Development of a C12A7 Electride Hollow Cathode and Joint Operation with a Plasma Thruster

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Abstract: **A hollow cathode using the low work function material emitter material C12A7 electride is being developed at the Institute of Aerospace Engineering at the Technische Universität Dresden. New design iteration of the cathode is presented with operational characteristics at hand. In particular, a cathode based on a disk like emitter is presented. Furthermore, the discharge behavior of the plasma was analyzed and the operation of the cathode adapted accordingly. Changing the electrical setup, significant improvements concerning the discharge stability could be made. Discharge currents up to 5A have been achieved. The ignition of the cathode and to the anode are much more reliable than before. For 1A discharge current, an equilibrium temperature of the cathode body of 100°C is reported. Finally, the cathode was successfully operated with the TUD-H3-P Hell-effect thruster for several hours of time.**

I.Introduction

WITH the increasing usage of electric propulsion systems to operate and navigate spacecraft in Orbit and beyond, the need for sufficient electron sources does increase, too. Some thruster systems like the most common used Hall-effect thruster and gridded ion thruster do need electron emitters in order to generate the operational plasma / supply free electrons and be able to operate. Another major task for the electron emitters is the neutralization of the charged ion beams of said thruster systems as well as to prevent the electrical charge up of spacecraft systems.

At the Institute of Aerospace Engineering at the Technische Universität Dresden a hollow cathode is being developed, featuring the low work function material C12A7 electride. Initial reports from literature suggested an extremely low work function[1,2], encouraging the development of a cathode operating at much lower temperature. However, more recent measurements rather support a value in the range of 2.4 eV to 2.8 eV[3], being similar to state of the art materials.

Still, operational characteristics of the cathode can be promising. The cathode was heaterless ignited and did operate for more than 300 hours with little shown degradation effects. Furthermore, the temperature of the cathode body during that time did pan in the order of 150°C, speaking for very low operational temperatures of the material[4].

In the following chapters, the most recent advances in the development of a C12A7 electride cathode are presented, including improved setups and stability analysis and corresponding improvements in the cathode setup and operations. In addition to that, initial experiments with disk like emitters have been made with results presented. Finally, operational characteristics of the cathode with the institutes Hall-effect thruster will be presented.

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II.C12A7 Analyze the Hollow Cathode Discharge using an Oscilloscope

After achieving more than 300 hours of operation with one singe C12A7 electride insert, as previously reported at Ref. 4, the main concern in the development of the cathode was the reliability and stability of the discharge. Therefore, the design of the cathode was optimized with lessons learned from the previous iterations. After successfully achieving a plasma discharge with the new design, measurements using an oscilloscope were made in order to determine the plasma behavior during the discharge.

A. Improved Cathode setup

A number of major changes were implemented into a new design of the cathode. First, the design of the keeper was thoroughly reworked. It is now easily mounted on the isolators (screwed) and can be contacted using a lug. The insulation of the keeper itself is made of the machinable ceramic *Rescor 902*, allowing an easy and reliant manufacturing. Undercuts at the circumference of the ceramic allow for the prevention of buildups and therefore the appearance of leakage currents.

The general idea of the cathode is still to get rid of excess heat from the emitter insert. Therefore, the cathode body is made of copper, utilizing its great thermal and electrical conductivity. Furthermore, great cross sections and small distances are used, to reduce temperature gradients in the cathode.

The last major point that will be discussed here is the availability of the temperature measurement. A small hole was drilled into the cathode body just beside the insert, allowing for a temperature measurement close to the tip of the cathode. This should give a better understanding towards the actual temperature at the insert, even though in actual temperature at the electron emitting area is still amiss.

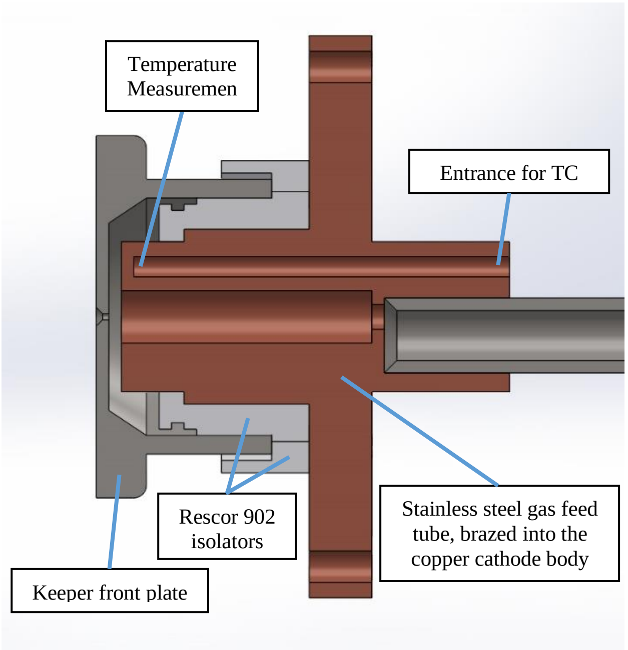

Figure 1. Hollow Cathode Design. *Design of the hollow cathode, optimized for even temperature distribution and easy manufacturing and assembly. A small hole besides the central axis of the copper body allows thermocouple measurements at the tip of the cathode body.*

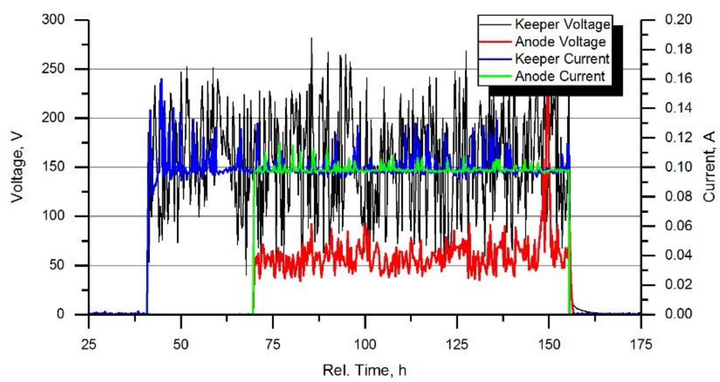

Figure 2. Initial Characteristic of Cathode operation. *Voltage and Current at Keeper and Anode over time for an initial operation. Power supplies operate at set current limits, but voltages significantly fluctuate.*

B. Initial Cathode operation

First tests of the cathode were conducted using a standard diode setup to operate the cathode. Here, the insert was grounded and both the keeper and the anode were connected to their respective power supply, with pre-resistors added in between. For operation, krypton was used as propellant. Successful ignition was achieved at 1 sccm to 5 sccm mass flow rate and at voltages below 400 V. For initial operation, the current limit was set to 0.1 A. In general, the ignition behavior was immediate and reliable, meaning that the power supplies did reach the current limit always right away. Unfortunately, the voltages at the electrodes did fluctuate significantly, as can be seen in Fig. 2. This kind of fluctuation is in contrast to previously reported characteristics of operation.

C. Measurements using an oscilloscope

After first initial results with the new setup, measurements with an oscilloscope were planned to improve the understanding of plasma behavior during discharge as well as the enormous oscillations in the keeper and anode voltages respectively. 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 Fig. 3.

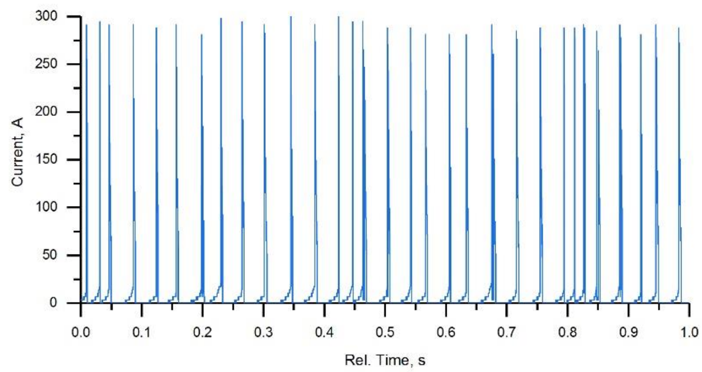

Figure 3. Plasma Stability using Oscilloscope. *Voltage over the pre-resistor at the keeper, being in direct correlation to the emission current flowing. Sharp peaks from 0 V to about 300 V indicate more of an On/Off behavior than a continuous discharge.*

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 over and over again, 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.

D. Electrical Setup

Analyzing the discharge behavior of the cathode it got apparent, that the power supplies seem to be incapable of operating the cathode from ignition continuously. Still, at some points stable discharges with voltages in the order of 50 V to 80 V were observed. Therefore, the electrical setup was improved as can be seen in Fig. 4. Here, there electron emitter insert was biased negatively, while the Keeper and Anode both could be set at a positive voltage. After igniting the discharge, the power supplies at keeper and anode respectively would not be able to extinguish the discharge, which would now be controlled by the bias power supply. For the power supplies, *Delta Electronika SM660-AR-11* were used for each of the electrodes.

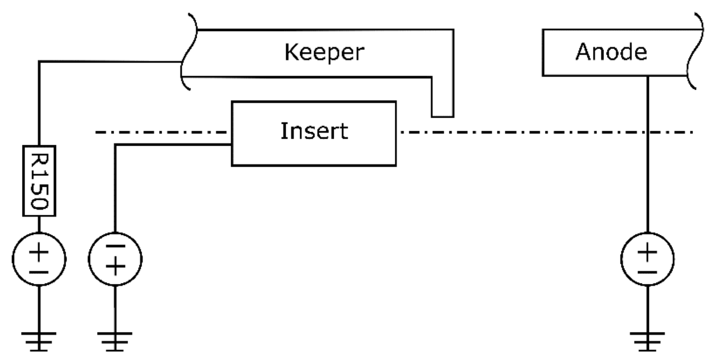

Figure 4. Alternative electrical Setup. *Electrical Setup for Cathode operation with the possibility to negatively bias the emitter insert.*

E. Initial operation of new electrical 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 a characteristic can be seen in Fig. 5. 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 Fig. 5, 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.

The difference in current at keeper and anode is purely defined by the size of the pre-resistor. 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 Fig. 5, the keeper pre-resistor was at 150 Ω and 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-resistor will be able 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.

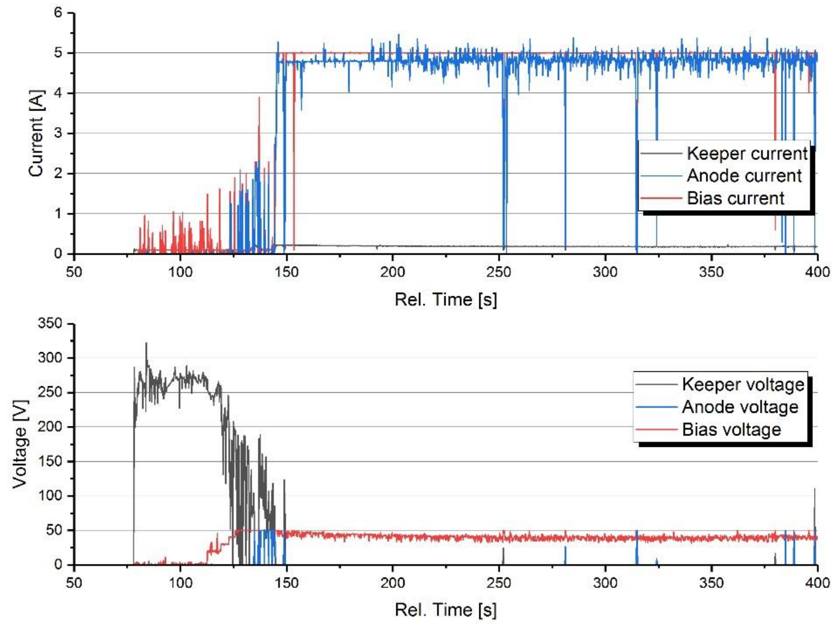

Figure 5. Initial Operation with 5 A emission current. *Characteristic of cathode emitting at about 5 A, whereof 4.8 A reach the anode. Both voltages at keeper and anode at zero, discharge only controlled by the bias power supply.*

Emission current up to 5 A have been achieved in stable operation. However, after about six minutes of operation at this current limit, the anode started to glow, indicating an overheating of this part of the setup. 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.

III. C12A7 Electride Disk Hollow Cathode Design

One of the major drawback of operating the C12A7 electride in a hollow cathode setup is, that at one point the insert would most often been melted, failing operation. Still, emission currents could be achieved most of the time. Therefore, it was decided to test the cathode with a disk like emitter. 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. Second, no great temperature gradient is expected for the tablet emitter, as for the hollow cylinder insert, which will not lead to thermal stress inside the emitter material. 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 oh cathodes using a tablet / disk as emitter[5].

F. Disk Emitter Design

The following will describe the design of the cathode featuring a disk as electron emitter. 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. The general design of the cathode in sectional view can be seen in Fig. 6.

Like with previous designs used to operate the C12A7 electride as emitter material, the major objective of the design is to have a highly thermally conductive base to get rid of excessive heat from the emitter insert. A radiator is added, to reduce the temperature of the cathode by radiation. The keeper is insulated using the machinable ceramic *Rescor 902*, allowing for an easy setup of the cathode. The keeper itself has a small orifice in the order of 0.5 mm and below, in order to increase the pressure at the disk emitter and allow for an easy operation.

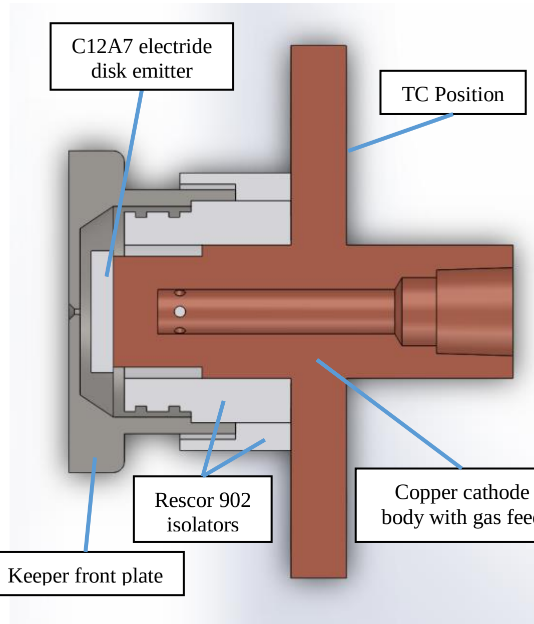

Figure 6. Hollow Cathode Disk Emitter Design. *Design featuring a disk emitter for electron emission in sectional view.*

G. Disk Emitter Characteristic

The electrical setup with the bias at the emitter was used to operate the hollow cathode at 5 sccm of krypton. The discharge behaved just as expected: The ignition was instant and very reliable, after adding the bias the voltages at keeper and anode dropped to zero and the discharge itself was very stable. The discharge itself did have some interruptions itself, why the cathode was tested at an inflated mass flow rate. Still, the system operated stable and reached a thermal equilibrium. The corresponding characteristic can be seen in Fig. 7.

The cathode operated with 0.75 A reaching the anode and 0.1 A the keeper for more than 2 hours stable. During this time, the bias was at the set 1 A current limit and about 30 V. The missing currents is flowing at the chamber facility. The temperature of the cathode for this discharge saturated at around 100°C. Even though the temperature was not measured at the electron emitting surface itself, this still is a great value for the overall temperature of the cathode. No significant gradient is expected inside the copper cathode body. If so, only inside the insert itself.

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 (order of 0.2 V oscillations) 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.

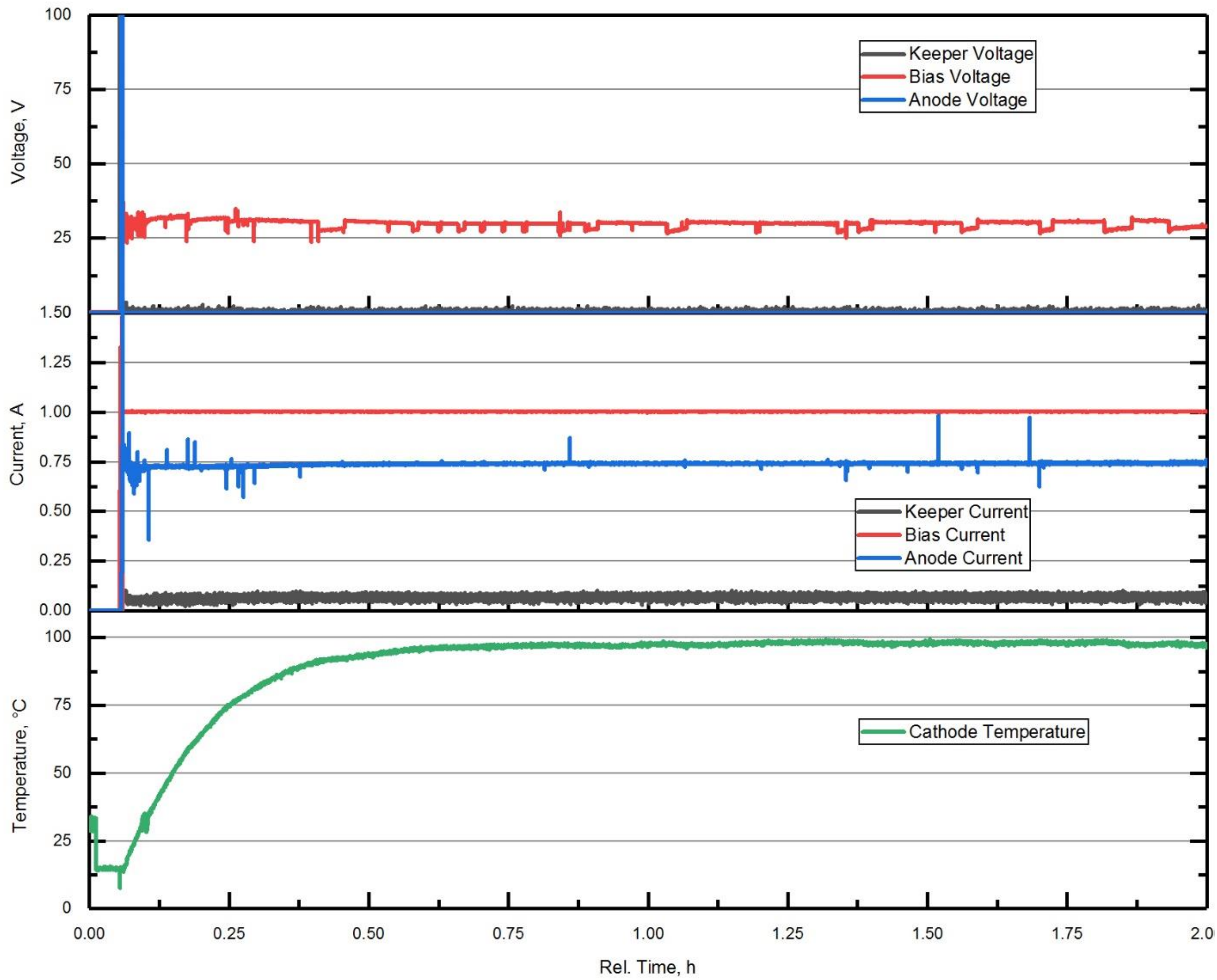

Figure 7. Hollow Cathode Disk Emitter Characteristic. *Voltage and Current Characteristic of hollow cathode with C12A7 electride disk emitters for about 2 hours. Temperature reach equilibrium at about 100°C.*

H. Conclusion of Hollow Cathode Development

Overall, the stability of the hollow cathode discharge was increased significantly. After achieving more than 300 hours and having stable ignitions and discharges really supports the usage of C12A7 electride as hollow cathode electron emitters.

The two major points that were changed are the electrical setup of the cathode and the usage of a disk emitter. Using the disk emitter has advantages concerning the manufacturing of the emitter material and the thermal uniformity across the emitter itself. Furthermore, there could be a potentially bigger emitting area improving the performance of the cathode. At the same time, challenges concerning the design of the cathode arise. How will the tablet be held in the cathode? What plasma interaction will occur with the cathode keeper? Just to name two of the most intrusive points. Still, such a cathode seems to be good alternative to state of the art hollow cylinder cathodes.

Changing the electrical setup of the cathode to operate with the bias at the emitter was significant, as the power supplies seemed not able to get from the repeated ignitions to stable operation regimes. The high ignition currents do need to be respected. Either way, the low voltage regimes as well as the easy control once ignited support to capability of using C12A7 electride as emitter material in hollow cathodes.

IV. C12A7 Electride Hollow Cathode with TUD-H3-P Hall-effect Thruster

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-SiO2) and uses permanent magnets to establish the magnetic field. During the test series, the current ranged from approximately 0.5 A up to 1.6 A, where the cathode should be operate sufficiently. The thruster will be presented at a corresponding paper at this conference[6].

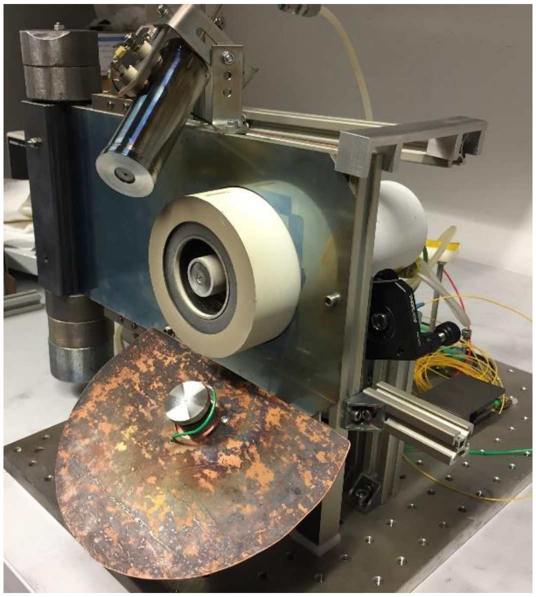

Figure 8. Cathode and thruster on thrust balance. *Setup for thruster and cathode (below) at the compact torsional thrust balance for testing.*

I. Joint Operation

Both thruster and cathode were mounted at a compact thrust pendulum stand that was developed at the institute[7]. The cathode itself was positioned slightly below the thruster, as can be seen in Fig. 8. The goal of the test was the verification of the joint operation of both systems.

For the Operation, krypton was used as propellant. After ignition of the cathode, the thruster did operate stable immediately. Adjusting the currents, voltages and mass flow of the thruster as known from previous tests, the thruster was set into a focused mode, as can be seen in Fig. 9. Here, the best characteristic of the thruster can be expected. The cathode did operate just fine through all the different operational conditions of the thruster.

Significant insight was achieved into the operation and stability of the discharge when varying the bias potential at the cathode operation. As also seen in Fig. 10, there is a significant noise at the thruster anode discharge. When reducing the bias current limit, this noise was reduced, too. Actually, at some point the bias voltage even collapsed while a very small keeper voltage appeared. At this point, the power needed to operate the system was reduced significantly, optimizing the characteristics of the thruster and cathode discharge. In general, this shows that there has to be a careful evaluation, how to optimal operate the cathode, depending on the current and voltage supply at hand,

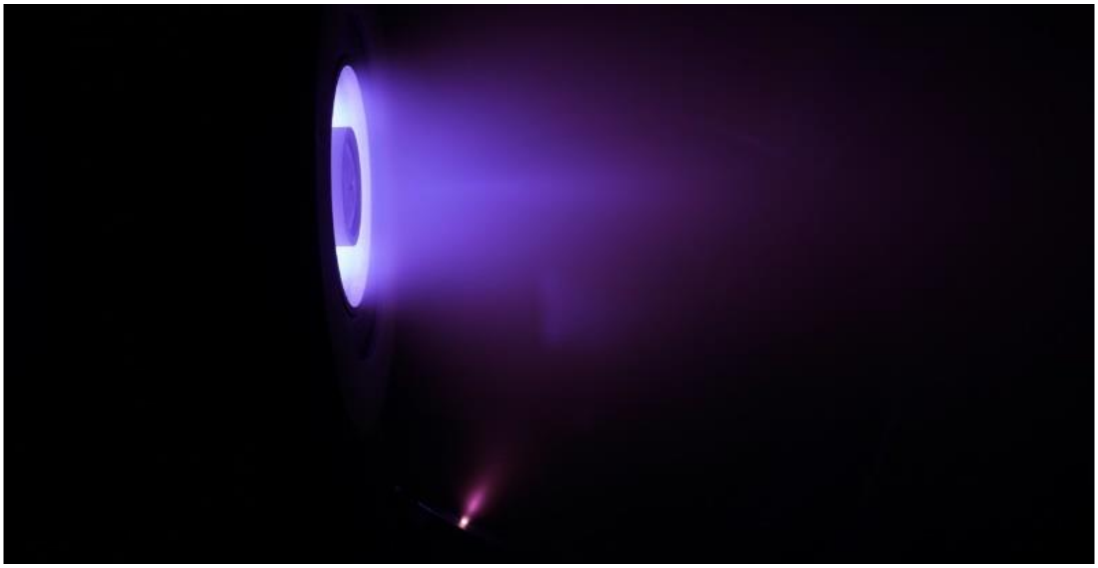

Figure 9. Joint operation of cathode and thruster. *TUD-H3-P Hall-effect thruster operating with the C12A7 electride hollow cathode.*

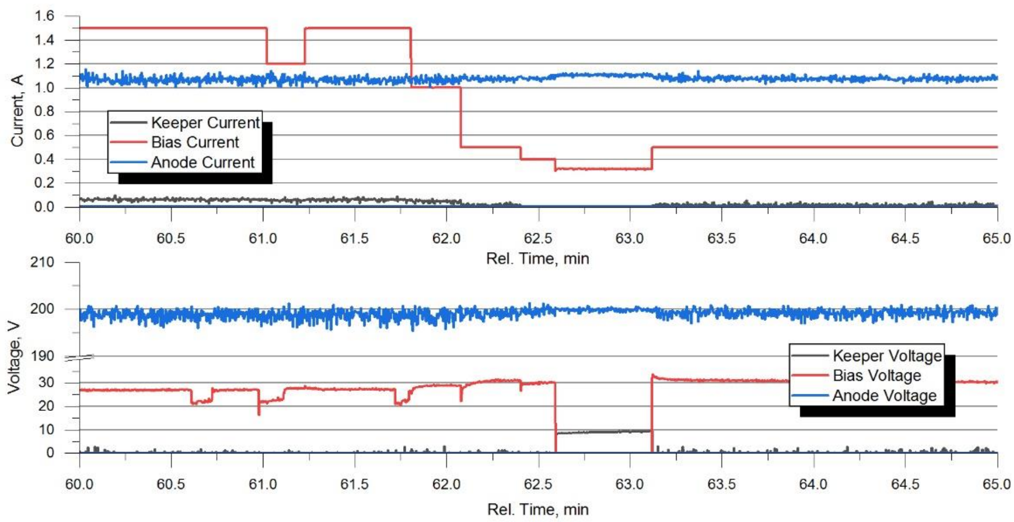

Figure 10. Characteristic of joint operation of cathode and thruster. *Voltage and current for cathode and thruster with different bias current limits, showing the influence of cathode operational condition and thruster stability.*

the thruster system operated with or the neutralization approach targeted to. The cathode showed good operational conditions at a number of these applications.

V.Conclusion

The present paper detailed the most recent advances in the development of the C12A7 electride hollow cathode. Stable discharge has been achieved for currents up to 5 A, but improvements concerning the test-setup have to be made, especially concerning the thermal stability of the anode, to continue testing at such high emission currents. With the new disk like setup, very stable discharge characteristics have been achieved with overall cathode temperatures in the order of 100°C, which would be very low for comparable electron emitting systems. Finally, operational characteristics of the cathode with the TUD-H3-P Hall-effect thruster have been presented. Both systems operated perfectly together for several hours and a long duration testing of both systems will be conducted soon.

Acknowledgments

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