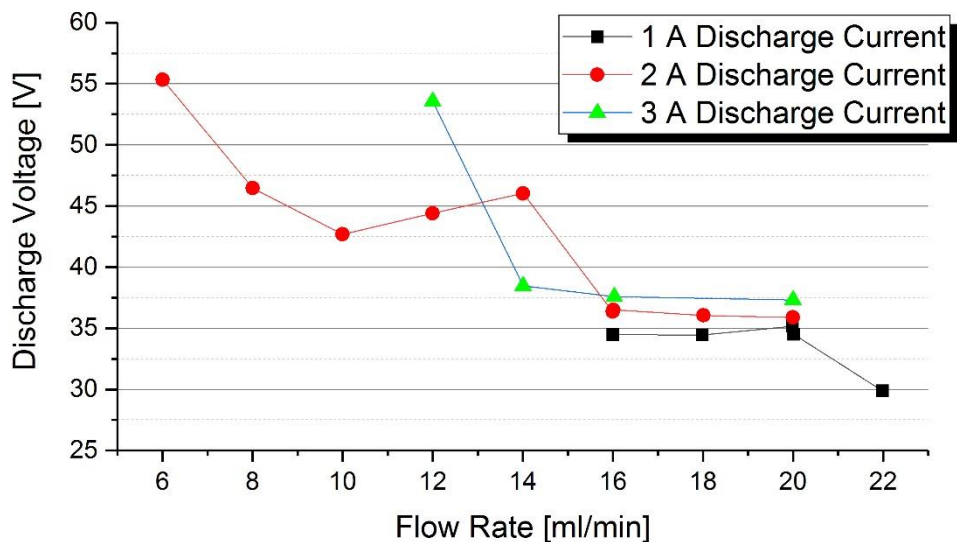


Figure 5.5-3 Discharge Voltage over flow rate at constant currents between 1 A and 3 A. Clear indication of plasma mode transitions.

5.6 Overall Operation

Up until now, we had the starting phase, then the cathode operated for more than 800 hours continuously. At this point, the basic I-V Characteristic was made and the operation without resistor at the anode was tested. Because the discharge extinguished here, the cathode was reignited once again to operate as long as possible, i.e. until the krypton propellant did run out (which was to be expected). Another 150 hours of operation were achieved, adding up to a total of 950 hours in total. The Current and voltage over time can be seen in Figure 5.6-1. For this graph, which represents the total discharge, the ignition time as well as the period of the I-V Characteristic was removed, leaving only the stable discharge conditions.

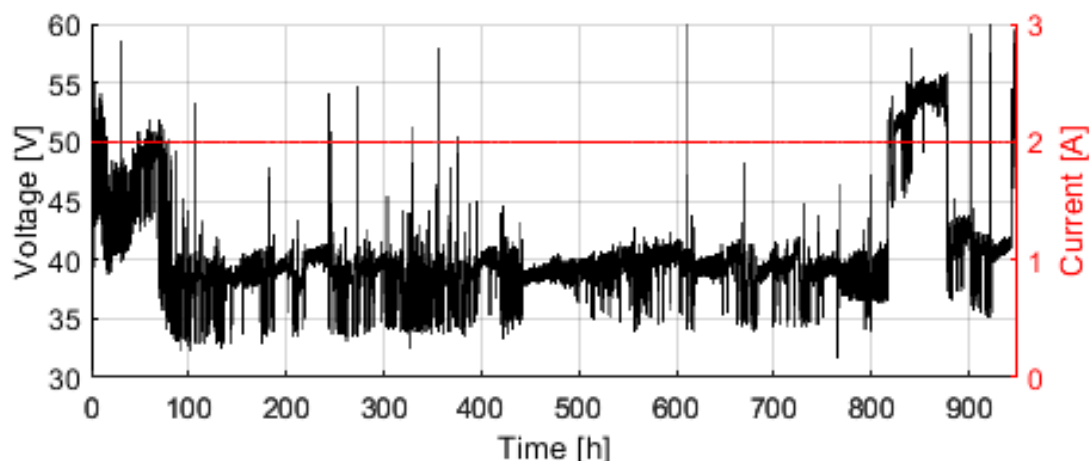


Figure 5.6-1 Current and voltage over time for complete endurance test. Phase of ignition and cathode characteristic has been removed.

The discharge for the first 800 hours has been already discussed previously. At the re-ignition after the cathode characteristic, the cathode had a slightly higher discharge voltage (50 V to 55 V) again. During that time, the appearance of the discharge was again characterized by a diffuse plasma between the keeper and the anode, as reported previously for the first hours of the endurance test (see Figure 5.4-2b)). Furthermore, the noise of the current signal observed by the oscilloscope was slightly higher, correlating with the experience from the beginning of the endurance test.

After about 50 hours of operation, the appearance switched back to the orange glow of the keeper, without any diffuse plasma. The discharge voltage did drop

back to the 40 V level, at which it was operating for most part of the endurance test already.

In the end, when the mass flow rate did decline, the voltage increased again over time as the state of the plasma did change. Figure 5.6-2 shows the discharge voltage and mass flow rate over time. However, this graph needs to be considered very carefully, as there seemed to be a significant hysteresis when changing the mass flow rate, observed for instance during the cathode characteristics. The mass flow rate measured would probably not be the exact value currently flowing through the cathode through the high dynamic of different pressures, cross sections and volumes in the design. Nevertheless, this process happens over several hours of time, where a hysteresis of some minutes should not weight in that much.

After a slight decrease of flow rate (18 sccm), the discharge already switches in the plume mode, as experienced already during the I-V characteristics. After that, the discharge voltage is still quite stable, maybe only a slight increase in the voltage may be identified. At about 8 sccm of mass flow rate, the discharge extinguishes completely.

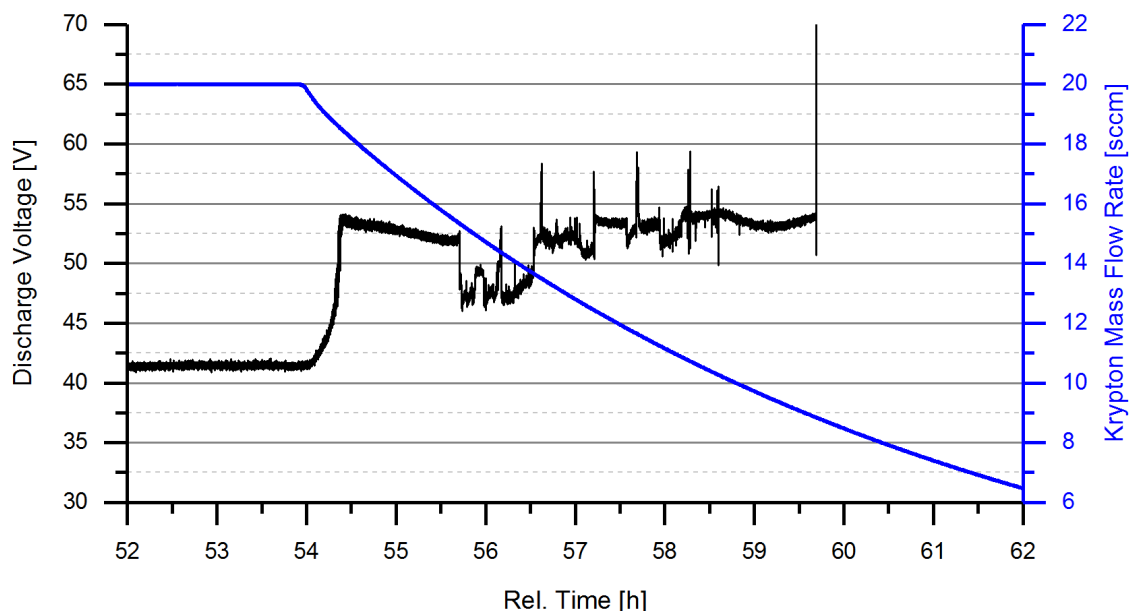


Figure 5.6-2 During the run off of krypton, the mass flow rate decreases continuously. Corresponding discharge voltage during that time until shutdown of discharge.

5.7 Temperature

During the endurance test, the temperature was logged independently by a dedicated data-logger (Testo 176-T4). The plot can be seen in Figure 5.7-1. The relative time cannot be directly correlated to the otherwise presented data. The temperature plot is therefore plotted over the overall testing period. Still, we have a clear indication of the temperature during the discharge.

For the first part of the test, the temperature is in the range between 95°C and 105°C. For the later part, the range increases somewhat and is not between 80°C and 110°C. Overall, these results are amazing, as they showcase the low steady state temperature during 2 A discharge operation.

The temperature seems to be dependent on the plasma state. Some prolonged phases correlate with also stable voltage phases previously reported (see Figure 5.4-1). This suggest, that the operational temperature for the 40 V state would be about 10°C above the 35 V discharge condition.

At around 950 hours of experimental time, the temperature falls back to room temperature. During this phase, the discharge was off over night. After that, the maximum temperature is reached which correlates with the high discharge voltage and the plasma appearance reported during that time.

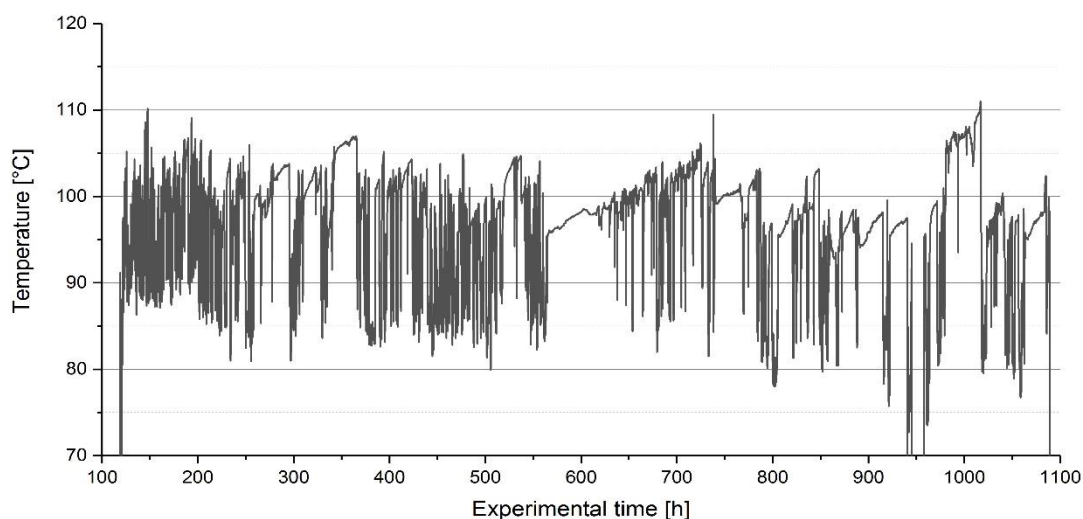


Figure 5.7-1 Temperature logged at the backside of the copper cathode body. Experimental time is not equal to relative operational time!



5.8 Discussion of the Endurance Test

Overall, a successful endurance test has been performed. We nearly reached 1000 hours, which was the goal of the test and have only been limited by the supply of krypton propellant. With the discharge current of 2 A we are also much closer at the desired parameters for the cathode for this project. Higher discharge currents have also been no problem, and have only been limited by the anode resistor power rating. During the cathode characteristic, the discharge without resistor was already successful, and will be tested again in the near future with higher currents. However, to not mix too many different and challenging things together, and (as previously stated) to be able to assess the influence of the operation time on the emitter material, no such test was done at this point.

The characteristics of the cathode suggest, that higher discharge currents could allow for lower mass flow rates of the system. Obviously, the mass flow rate is the major concern of the cathode operation as of now. 20 sccm is just much too high. However, the characteristics support the fact, that, for the given setup and cathode geometry, this was the lowest mass flow rate for a reasonable endurance test, i.e. to achieve spot mode at this current level. Significant improvements have to be made here, also at the "lower" discharge currents.

Besides the discharge current, the multi orifice (as reported in section 4.4.5) showed promising potential to reduce the mass flow rate. With this technology, the capability of endurance operation could be critical, and needs to be tested. Overall, the orifice size seems to be the most critical feature for limiting the mass flow rate of the system.

The change of the plasma mode has been clearly observed during the cathode characterization. However, another change in the discharge potential had been observed, that does not correlate with any change of the plasma mode (see Figure 5.4-4). During the first part of the endurance test, this potential did come from a change in the bias voltage, which could have suggested that the leakage current was the reason for these variations. However, during the second part of the endurance test, these voltage jumps did prevail, even though no bias potential set any more. So far, no sophisticated reason has been found to explain this phenomenon. We will need to further observe these changes in future testing.



The temperature during the experiment is exceptionally low, which is great to highlight the potential of the material. Only 5 mm of copper are between the probe and the backside of the sample, so no great temperature gradient is expected here. However, there could still be a significant gradient in the sample itself. Either way, there seems to be a lot going on with the sample and the plasma in the cathode that would most likely not be explained by thermionic emission itself (see work function tests in the order of 2.4 eV). It should be rather interesting to find out, what exactly that is.

For the endurance test, the sample was successfully mounted at the cathode even at 2 A discharge current using the silver-doped epoxy. However, the adhesive mounting seems to be not reliable enough. A mechanical hold down mechanism was designed but not tested, yet.

Finally, the endurance test showed again the sensibility of the electronics of the system. In the beginning, the cathode did extinguish a few times, before running for hundreds of hours. During the cathode characteristic, the cathode also did run without resistor for some time, before shutting down again. However, the re-ignition of the system was always very successful, even from room temperature without any instabilities. It should be considered to deal with these shutdowns of the cathode in this diode test with a software solution: observing whether the discharge is still running or extinguished. If the latter is the case, then initiate an ignition procedure with a pre resistor in line of the cathode. After successful ignition, remove this resistor (via a relay) and dial up the current limit for the discharge.

5.9 Post-Operation Analysis

After running out of krypton expellant to operate the cathode, we decided to finalize the test campaign and start the post operation analysis of the cathode. The following chapter will describe the first findings when dismantling the cathode. However, more detailed analysis and measurements will be initiated, to clear as much open questions as possible.

C12A7 electride insert

The insert seems overall in a bad condition. Figure 5.9-1 shows a microscopic view of the insert. Serious thermal stress into the material is indicated by the melted phases on the surface, the discoloring of the entire probe as well as the fractures in the sample that splits the disk into several pieces.

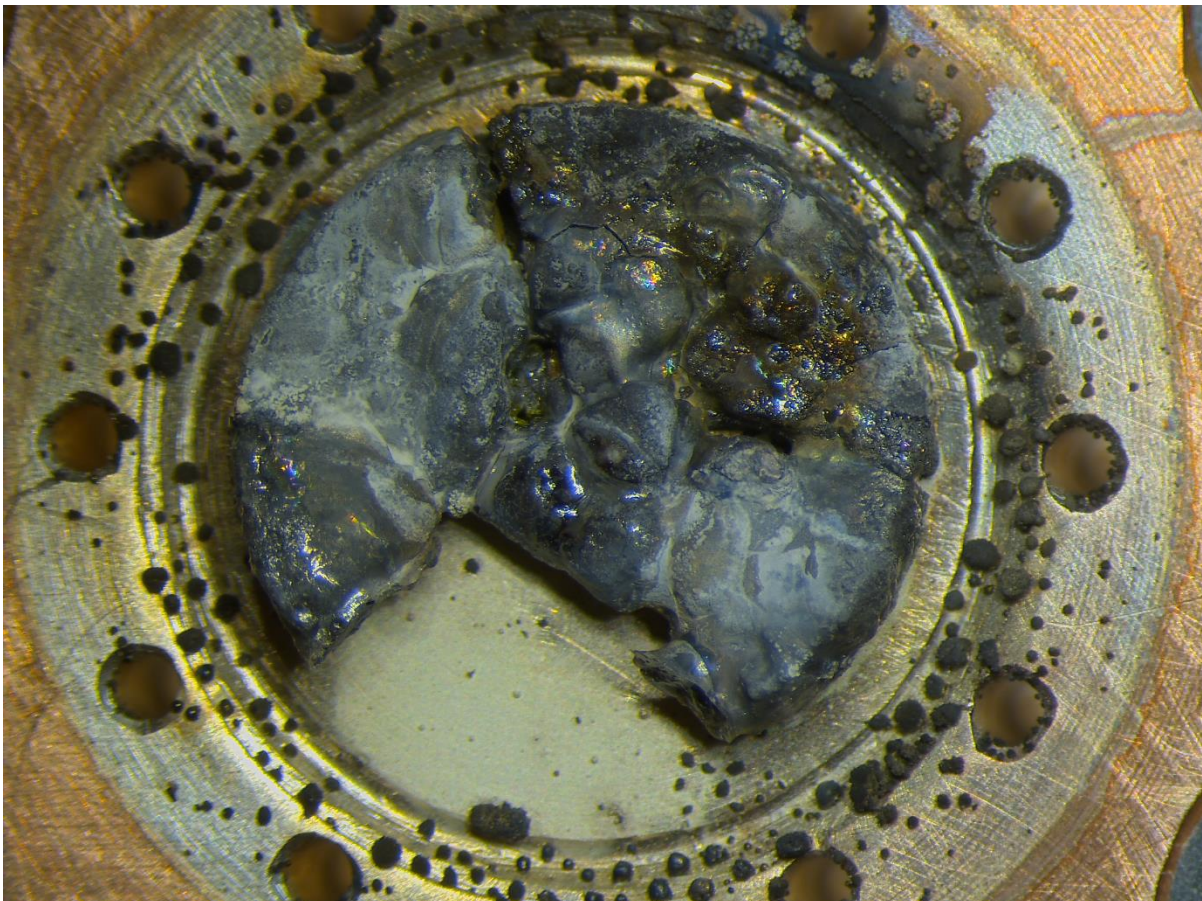


Figure 5.9-1 Microscopic view of the sample after operation. Unfortunately, a small piece did fall off after a mishap.



Overall, the emitter disk was still connected to the cathode body, and did not fall off as often reported with other contacting pastes. However, some phases seemed to be slightly lifted from the surface. Especially the part that later did fall off, after the cathode body was bumped by accident. At its original place, one can clearly see the silver paste still on the copper body. The other parts are still tight onto the surface.

Next to the fractures that obviously led to the removal of the missing part, other serious rifts can be detected. However, the area in between seems to be partially melted together again. Overall, the entire surface has this rounded appearance that is typically for a melted area. Some areas are more of a dull grey, while others are of a shiny black. A third kind of area seems to be greenish-brown, especially the deeper parts of the surface that can be seen. Black, green and white are the typical colors of the ceramic, so nothing unexpected here. The melting point of C12A7 is 1410 °C, which was apparently achieved by local heating during the measurement.

Around the sample itself, numerous particles did build up. They are black of color, and quite round like melting beads. Partially, they build up quite high, why they are very difficult to picture decently. On the surface of these beads, there are again smaller beads. A more detailed analysis had to be done, to evaluate what kind of material these are made of (see section 5.9).

Keeper plate

At the front side of the keeper, a small bead was close to the orifice. Furthermore, the orifice itself seemed to be slightly raddled. Overall, the area around the orifice was colored black, as can be seen in Figure 5.9-3.

More severe was the backside of the keeper. Here, a significant buildup happened around the orifice region. Figure 5.9-2 shows the buildup from the side and frontal. The orifice itself has not been clogged. In the middle, the material was of a grey to white color and seemed to be as one molten and solidified body around the orifice. Further away from the orifice, the color changed to a more brownish color, the buildup was much lower and numerous beads appeared. These beads seem resembling to those reported next to the emitter disk. However, the color does not match at all.

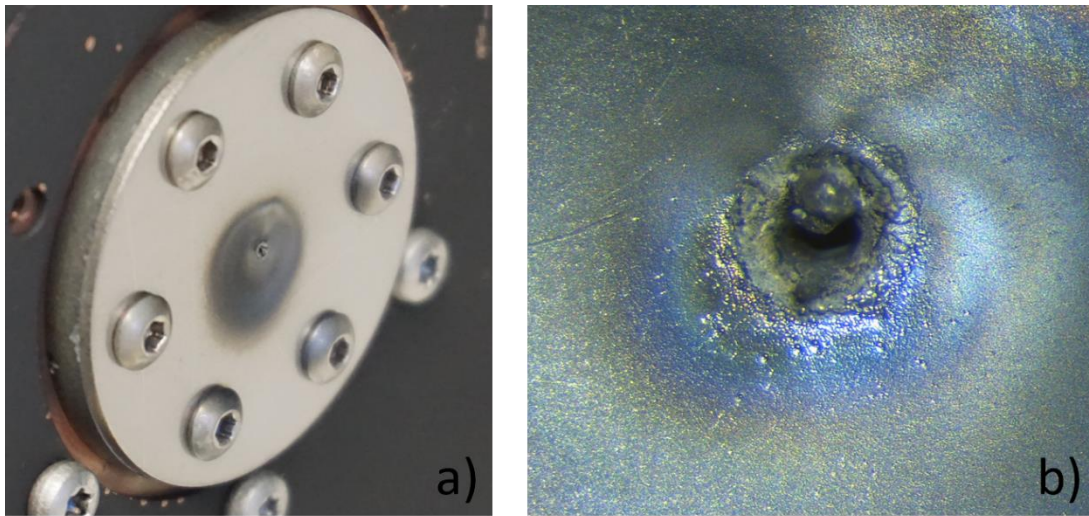


Figure 5.9-3 Keeper front. a) Discoloring around the orifice region. b) Raddled orifice with melting bead und microscope.

The white color may suggest that the buildup be made of alumina and calcium oxide. Further analysis have to confirm this theory. If so, the material would be removal from the emitter insert, which would be not ideal for the long-term operation of the material itself.

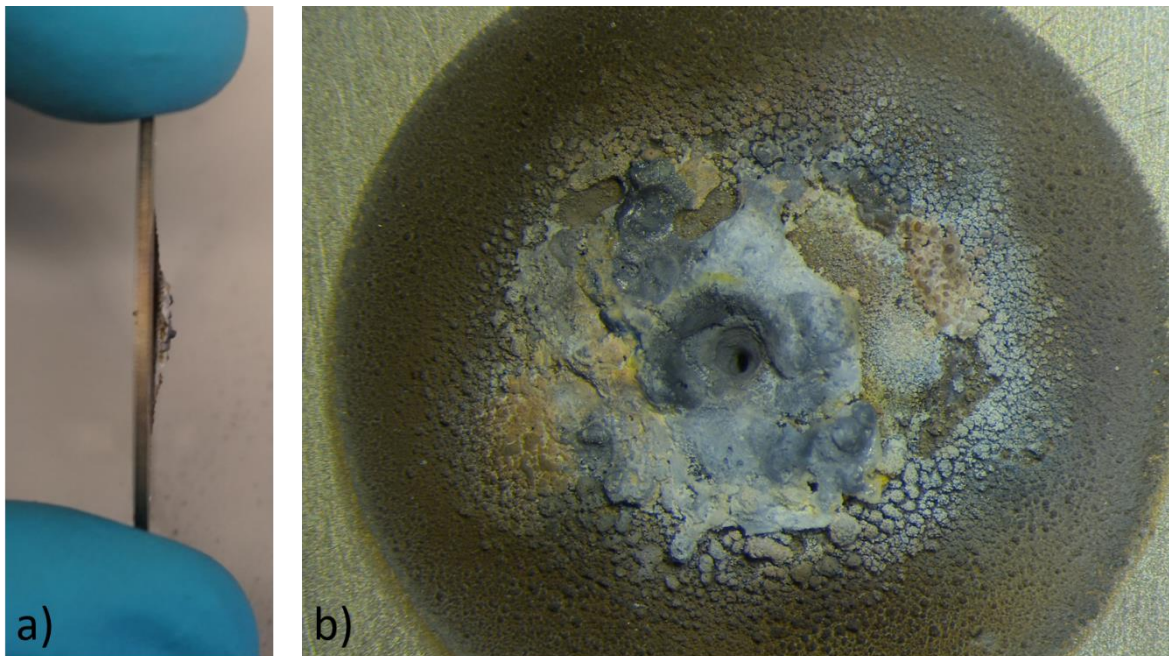


Figure 5.9-2 Keeper backside. a) Build up side view. b) Build up frontal with microscope.

Discoloring of the anode

When removing the cathode from the chamber, the anode had a clear blue coloring on the outer surface, which has been previously been painted black using a graphite spray. The discoloration can be seen in Figure 5.9-4. Although a slight blue coloring had been observed before at the end of the anode, no such change was expected. The pattern on the surface could indicate that there may be some correlation to residues on the surface of the copper. However, the anode body was thoroughly cleaned before being painted and later not touched on the outer surface.

Furthermore, there is a slight silver discoloration at the first centimeter of the inner surface of the anode (see Figure 5.9-4). Most probably, this is due to increased temperature during the long duration plasma discharge. A coating is not expected; however, a material analysis may be done later on, if possible and necessary.

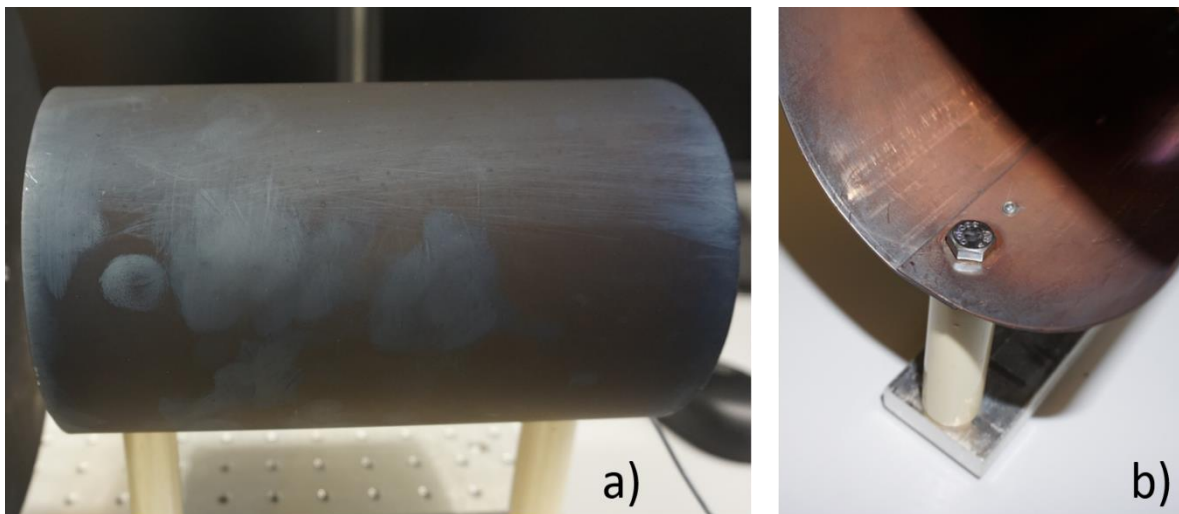


Figure 5.9-4 Discoloring of the anode. a) Large blue areas on the outer, black coated surface. b) Silverfish color at the inner surface (close to cathode).

Further Analysis of the Microstructure

The initial analysis already showed severe changes in the material of the C12A7 electrider after the endurance test. In addition, several depositions did occur, where we need to find out what material they are made of. Therefore, the sample were delivered to the Fraunhofer IKTS for a more detailed analysis.

First, the electrider sample still attached to the cathode copper body was embedded into a resin and then carefully cut using a diamond saw. Then, the polished cross section was examined using a SEM (scanning electron microscope). Figure 5.9-5 shows the SEM pictures with the lowest magnification. As observed before, the sample was divided into three bulk pieces. In addition to that, several cracks can be observed. Also, there seemed to be a partial internal porosity. Some areas seem to be still quite homogeneous, while the electron emitting surface is influenced by the generated plasma as well as thermal stress.

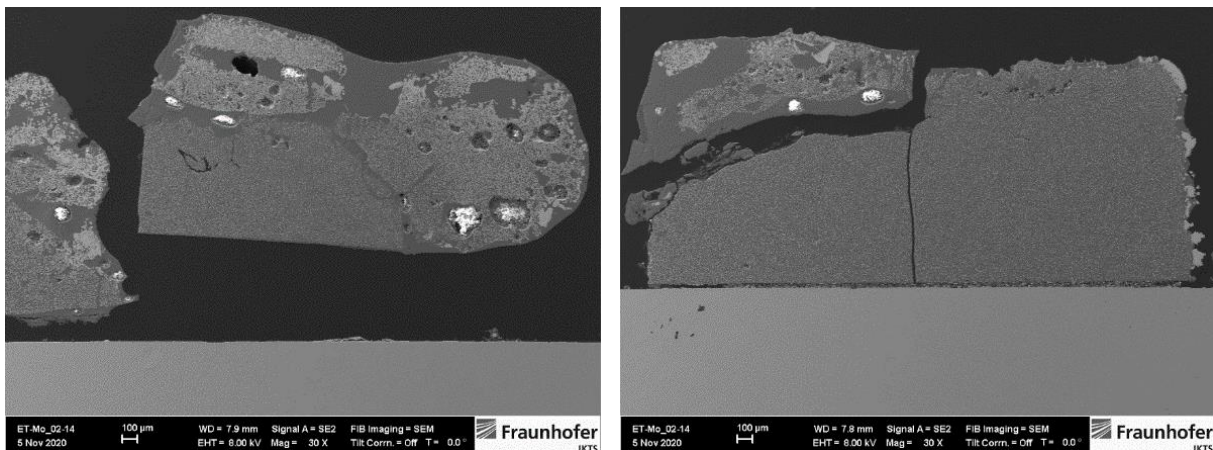


Figure 5.9-5 SEM pictures of cross sectional view of C12A7 with Mo addition electrider after endurance test on the copper substrate.

Figure 5.9-6 is a more detailed view of a part of the electrider emitter that was still attached to the copper substrate. The silver epoxy used for contacting the sample to the cathode body seems suitable and is still intact, only minor evaporation at the lower left corner, where it has been directly exposed to the plasma, can be observed. This supports the result, that the epoxy is a great contacting substance for the electrider. In addition, the temperature can't be well above 150°C at this point, as this is the maximal operation temperature of the epoxy and no thermal stress has been detected there.

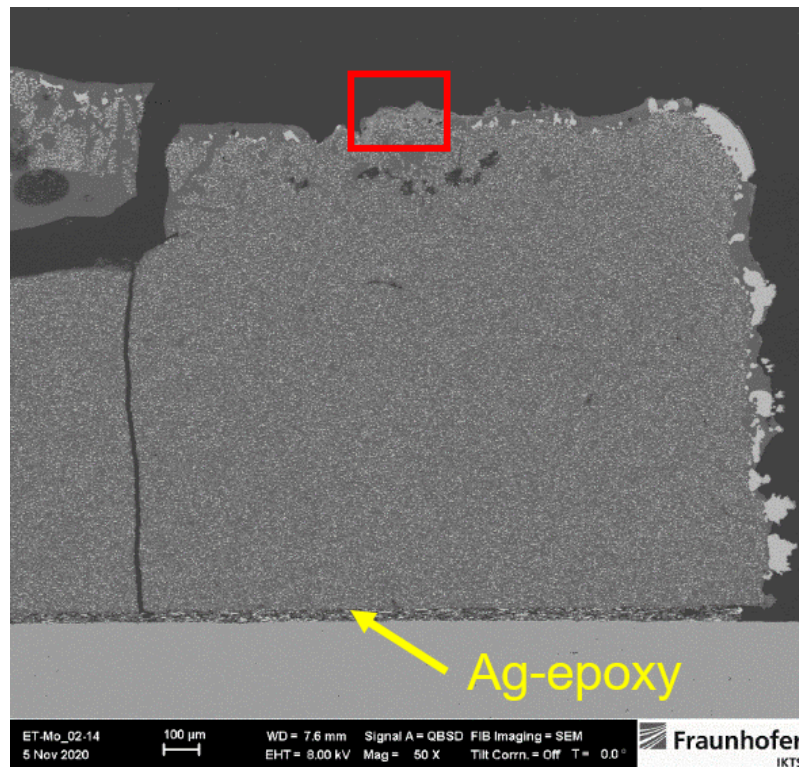


Figure 5.9-6 Silver Epoxy in great shape after enduracne test. Bulk electride material also still in great condition for electron emission.

An interesting fact is, that the material surface with contact to the plasma is decomposed, whereas the bulk material on side of the substrate is still intact. The electride and the added molybdenum are still evenly distributed in the bulk of the emitter. Only at the surface of the emitter, significant changes can be detected. This can be seen in more detail in Figure 5.9-7, which is a part of the upper surface of Figure 5.9-6. To have as much good electride material still available can be a great indication that the lifetime of the emitter could have been much longer than what it was tested (950 hours).

Figure 5.9-8 is again a more detailed view of the same part of the cross section. At this section, EDX analysis have been made to determine the composition at the surface. Standard would be the evenly distributed molybdenum and electride phases, as it is seen in the lower parts of Figure 5.9-8 for the bulk material of the emitter. However, at the surface, new compositions did arise. As labeled in Figure

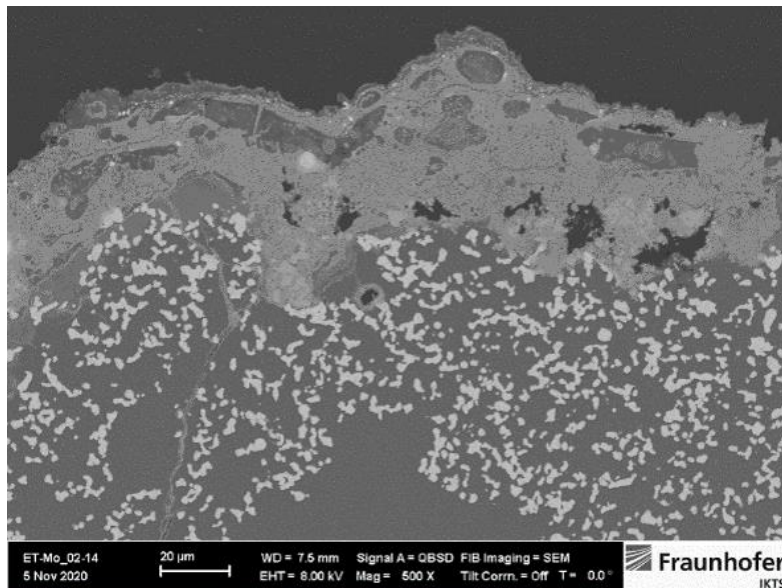


Figure 5.9-7 Detailed view of upper surface, exposed to plasma.

5.9-8, there are now several different mixtures of the calcium aluminate and the molybdenum. The formation of such phases suggest indeed the presence of very high temperatures, which are necessary for such transformation. It is uncertain, what the influence of these phases are onto the discharge itself, and how they change over time.

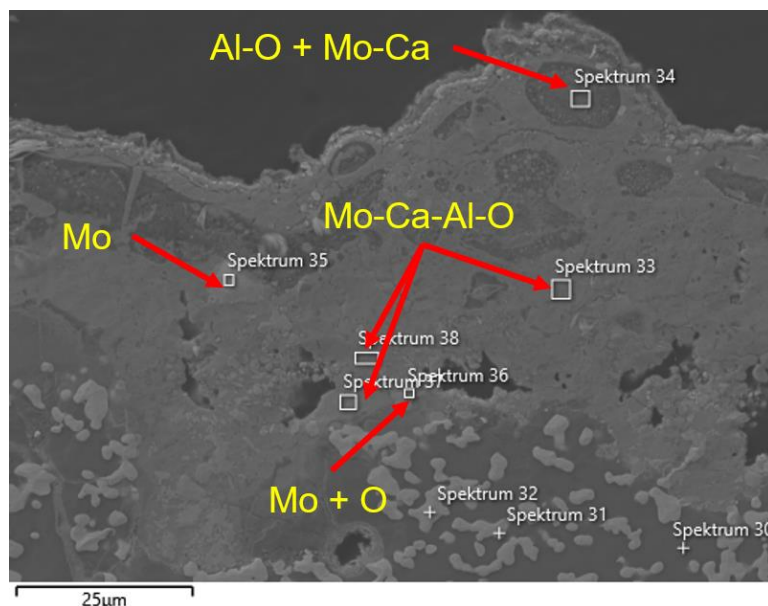


Figure 5.9-8 Analysis of phase distribution in surface area

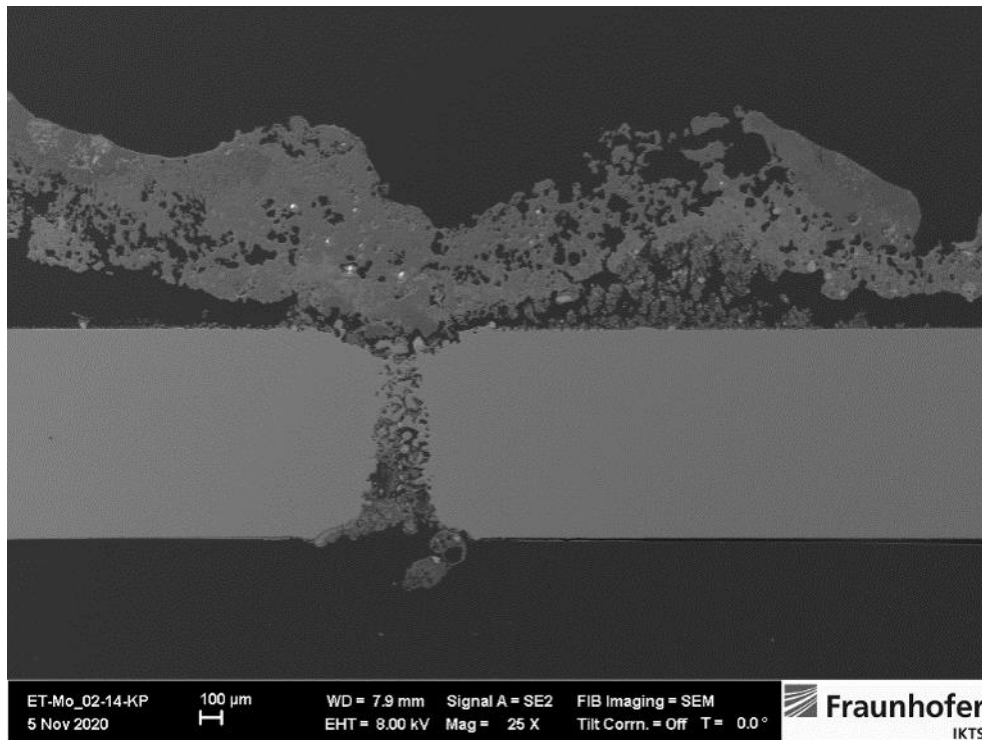


Figure 5.9-9 Cross sectional view of keeper depletions.

After examining the emitter, another cross sectional cut has been done from the Keeper and the reported depletions. Figure 5.9-9 shows a cut close to the orifice region. As expected, the depletions is very brittle and not dense, and about 1mm in height. Figure 5.9-10 depicts a more detailed view close to the surface of the keeper. In the lower parts of the picture, the stainless steel keeper can be seen, and the depletions on top. Phases of pure molybdenum have been observed but also mix phases of molybdenum with calcium oxide and alumina. It can be concluded, that material from the emitter did evaporate during plasma operation and did condense close to the keeper orifice, probably in the general direction of the propellant flow direction.

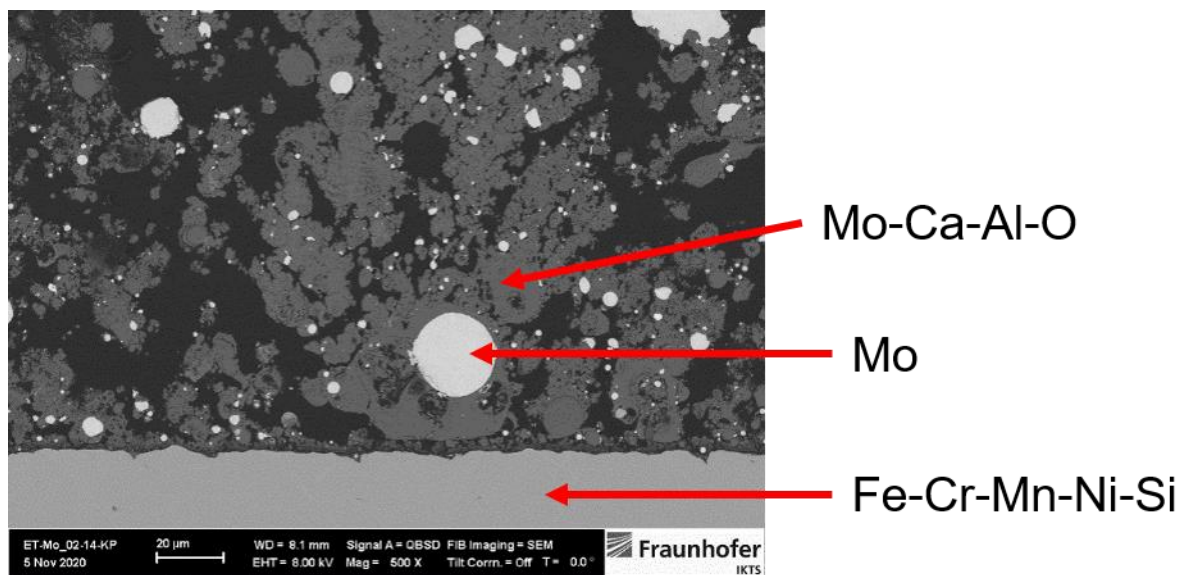


Figure 5.9-10 Analysis of composition phases of keeper depletions



5.10 Conclusion WP6

A successful endurance test of hollow cathode operation at 2 A discharge current has been achieved. The single insert operated a total of 950 hours and only failed due to lack of propellant. This is, to the best of our knowledge, the longest operation of an electrified hollow cathode reported. The cathode body temperature during the endurance operation was roughly 100°C, which is lower than with comparable cathodes. Two major drawbacks need to be considered: The mass flow rate and the power loss at the anode due to the pre-resistor.

The mass flow rate was set to 20 sccm. This was the initial value and we kept it constant for this experiment. Granted, such a mass flow rate is much too high, and needs to be improved significantly! During the I-V characteristic, we examined the discharge stability for reduced mass flows. Numerous changes in the plasma modes were observed and documented. Lowest mass flow rate was 6 sccm at which the discharge did shut down. Nevertheless, we need to consider the fact that an oversized orifice has been used for this campaign, and will be lower with an adequate orifice size. Lower mass flow rates with stable operation have been reported. Furthermore, first results with the multi orifice show very promising results to further reduce the mass flow rate of the discharge significantly.

During most part of the endurance test, a pre-resistor was positioned in line of the anode and its power supply. This is a huge power loss that needs to be evaluated. For the actual use case of a hollow cathode, the anode would be either a plasma thruster or the space plasma. These should have significant influence on the stability of the discharge. It is safe to assume that the resistor was only needed to support the control of the power supply, therefore should be no deal-breaker for the overall performance of the cathode at this point.

A first post analysis of the emitter sample showed severe degradation of the material. However, further analysis of the material indicated that only the surface exposed to plasma showed degradation. The bulk material of the emitter sample without contact to the plasma was still intact as known from manufacturing.

- Design of cathode for lifetime tests → done
- Test of first insert with overall >1000h → done
- Test of second insert with overall >1000h → not concluded
- Report degradation effects over operational time → done



6 WP7 – HALL THRUSTER – CATHODE TESTING

The aim of the work package has been to test the heaterless electrified hollow cathode, developed in the previous chapters, with different plasma thrusters. At foremost, the testing with the Hall-effect thruster at our institute was planned and conducted as described in the following sections.

In addition to that, the operation of the electrified hollow cathode with the MiXI thruster at UCLA was planned. A first test campaign was held during the second year interim report meeting in LA. Unfortunately, due to the then arising pandemic situation, no further test campaigns could be scheduled and conducted. Same goes for any test campaign of the electrified cathode with plasma thrusters at the AFRL facilities, which was originally discussed.

6.1 Hall-Effect Thruster TUD-H3-P

The TUD-H3-P is the third iteration of Hall-effect thrusters (HETs) developed at the Technische Universität Dresden with the goal to increase the thrust efficiency compared to its predecessors and was designed for a nominal discharge power of 200 W. It represents a classic SPT-type HET with dielectric channel walls made of borosil ($BN-SiO_2$) and uses permanent magnets to establish the magnetic field. The thruster was designed in the scope of his master thesis by N. Gondol [17].

The design process of the TUD-H3-P was based on the application of scaling laws from literature to an optimized reference thruster in order to obtain first estimations of the thruster dimensions as well as operating conditions for a given power level. With a mean diameter of 36 mm and a channel width of 12 mm, the thruster shows a wider channel gap compared to most 200 W thrusters in order to decrease the surface-to-volume ratio and lower the wall power losses that typically lead to overheating, erosion and lifetime limitation.

The necessary magnetic field is generated by an inner SmCo ring magnet concentric to the discharge channel and a configuration of 47 SmCo bar magnets arranged on the outside of and concentric to the channel. A magnetic shunt – i.e., a steel ring that can be slipped over the outer SmCo magnets – was additionally implemented to be able to adjust the peak magnetic flux density within the channel in the range of 15 mT to 30 mT. The magnetically conductive parts of the thruster

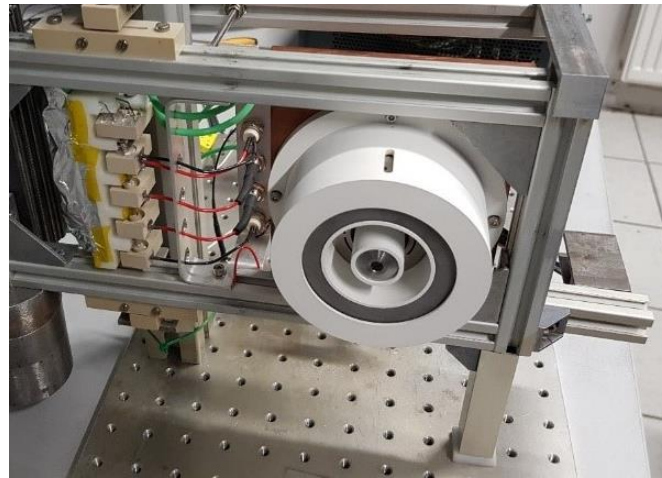


Figure 6.1-1 Hall-Effect Thruster mounted on the compact pendulum thrust balance.

are made of soft iron, i.e., technically pure iron that provides a high saturation flux density >2 T. Since the ionization efficiency is often reduced in small-scale HETs, an additional magnetic screen was installed that increases the gradient of the magnetic flux density from the channel exit plane toward the anode and therefore promotes electron confinement and ionization.

A thorough thermal design is mainly necessary to keep the temperature of the permanent magnets within the operational limits (350°C for SmCo magnets). The thermal conduction paths include copper components that evacuate heat from the front of the thruster – where the highest temperatures occur – to the back of the thruster. There, a cylindrical aluminum radiator covered with a thermally emissive varnish radiates excess heat to the vacuum chamber walls. Additionally, an aluminum top covered with the same varnish promotes radiation and protects the thruster from spark discharges.

Initial characterization tests were conducted in the laboratories of the Institute of Aerospace Engineering of the TUD with krypton as the propellant and different magnetic field configurations. A torsional pendulum thrust balance, developed by O. Neunzig [18], was used to take thrust measurements during operation. The thruster showed stable operation and highest performance at 17 mT peak magnetic flux density with thrust levels exceeding 10 mN and I_{sp} well above 1000 s. Tests with xenon have also been conducted and resulted in a significant increase in thrust and thruster efficiency.

The discharge current, i.e., the current flowing between the hollow cathode and the anode, depends highly on the mass flow rate through the thruster and the magnetic field, and must be provided by the hollow cathode. During the test series, the current ranged from approximately 0.5 A up to 1.6 A.

6.2 Setup of HET with C12A7 electrified Hollow Cathode

The Hall-effect thruster TUD-H3-P was mounted at the compact thrust balance. The cathode itself was positioned below the balance on the breadboard. Therefore, no valid thrust measurement will be possible. Either way, the goal of the test was to verify the operation of the cathode with the thruster with a characteristic of the cathode, and not the thruster. The setup can be seen in Figure 6.2-1.

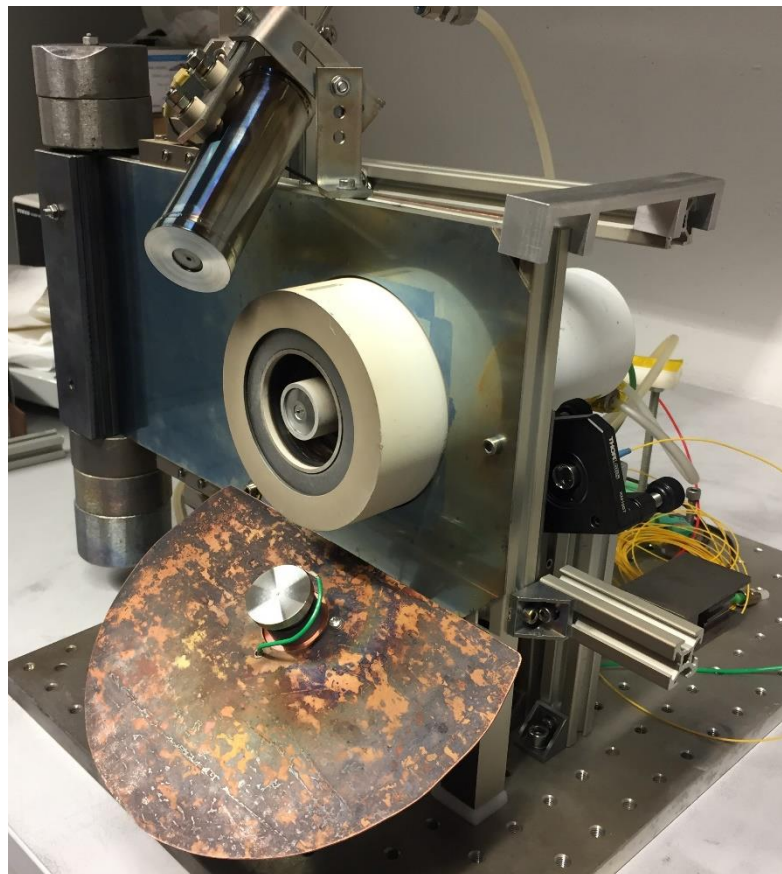


Figure 6.2-1 Hall-Effect Thruster mounted on the compact pendulum thrust balance with two cathodes. The C12A7 electrified cathode with radiator below the thruster, not at the thrust balance itself.

6.3 Operation of Cathode and Thruster

As propellant, krypton is used for the operation of the cathode. For the first ignition, 20 sccm were set at the thruster and the cathode. The ignition of the thruster was very reliable. As expected from previous tests with the thruster, the system is in a defuse mode. In order to get it into an efficient focused mode, the mass flow has to be decreased. The mass flow at the cathode was set to 10 sccm, as this was the value used with the old cathode and thruster. After that, the mass flow at the thruster was reduced stepwise to 9 sccm.

Thruster and cathode do operate together just fine. Different plasma conditions can be achieved, one exemplary shown in Figure 6.3-1. Overall, the thruster and cathode did operate together for more than 1 hour. Unfortunately, no temperature measurement could be made, as the thermocouple was damaged.

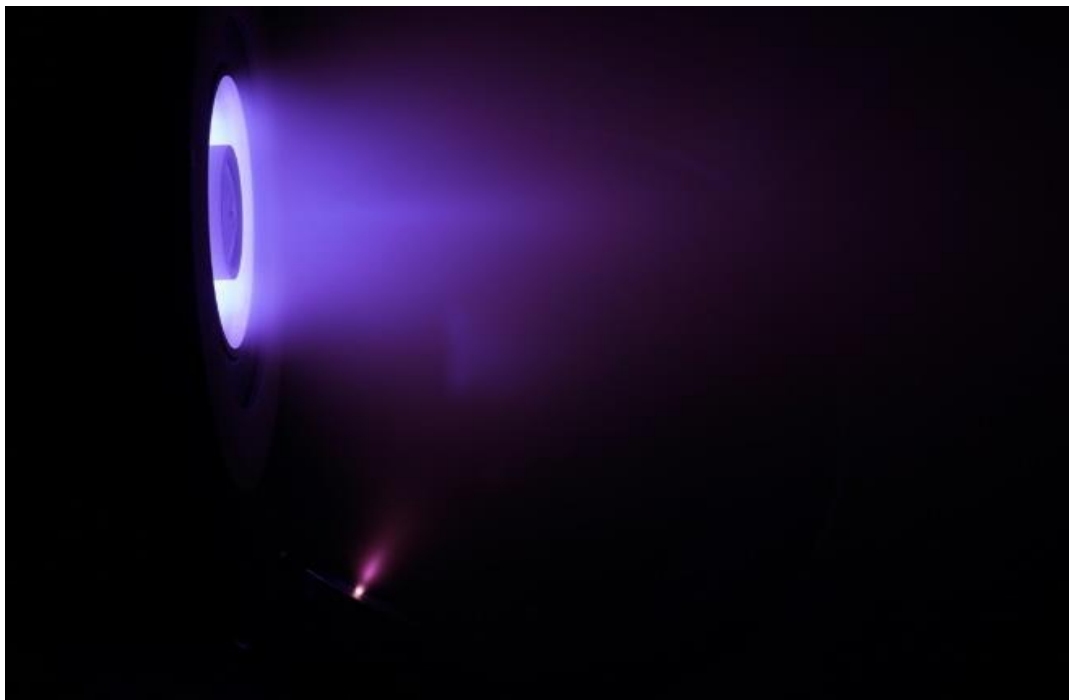


Figure 6.3-1 Operation of C12A7 electride hollow cathode with TUD-H3-P Hall-Effect thruster in focused mode.

6.4 Characteristic of operation

The characteristic of the cathode with the thruster for the initial test can be seen in Figure 6.4-1. The bias was at 1A current limit and the voltage reached about 30 V. At the anode, the voltage was set at 200 V with about $0.8 \text{ A} \pm 0.1 \text{ A}$ current. The current at the anode was rather noisy. The thruster did operate for more than 20 minutes before being shut down.

In a second test, the cathode was operated for about 50 minutes. Part of the characteristic can be seen in Figure 6.4-2. Initially, the bias current limit was set to 1.5 A, having about 28 V. The anode operated at 200V and 1.1A, but with a significant noise in the signal.

In order to get a better understanding of the discharge behavior of the cathode with the thruster, the current limits at the bias were adjusted. From the initial 1.5 A limit it was reduced stepwise to 0.3 A. Interestingly enough, the bias at the cathode does seem to have a significant influence in the stability of the plasma.

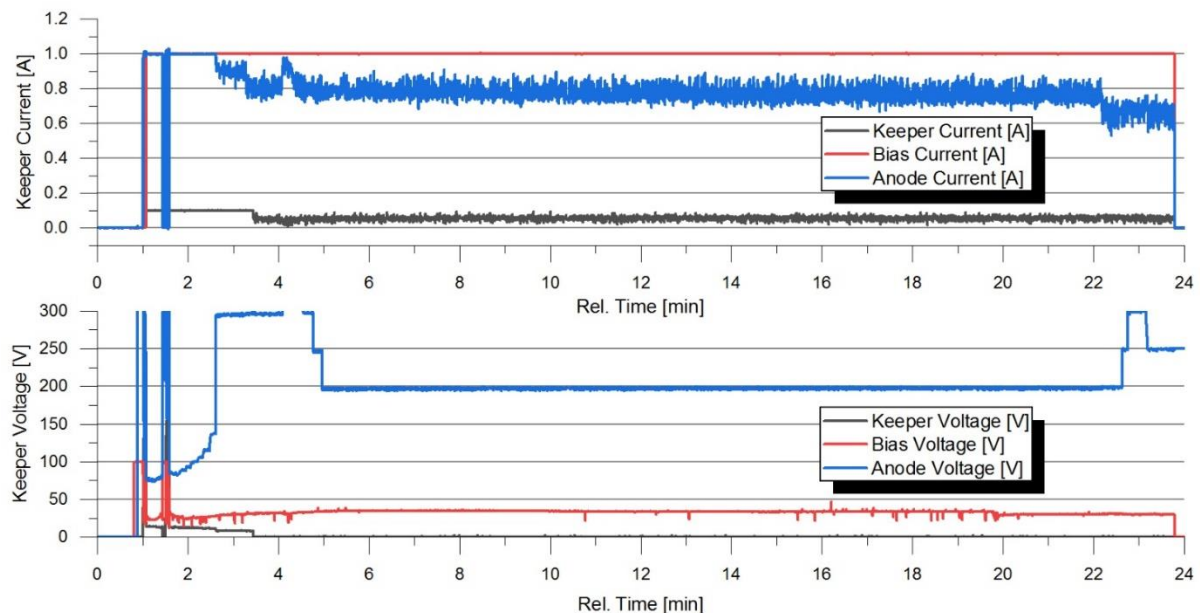


Figure 6.4-1 Characteristic of initial operation from C12A7 electride hollow cathode with TUD-H3-P Hall-Effect.

There we can see, that up to 0.4 A current limit, the voltage at the bias increases slightly, so does the current at the anode. Furthermore, the noise at the anode voltage decreases. However, most important is the characteristic, when the bias current limit is reduced to 0.3 A. Now, the bias current stays at 0.32 A but the voltage at the bias drops to 0V. In addition to that, the keeper voltage jumps to 8.8 V at a very small negative current. But most importantly, the anode voltage is visibly more stable.

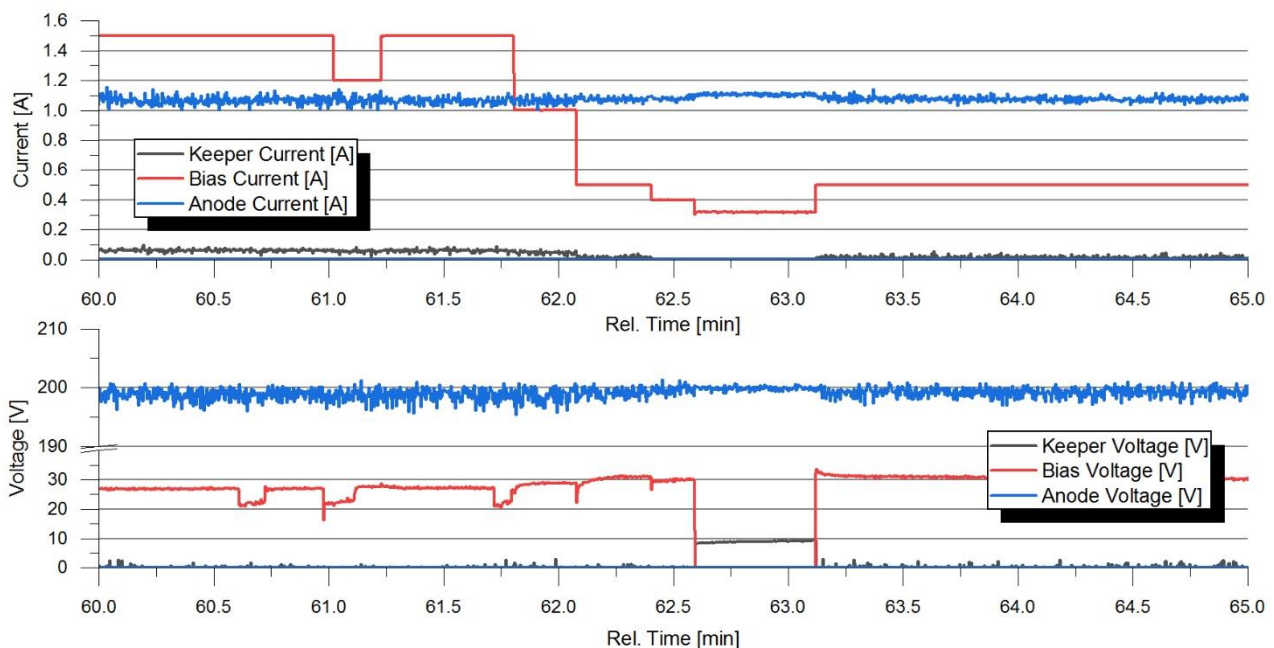


Figure 6.4-2 Characteristic of study with different bias current limits at cathode during the TUD-H3-P thruster operation. Notice the divider at the voltage axis.

Analyzing this behavior, it seems like the thruster works best with a certain amount of electrons from the cathode. At the beginning, this amount is too high, influencing the characteristic negatively. Decreasing the amount of electrons pushed into the plasma optimizes the stability of said discharge and also improves the power loss at the cathode itself. Either way, this behavior is very interesting but has to be verified with different operational conditions of the thruster itself in a more detailed test campaign.

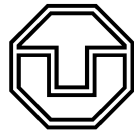


Table 6-1 Overview of cathode characteristic for operation with HET and different bias voltages

	Bias			Anode		Keeper		Power Bias+Keeper
	I _{set}	I _{is}	V	I	V	I	V	
set	-	-	100	1.4	200	0.1	0	-
61.5	1.5	1.5	27.3	1.06	200	0.06	0	40.95
62	1	1	28.9	1.06	200	0.05	0	28.9
62.25	0.5	0.5	30.8	1.07	200	0.01	0	15.4
62.5	0.4	0.4	30.7	1.08	200	0	0.1	12.28
62.75	0.3	0.32	0	1.1	200	-0.04	8.8	0.352

6.5 Hall-Effect Thruster TUD-H4-MS

A new iteration of the Hall-effect thruster at our institute was designed in implemented. The design has a magnetically shielded approach, as well as other different optimization ideas, that were supposed to be tested. A test campaign for the characterization of the thruster was conducted with the electrified hollow cathode.

The ignition of the thruster with the electrified cathode was successful and reliable. However, the design of the new thruster iteration seemed to have severe flaws, making it impossible to get stable ignition for any kind of characterization. One of the main challenges seemed to be propellant leakages at the backside of the thruster. In combination with a not ideal electrical connection, this led to plasma ignitions at the backside of the thruster and partial destruction. Consequently, no characteristic of the thruster was achieved. Any test campaign needed to be postponed until a complete overhaul of the thruster design was available.

6.6 Test with the MiXI Thruster at UCLA

A first initial test campaign of the heaterless electrified hollow cathode with the MiXI thruster at UCLA was conducted during the stay in LA for the second year interim report.



Figure 6.6-1 Operation of the C12A7 electride hollow cathode at one of the chambers at the Plasma and Space Propulsion Lab at UCLA.

Bevor implementing the thruster into the MiXI ion thruster [19], the cathode was tested at the UCLA Plasma and Space Propulsion Lab`s facilities. After some difficulties in finding the appropriate electrical setup, the cathode was ignited and operated successfully, as can be seen in Figure 6.6-1. This proves the applicability of the system to operate at different general setups, like vacuum chambers and power supplies.

After achieving such an operation, the goal was to implement a small design of the cathode into the MiXI thruster in order to use it as a discharge cathode of the thruster. Using it as a neutralizer cathode would have been much easier, but not as exiting in terms of potential operational advantages to previous cathodes.

Unfortunately, the thruster with the electride cathode as discharge cathode could not be ignited into a stable discharge. Only sparks as well as short instable conditions were achieved. The real reason for that is yet unknown. Probably the simplification of the setup as well as presumptions during preparation of the thruster and the cathode respectively. After understanding the system of each other in detail, some simple simplifications and better preparation should be sufficient, in order to get the thruster operated with the electride cathode.



6.7 Conclusion WP7

The heaterless C12A7 electride hollow cathode was successfully tested with the TUD-H3-P Hall-effect thruster at our very own institute. The discharge was very stable with an interesting characteristic concerning the relationship of currents and potential. A test campaign with the TUD-H4-MS needed to be abandoned due to severe flaws in the design of the thruster.

During the second year interim report in LA, an initial test campaign at UCLA with the MiXI Thruster was conducted. The operation of the cathode at the facilities was successful, but the operation with the thruster failed. Several optimizations were supposed to be implemented and tested at a later date. However, due to the pandemic situation no such campaign was feasible any more. Same goes for the testing of the cathode with plasma thrusters at AFRL.

- Test of cathode with TUD-H3-P → done
- Characterization with TUD-H3-P → done
- Test of cathode with MiXI ion thruster at UCLA → not concluded
- Characterization with MiXI ion thruster at UCLA → not concluded
- Test at AFRL lab with 5A cathode → not concluded



7 WP8 – ANALYTICAL MODEL

In parallel to the testing of the electride material in the thermionic cathode as well as the hollow cathode, an analytical model was to be implemented to aid the design process of the cathode.

During the first year of the project, a model using the simulation software COMSOL Multiphysics was used in order to simulate the plasma conditions of a hollow cathode. Even though this would not be an analytical model itself, it could be of great insight into the characteristic of the hollow cathode operation.

Although stable solutions could be achieved for specific geometric and operational parameters, the majority of computations diverged. This problem mainly arises from the plasma approach that is implemented in COMSOL. Here, the electron transport is modelled using the drift-diffusion approximation in combination with expressions accounting for plasma-chemical reactions and a solver for Poisson's equation. The drift-diffusion approximation is used when the gas pressure is higher than about 10 mtorr (1.33 Pa) and the plasma is weakly ionized [20]. Both constraints cannot be met throughout the computational domain. The pressure on the exterior of the hollow cathode lies typically in the range of $10e-7$ – $10e-5$ mbar ($10e-5$ Pa – $10e-3$ Pa) in the vacuum chamber used for testing. Moreover, the ionization degree within the narrow orifice can easily exceed 10 % [21].

For the second year of the project, it was thus decided to pursue a different approach of modelling. Generally, Particle-in-Cell codes and 2D analytical models provide the most accurate results, but their computational effort is very high. As a simpler alternative, a number of volume-averaged models of hollow cathodes found in literature have been examined and compared. The investigated models are listed in Table 7-1.

Table 7-1 Investigated 0D Models of Hollow Cathodes.

<i>Model</i>	<i>Description</i>
Goebel et al. [21]	Insert model
Mizrah et al. [22]	Orifice model
Mandell et al. [23]	Orifice model
Korkmaz [24]	Combined insert and orifice model
Albertoni et al. [25]	Combined insert and orifice model coupled with a lumped thermal model



Most 0D models have the shortcoming of not being self-consistent, i.e., experimental input or strong assumptions are necessary to obtain reasonable results, or being only valid in distinct regions of the hollow cathode. The only model with little to no external input apart from geometry, material properties and operational conditions that also solves for results in both the insert and orifice region is the one developed at Alta by Albertoni et al. [25]. Moreover, the thermal output of the model can easily be compared to experimental data. The model was thus considered for the hollow cathode developed at TUD and is described in detail below.

7.1 ALTA 0D Hollow Cathode Model

The model is divided into two sub-models, one for the orifice plasma and one for the emitter region. The heavy particles (ions and neutrals) are assumed to be in thermal equilibrium with the respective walls of the sub-model and to be much cooler than the electrons:

$$T_e > T_n = T_i = T_{wall} \quad (1)$$

The exterior pressure is considered sufficiently low for the heavy particles to reach supersonic conditions at the orifice exit:

$$Ma_{exit} = 1 \quad (2)$$

The electrons leaving the insert are assumed to be emitted along a fraction of the total insert surface, l_{eff} . The effective electron emission area A_{eff} is thus:

$$A_{eff} = 2\pi r_{ins} l_{eff} \quad (3)$$

The orifice model comprises three equations that are solved to obtain the orifice electron temperature, the plasma density and neutral density. The first equation is the ion conservation in the orifice:

$$e\pi r_{or}^2 l_{or} n_n n_e < \sigma_i v_e > = j_i (2\pi r_{or} l_{or} + \pi r_{or}^2) + j_{th} \pi r_{or}^2 \quad (4)$$

The left-hand side of Eq. (4) represents the ion production rate in the bulk plasma due to electron impact ionization, with $< \sigma_i v_e >$ being the ionization reaction rate coefficient [21]. The right-hand side of Eq. (4) describes the ion flux leaving the control volume. Here, j_i is the ion current density calculated from the Bohm criterion:

$$j_i = 0.61 n_e e \sqrt{\frac{e T_e}{m_n}} \quad (5)$$

and j_{th} is the thermal current density of ions:

$$j_{th} = en_e \sqrt{\frac{k_B T_n}{2\pi m_n}} \quad (6)$$

The second equation of the orifice model is the bulk plasma power balance, expressed by:

$$RI_d^2 = \dot{n}_{ion} < \epsilon_i > + \frac{5}{2} I_d (T_{e,or} - T_{e,ins}) \quad (7)$$

The Ohmic heating on the left-hand side of Eq. (7) is counter-balanced by the energy loss due to ionization and due to convection. The convection term in Eq. (7) represents a coupling between the orifice and the emitter model. In Ref. [25], the authors also account for a double-sheath between the boundary of the orifice and emitter. This was, however, neglected for the presented study in order to decrease complexity because the double-sheath represents an additional coupling between the two sub-models. The plasma resistance R is:

$$R = \eta \frac{l_{or}}{\pi r_{or}^2} \quad (8)$$

with η being the plasma resistivity:

$$\eta = \frac{\nu m_e}{n_e e} \quad (9)$$

In Eq. (9), ν is the total collision frequency that is the sum of the electron-ion collision frequency and the neutral-ion collision frequency. The third equation balances the pressure calculated by the kinetic gas theory to the static pressure expected from a choked flow condition in the orifice:

$$(n_e + n_n) k_B T_n \left(1 + \alpha \frac{e/k_B T_e}{T_n} \right) = \frac{\dot{m}}{\pi r_{or}^2} \sqrt{\frac{R_g T_n}{\gamma}} \left(1 + \alpha \frac{e/k_B T_e}{T_n} \right) \quad (10)$$

where α is the ionization degree.

Next, the insert model is solved, which consists of four equations to obtain the insert region electron temperature, the plasma density, the neutral density and the sheath potential ϕ_s . The current conservation at the insert surface is:

$$\frac{I_d}{A_{eff}} = j_i + j_{em} - j_{er} \quad (11)$$

j_{em} is the emission current density that is calculated by the Richardson-Dushman equation:

$$j_{em} = DT_c^2 \exp \left(- \frac{e\phi_{eff}}{k_B T_{ins}} \right) \quad (12)$$

ϕ_{eff} is the insert material work function reduced by the Schottky effect:

$$\phi_{eff} = \phi_{wf} - \sqrt{\frac{eE_c}{4\pi\epsilon_0}} \quad (13)$$

$$E_c = \sqrt{\frac{n_e k_B T_e}{\epsilon_0}} \left(2 \sqrt{1 + 2 \frac{\phi_s}{T_e}} - 4 \right)^2 \quad (14)$$

j_{er} in Eq. (11) accounts for the thermal electron current overcoming the electron repelling sheath potential:

$$j_{er} = \frac{1}{4} e n_e \exp\left(-\frac{\phi_s}{T_e}\right) \sqrt{\frac{8eT_e}{\pi m_e}} \quad (15)$$

The second equation of the emitter model is the ion conservation:

$$e\pi r_{ins}^2 l_{eff} n_n n_e < \sigma_i v_e > + j_i \pi r_{or}^2 = j_i (A_{eff} + \pi r_{ins}^2 - \pi r_{or}^2) + j_{th} \pi r_{ins}^2 \quad (16)$$

The ions that are created in the emitter control volume and the ions that enter the domain from the orifice are balanced by the ions lost to the insert, the orifice and the upstream part of the hollow cathode. The third equation is the bulk plasma power balance:

$$\begin{aligned} 2j_i \frac{k_B T_{ins}}{e} \pi r_{or}^2 + R I_d^2 + j_{em} \left(\phi_s + \frac{3}{2} \frac{k_B}{e} T_{ins} \right) A_{eff} \\ = \dot{n}_{out} \left(< \epsilon_i > + 2 \frac{k_B T_{ins}}{e} \right) + 2j_{er} \frac{k_B T_{ins}}{e} A_{eff} + \frac{5}{2} T_e I_d \end{aligned} \quad (17)$$

The last equation of the insert model is a balance of the pressure in the insert calculated using the kinetic gas theory and the pressure at the upstream end of the orifice assuming a linearized Poiseuille flow with a sonic condition at the orifice exit [26]:

$$\begin{aligned} (n_e + n_n) k_B T_n \left(1 + \alpha \frac{e/k_B T_e}{T_n} \right) \\ = \sqrt{\dot{m} \frac{16\mu}{\pi r_{or}^4} R_g T_n l_{or} + p_0^2} + \frac{1}{2} \frac{p_0}{R_g T_n} \bar{u}^2 (1 + K_l) \end{aligned} \quad (18)$$

with the sonic pressure p_0 being:

$$p_0 = \dot{m} R_g T_n \frac{4}{\pi d_{or}^2} \sqrt{\frac{1}{\gamma R_g T_n}} \quad (19)$$



and the average velocity of heavy particles in the orifice $\bar{u}$:

$$\bar{u} = \frac{d_{or}^2}{32\mu} \frac{(p_{ins} - p_0)}{l_{or}} \quad (20)$$

In Eq. (18), K_l represents a loss factor that is estimated with 0.5 [26]. Albertoni uses a hard-shell model to account for the dynamic viscosity μ . As suggested by Wordingham [27], a Chapman-Enskog approach to the Lennard-Jones potential was instead used because it is in better accordance with experimental data.

The plasma model described above is used as an input of a lumped thermal model. Here, the hollow cathode geometry is divided into several nodes that have a uniform temperature and a thermal network is established. Heat is transferred between the nodes by conduction and the exposed surfaces of the nodes radiate to the surrounding with an assumed temperature of 0 K. The base of the cathode is kept at an arbitrary 1000 K. There are two kinds of nodes that need to be considered in the thermal network. The first type is characterized by the external power input and thermal conduction. The power balance that needs to be solved for is:

$$0 = -P_{in} + (\sigma_{sb}T_i^4 - J_i) \frac{A_i\epsilon_i}{1 - \epsilon_i} + \sum_j (T_i - T_j) \frac{\lambda S_{ij}}{b_{ij}} \quad (21)$$

where J_i is the radiosity of node i , ϵ_i is the emissivity, λ is the thermal conductivity, S_{ij} is the conduction cross-section and b_{ij} is the conduction length. The second type of nodes is characterized by the respective radiosity. The power balance is thus:

$$0 = -(\sigma_{sb}T_i^4 - J_i) \frac{A_i\epsilon_i}{1 - \epsilon_i} + \sum_j (J_i - J_j) A_i F_{ij} \quad (22)$$

Here, F_{ij} is the geometrical viewing factor between nodes i and j . For radiation to the surrounding a viewing factor of 1 is assumed. The coupling between the plasma model and the thermal model is achieved via power inputs into the insert node (over a length of l_{eff}) and into the orifice node. The insert power is described by:

$$P_{ins} = P_{ion,w} + P_{er,w} - P_{em,w} \quad (23)$$

$P_{ion,w}$ accounts for the heating of the insert by ions recombining at the insert surface:

$$P_{ion,w} = j_i(\phi_s + \langle \epsilon_i \rangle - \phi_{wf}) A_{eff} \quad (24)$$

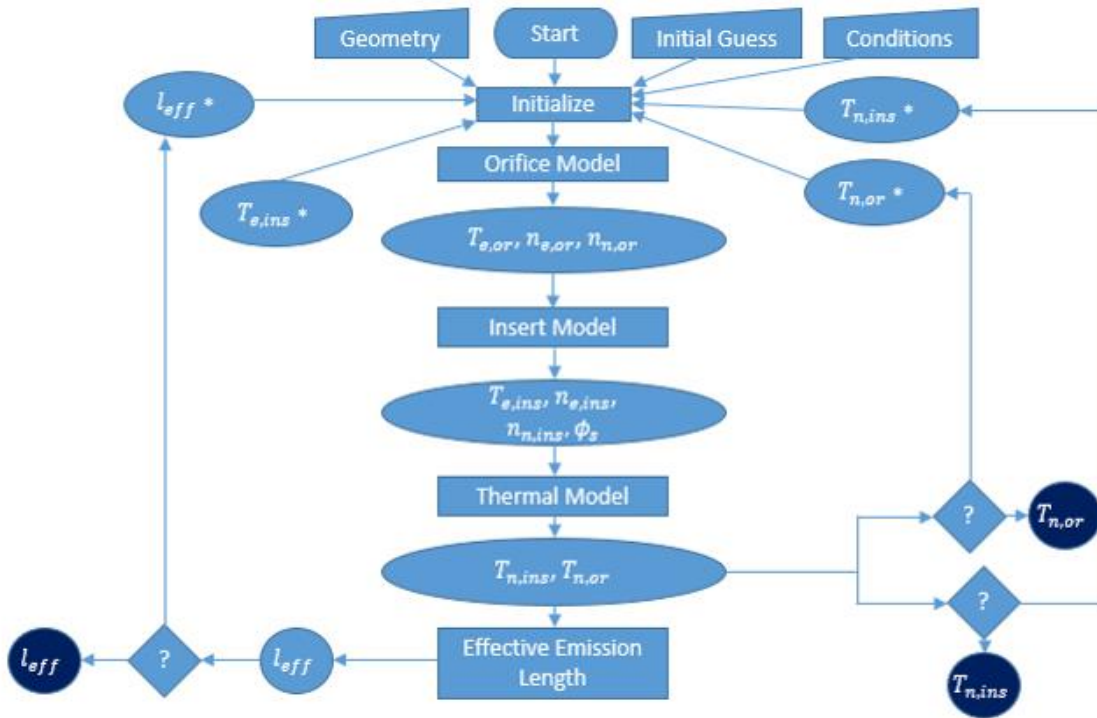


Figure 7.1-1 Flow chart of solution process of the 0D hollow cathode model, adapted from [16].

$P_{er,w}$ is the power input due to thermal electrons impacting the insert surface:

$$P_{er,w} = j_{er}(\phi_{wf} + 2T_e)A_{eff} \quad (25)$$

The insert is cooled by the thermionic emission power $P_{em,w}$:

$$P_{em,w} = j_{em}\left(\phi_{eff} + \frac{3}{2}T_e\right)A_{eff} \quad (26)$$

In the orifice, it is assumed that the entire Ohmic heating is transferred into the orifice walls.

The iterative solution procedure of the complete model is illustrated in Figure 7.1-1. For the first iteration cycle, initial guesses of the plasma parameters are necessary. The initial guess was shown to notably influence both computation time and convergence.



7.2 Test Model of a Cylindrical Hollow Cathode

An exemplary hollow cathode was modelled and the model output examined. The cathode geometry is similar to the one described in Ref. [25] but has a longer orifice and a slightly larger orifice diameter. The original dimensions did not provide stable solutions. The geometry is summarized in Table 7-2.

Table 7-2 Dimensions of benchmark Hollow Cathode

Parameter	Value
Orifice diameter	0.4 mm
Orifice length	0.74 mm
Insert inner diameter	3 mm
Insert outer diameter	6.9 mm
Cathode tube outer diameter	7.5 mm

The cathode tube is made of tantalum and the insert material is LaB6. The internal radiation was neglected for the presented study as well as heat transfer by convection. Both will be considered in future versions. Table 7-3 lists material properties that were implemented in the model.

Table 7-3 Implemented Material Properties

Material	Thermal Conductivity [W/(mK)]	Emissivity	Work Function [eV]	Richardson coefficient [A/m ² /K ²]
Tantalum	57.5	0.19	-	-
LaB6	47	-	2.66 [21]	290000 [21]

Figure 7.2-1 and Figure 7.2-2 show the division of the geometry into nodes and the thermal network, respectively.

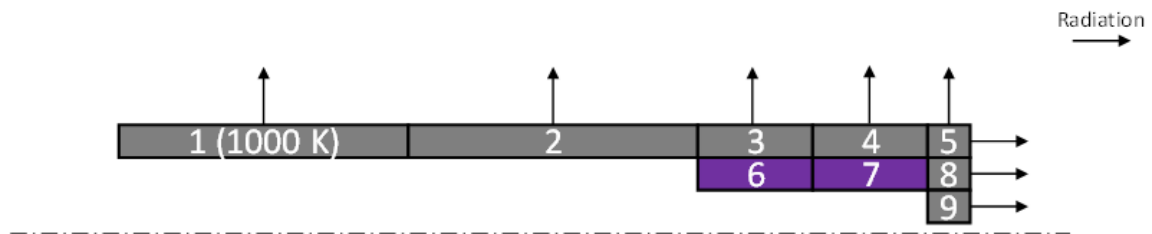


Figure 7.2-1 Nodes and radiating surfaces of the benchmark hollow cathode.

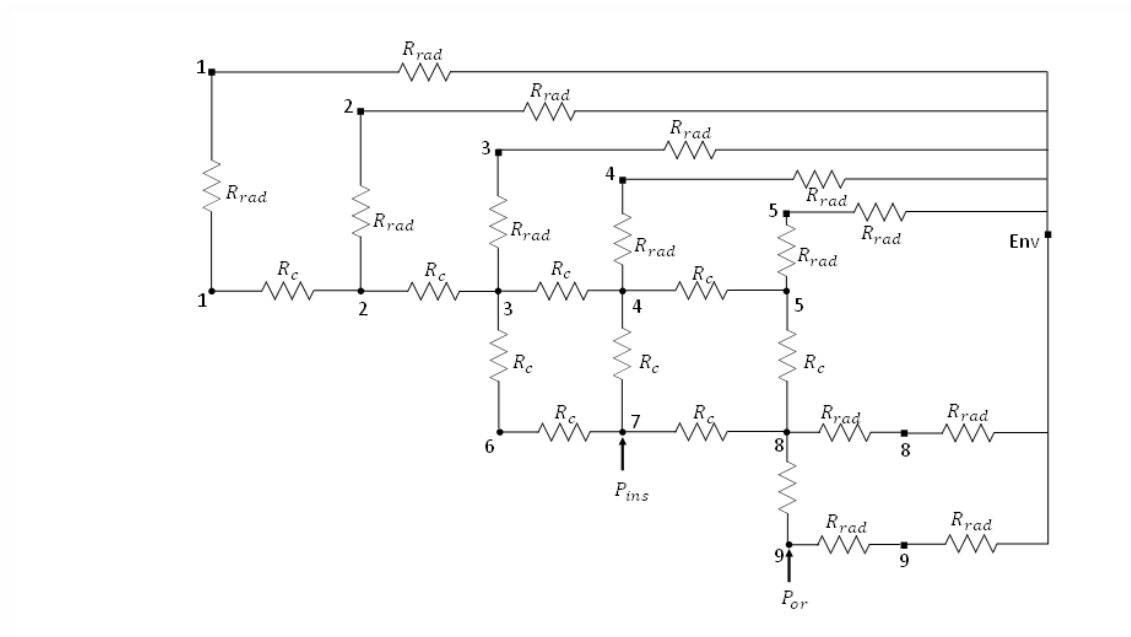


Figure 7.2-2 Thermal network implemented in the thermal model.

7.3 Model results

The obtained results of the model are summarized in Figure 7.3-1 to Figure 7.3-2. The trends and orders of magnitude of the results are very close to the solutions presented in [25].

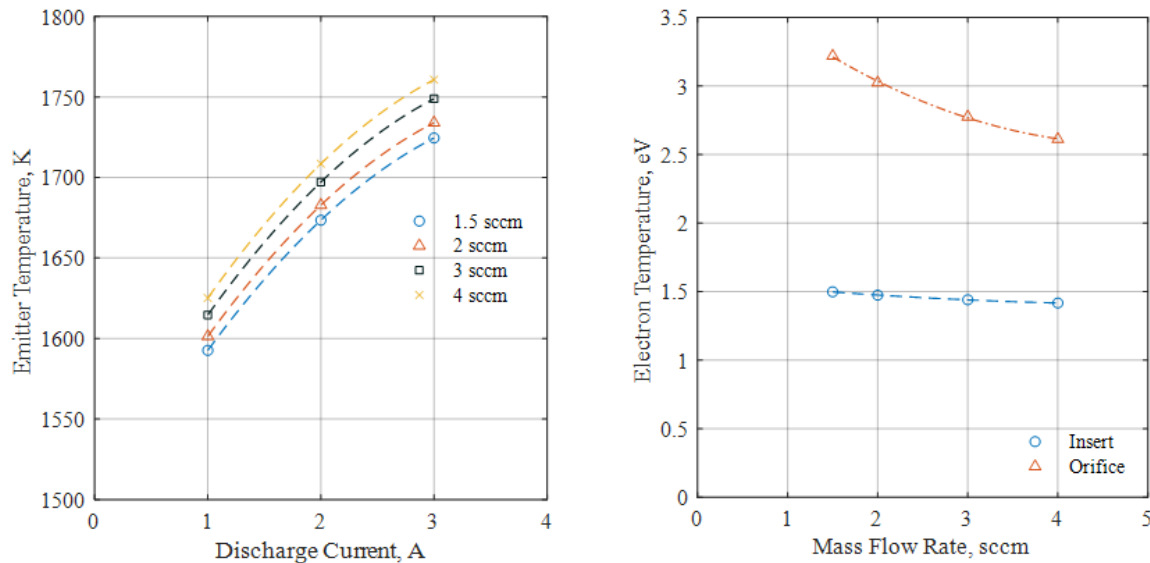


Figure 7.3-1 a) Emitter temperature as function of discharge current and mass flow rate. b) Electron temperature in insert and orifice region at 3 A discharge current

Figure 7.3-1a) indicates that emitter temperature increases with increasing discharge current and mass flow rate. Increasing the discharge current results in higher Ohmic losses in the orifice and thus wall temperatures, while an increase in mass flow rate leads to an increased pressure in the emitter region and thus temperature. The obtained emitter temperatures are typical of LaB6 hollow cathodes. The trends in electron temperature in the two hollow cathode regions depicted in Figure 7.3-1b) were also observed in Ref. [25]. The insert electron temperature only changes slightly with mass flow rate, while the orifice electron temperature notably rises as the mass flow rate is decreased.

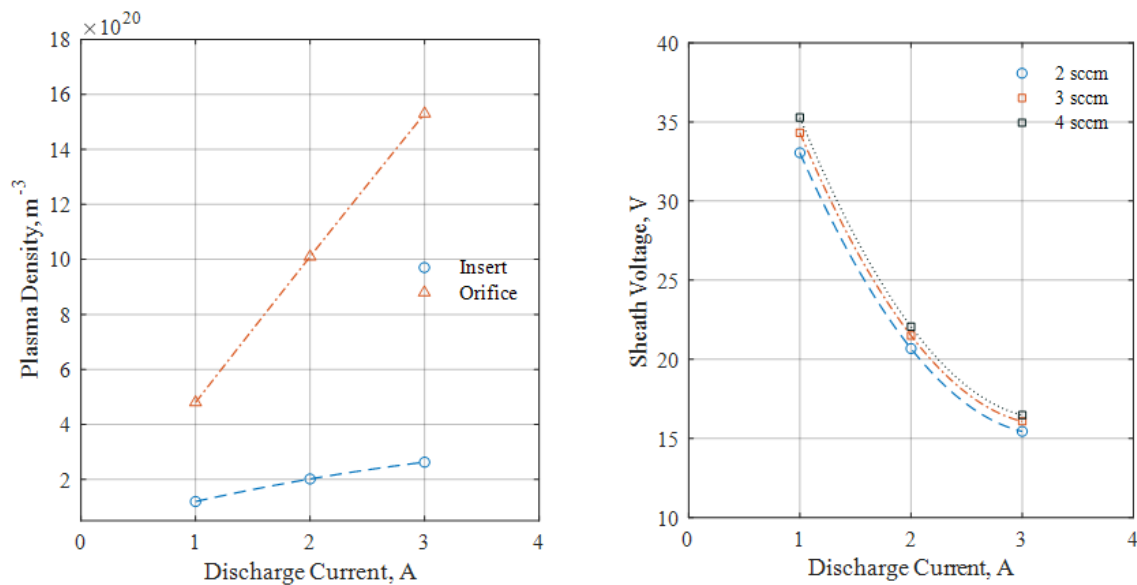


Figure 7.3-2 a) Plasma density in insert and orifice region at 3 sccm mass flow rate. b) Sheath potential as function of discharge current and mass flow rate.

Figure 7.3-2a) shows an increase of plasma density as the discharge current is increased and a significantly higher orifice plasma density compared to the insert plasma density. This trend is typical of hollow cathode discharges since the narrow orifice leads to very high current densities and thus heating of the plasma, which promotes ionization. In Figure 7.3-2b), the sheath potential is depicted as a function of mass flow rate and discharge current. It is evident that the sheath voltage significantly increases as the discharge current is decreased, which is consistent with the findings of Albertoni [25] and Goebel [21].

7.4 Tablet Emitter Geometry

The concept of the 0D model described above can be adapted to hollow cathodes using C12A7 tablet inserts, as they are used in the experimental setup describes in the previous sections. This necessitates subtle changes in the orifice and insert model due to the different geometry. It is also assumed that the tablet emits electrons over the entire surface. In preliminary modelling efforts, the work function of C12A7 was estimated with 2.4 eV, while the constant D in Eq. (12) was assumed to be equal to LaB6. However, a stable solution was only obtained at emitter and orifice temperatures comparable to cylindrical LaB6 insert in the order of 1700 K, summarized in Figure 7.4-1 to Figure 7.4-2. As the trends of electron temperature and plasma density are very similar to cylindrical insert, the emitter temperature does not change significantly over the investigated range of current and mass flow rate. Also, the sheath potential is notably lower compared to cylindrical insert and increases rather than decreases with increasing current.

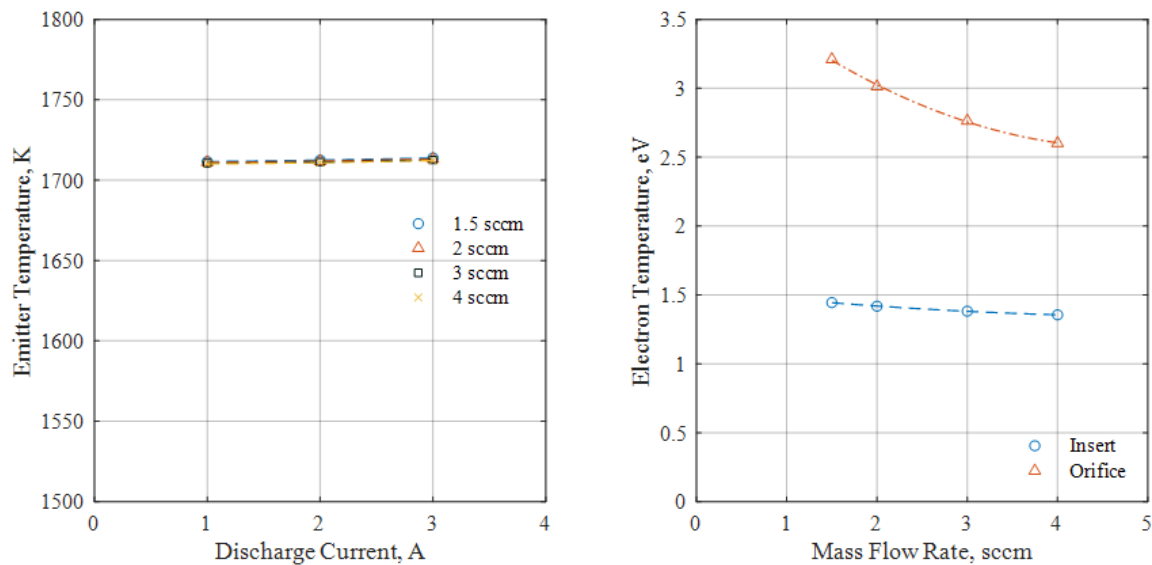


Figure 7.4-1 a) C12A7 tablet temperature b) Electron temperature in insert and orifice region at 3 A discharge current (tablet)

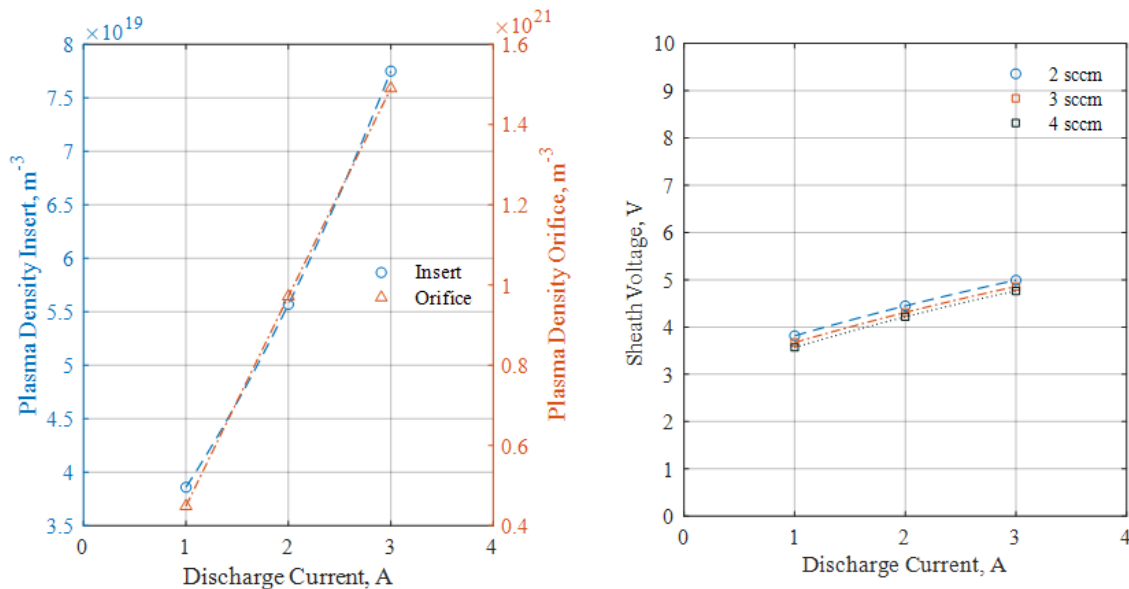


Figure 7.4-2 a) Plasma density in insert an orifice region at 3 sccm mass flow rate (tablet). b) Sheath potential as function of discharge current and mass flow rate (tablet).

The obtained emitter temperatures are in strong contradiction to temperature measurements of the TUD hollow cathode that shows temperatures of approximately 400 K at the cathode base. Up to now, no solution could be achieved at temperatures this low.

7.5 Discussing WP8

The previous chapters described the attempts to get a better theoretical understanding of the electrified hollow cathode using numerical simulations and a 0D analytical model. Still, the results obtained have not been ideal. The reasons therefore are manifold.

One major uncertainty are the material parameters of the C12A7 electride. Numerous tests have been made to evaluate the characteristics of the material as described in chapter 3. However, as discussed there, did the tests not results in defined parameters for instant for the work function as well as the Richardson-



Dushman coefficient, which are fundamental for the performance of the models. This problem is with many more parameters for the material.

The vastly different results of the thermionic diode as well as the hollow cathode suggest some kind of additional interaction between the plasma and the emitter material. It could be the plasma cleaning of the first layers of the material or some kind of activation of the material from the plasma. Another possibility could be electric field effects due to the nanocage structures of the material. In addition to that, the connectivity of the C12A7 electride to the surrounding metals, be it the cathode base or the additives (Mo or Ti), is highly uncertain. Such effects make predictions of the physical effects inside the system difficult to evaluate and reduce the reliability of the model. Due to the vastly different characteristic of the material to state of the art emitter materials, it is difficult to draw correlations from the experience with the other materials.

In addition to the material uncertainties, the development of the hollow cathode went towards the usage of the tablet shaped inserts, as will be discussed separately in chapter 8. However, most models and predictions in literature are for the hollow cylinder setup. It is obviously, that this is a severe difference in the constraints to the models and that this would render many models insufficient for us to use. It is to no surprise, that simple adjustments will not be sufficient to get any reliable results. Rather, completely new models need to be implemented.

Due to the rather big challenges with these models, it was decided to not get any more involved with these models. The focus was more towards the characterization of the diode and cathode discharges. The understanding of the discharge behavior is just not mature enough, to make any sufficient model predictions as of now.

7.6 Conclusion WP8

Modelling efforts of hollow cathodes using the COMSOL Multiphysics plasma module have not provided satisfactory results. As an alternative, 0D models have been investigated and compared. The self-consistent hollow cathode model by ALTA was deemed to be suitable for modelling the TUD hollow cathode, because thermal measurements can easily be compared to the model output. A hollow cathode with a cylindrical LaB6 insert and a similar geometry to the benchmark hollow



cathode used by ALTA was successfully modelled. The results are in good agreement with the results reported in [25].

Preliminary efforts have been made to implement a hollow cathode with a C12A7 tablet insert. Although a stable solution could be obtained for specific operational conditions, the output of the thermal model showed cathode temperatures that far exceed temperatures obtained by measurements.

Overall, the further work on simulations and models came to a halt due to the high amount of uncertainties with the material and the process within the cathode. As of now, the understanding of the behaviour of the materials seems not mature enough to justify any model predictions for the design of a hollow cathode.



8 HOLLOW CYLINDER VS TABLET SHAPED INSERTS

Over the course of the project, the hollow cathode went from using hollow cylinder shaped inserts to disk like / tablet inserts for electron emission. In the following chapter, we want to discuss the reasoning behind this change and how we think it will continue down the stretch.

At the beginning of the development, a hollow cylinder insert was the obvious choice, since it is how most state of the art hollow cathodes are build. Looking into literature about the theory of hollow cathodes, and about different design approaches, the hollow cylinder is most often the common factor here. And not without reason, since such a setup has many advantages, including the surrounding of the plasma by low work function material and therefore getting the most of the plasma. Also the simplicity for heating it up, the possibilities for designing the temperature gradient and the implementation and effect of the cathode orifice. Overall, the hollow cylinder is just the most effective way for designing a state of the art hollow cathode.

Still, disk like emitters have also been reported in literature [10]. In addition to that, they are commonly used for single use hollow cathodes, in particular for plasma and particle sources in laboratory scale. The availability of such designs cannot be neglected.

The reasoning for using disk like emitters is diverse. First, disk emitters are much easier to manufacture. Second, the temperature gradient in the ceramic is expected to be much lower than for hollow cathode emitters (maximum material thickness of 2mm for the disk compared to the emitter length up to 10mm for the hollow cylinder). As the electride is still a ceramic, it is susceptible for too much stress like the one induced by thermal temperature gradients. Furthermore, if it comes to an overheating of the system and therefore the melting of partial areas of the surface, the hollow cylinder is prone to clog, much more than the disk shaped emitter.

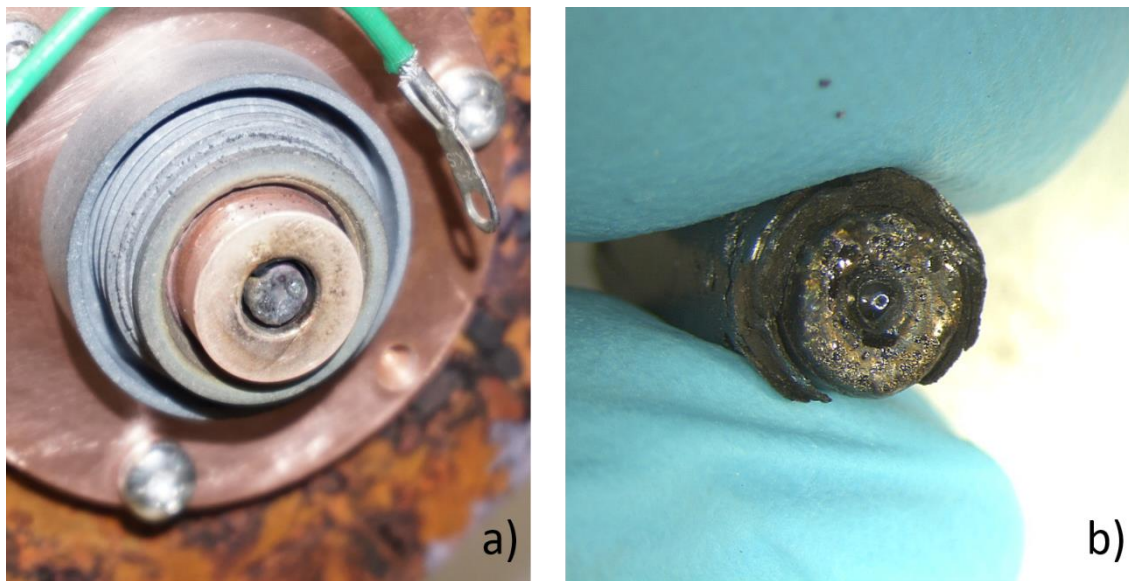


Figure 7.6-1 Hollow cylinder C12A7 electride insert with melted phases that resulted in a clogging of the emitter.

Especially the clogging of the hollow cylinder was reported several times again, as shown in Figure 7.6-1. Even though the discharge characteristics may be fine, such a clogging would be fatal for the operation of the hollow cathode. For the disk like emitters, a clogging from melting of the surface of the emitter is uncommon. Although melted surfaces have been identified several times (Figure 7.6-2), it never resulted into a clogging like with the hollow cylinder emitter geometries.

As one would expect, the clogging of the cathode becomes more severe for higher emission currents of the cathode. Due to the higher current, the temperature of the emitter need to increase making it all the more susceptible for failure. During the 300 hour test with the hollow cylinder, the anode was only partial active and the current limit in the order of 0.2 A. During the 950 hour endurance test however, the emission current was set to 2 A. At such a current limit, the hollow cylinder did fail repeatedly.

However, one significant advantage of the hollow cylinder was the low mass flow rate used for operation. Operation has been achieved up to 2 sccm. Figure 7.6-3

Characteristic of Cathode with hollow cylinder with 5 sccm. This is significant below the mass flow rates achieved with the disk emitter (often in the order of 15 sccm to 20 sccm). At the same time, there are many more parameters that influence the mass flow rate of the system, like for instance the orifice size, the number of orifices, the distance between emitter and keeper, the used propellant and so on. In particular, the multi-orifice campaigns, described in section 4.4.5, seemed to be quite promising concerning the reduction of mass flow rate for the planar hollow cathode design.

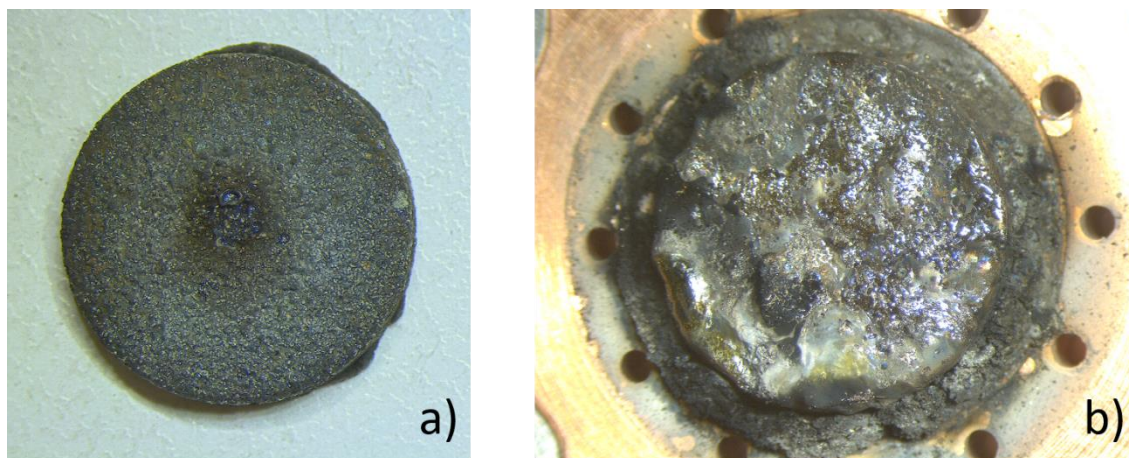


Figure 7.6-2 Different disk samples after operation in hollow cathode emitter.

Overall, the safe operation of the hollow cathode has a much higher priority for us than the parametric values as of right now. In particular since the focus was more on design of a cathode operating at higher emission currents, as required by the plasma thrusters for space propulsion. It may be good practice, to keep the hollow cylinder design in mind and revisit its performance once the performance as well as the corresponding electronics have been optimized, and the ideal composition of the material has been found. As of now, the tablet insert will be the baseline for any further tests at our institute.

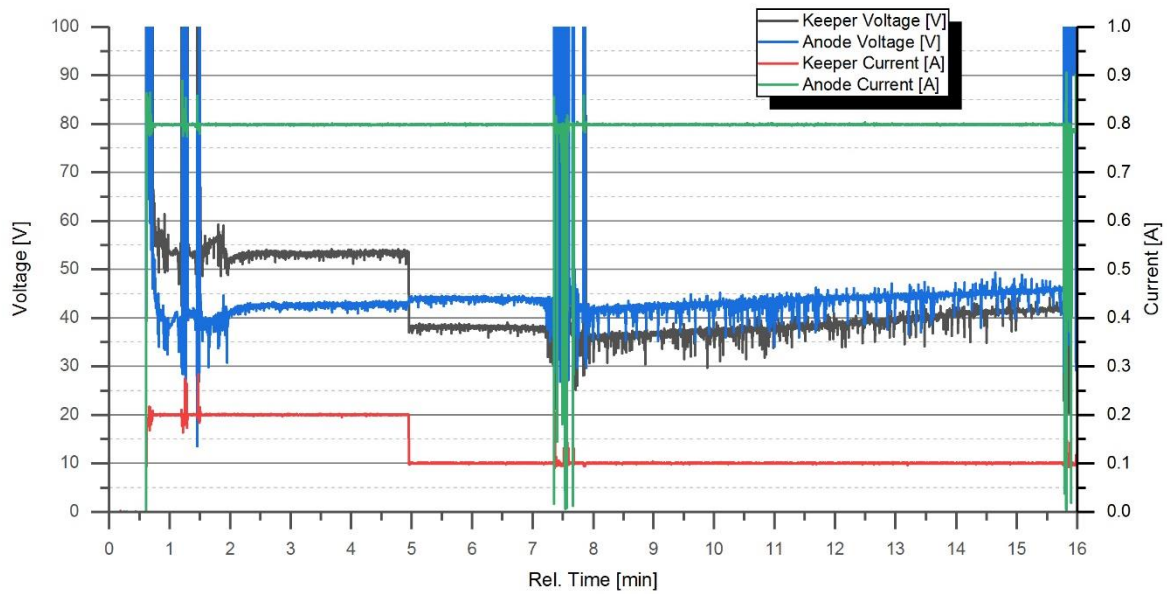


Figure 7.6-3 Characteristic of Cathode with hollow cylinder with 5 sccm.



9 SUMMARY

Over the course of the project, a heaterless C12A7 electride hollow cathode has been developed and significantly matured. Starting from instable operation conditions of several seconds to few minutes, we reached a maturity of the system that allows stable and reliable ignition, continuous operation for hours, variation of discharge parameters over a wide range and joint operation with plasma thrusters.

In joint development with our partner, the Fraunhofer IKTS, the C12A7 electride has been optimized to a point, where we have great material parameters for electron emission. The addition of molybdenum as well as titanium additives was a first in literature and a significant improvement for the cathode operation. Numerous material characteristics have been measured and discussed accordingly (section 2). In addition to that, a dedicated setup to measure thermionic emission was developed and used successfully to verify the work function of the material (2.4 eV – 2.8 eV).

The design of the hollow cathode has been improved continuously, reaching a modular setup that allows very fast and easy modification of parameters. The setup utilizes disk like inserts that allow higher emission currents while ensuring safe operation for the entire lifetime of the cathode.

A lot of experience was gained operating the system, reaching a point, where the system can be ignited immediately and very reliably and operate stable for hundreds of hours continuously. Most importantly, we have been able to achieve a 950 hours endurance test of the C12A7 electride hollow cathode at 2 A discharge current. The test was terminated not due to problems with the cathode, but due to the lack of krypton expellant. There was no indication that the cathode would not have been able to operate further. Again, this test is a huge milestone in the development of the cathode.

At the same time, the temperature during the endurance test was even with the further reduced setup only around 100°C, which is much lower than reported for any state of the art cathode. This again shows the huge potential of the emitter material for electron emission, even though work function measurements based on thermionic emission in a diode configuration do not seem to be supporting the initially low work functions that have been reported.



The C12A7 electride hollow cathode has been operated successfully with the Hall-effect thruster TUD-H3-P at our institute. A test campaign with the next iteration, TUD-H4-MS did only fail due to severe flaws in the thruster design. At the same time, the cathode was operated at UCLA, but a joint operation with the MiXI thruster was not successful at this time. The miniaturization of the cathode has to be improved here.

Overall, all the major tasks defined in the work packages have been fulfilled. Further tests with other plasma thrusters could not be done due to the unfortunate travel restriction during the COVID-19 pandemic. Testing with other thruster systems in the near future could be opportunity to display the maturity of the system.

In addition to tests with other plasma sources, the development of the cathode could be continued. Significant insight was gained concerning the influence of the electronics on the performance and stability of the plasma discharge. The development of a dedicated power electronics could be very beneficial. This could potentially also improve the plasma stability, which was a major concern in the experiments during the project.

The latest work function tests showed great performances of the C12A7 electride being doped with titanium. Using this material in a hollow cathode was not yet feasible and could be quite intriguing. However, the manufacturing process of these samples is rather difficult due to the hazardous properties of the fine-grained titanium powder.

The major drawback of the tablet inserts is the high mass flow rate needed for stable operation. The reduction of the mass flow rate should be a major goal. One promising path could be the implementation of multi-orifices. First tests showed great potential for a reduction of the mass flow rate needed for operation. Since there are numerous parameters to play with, this could be quite an interesting parametric study.

In the end, a very promising C12A7 electride hollow cathode was designed, manufactured and tested, and should now be a baseline for further development.



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