Status of the THALES Tungsten/Osmium Mixed-Metal Hollow Cathode Neutralizer Development

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Abstract: HKN 5000 hollow cathode neutralizers developed by THALES Electron Devices GmbH are based on a Tungsten/Osmium W/Os mixed metal cathode impregnated with Barium Calcium Aluminate as electron emitter. This cathode technology has a reduced work function and allows for reduced cathode temperatures and increased lifetimes compared to conventional Tungsten based cathodes. Being used as cathode material for the electron gun of Traveling Wave Tubes TWTs for satellite application, the THALES W/Os cathode technology has demonstrated more than 200 millions of successful operational hours in space. HKN 5000 neutralizers, which are being developed under support of German Space Agency DLR, are designed to deliver neutralizing currents of up to 5 A for ion thrusters, in particular for THALES High Efficiency Multi Stage Plasma Thrusters (HEMP-Ts). HKN 5000 breadboard (BB) models have shown very good performance with respect to low power and propellant consumption. Recently, HKN 5000 elegant breadboard (EBB) models have been developed, which are exclusively based on space-qualified manufacturing technologies derived from TWT production. This paper reviews the physics and technology of the THALES W/Os based hollow cathode neutralizers and presents operational and performance characteristics of the HKN 5000 BB and EBB models.

I. Introduction

THALES Electron Devices TED is currently developing an ion propulsion system based on its own developed High Efficiency Multistage Thruster (HEMP-T) and Hollow Cathode Neutralizer (HKN) technologies for small to large telecommunication satellites and scientific missions. This so-called HEMP Thruster Assembly (HTA) consists of several HEMP Thruster Modules (HTMs), each of which includes, amongst other components, a HEMP 3050 thruster and a HKN 5000 neutralizer to provide current-equivalent neutralization of the emitted propulsive ion beam[1].

TED has started its hollow cathode neutralizer development for the HEMP-T based propulsion system in 2002 in course of a program supported by German Space Agency DLR. Neutralizer development was on the one hand motivated by TED's previous fruitful works in co-operation with University of Giessen for Astrium-ST's RIT 10 ion propulsion system for the EURECA mission[2,3]. In addition, TED's Traveling Wave Tube (TWT) long-life space-qualified cathode technology based on a Tungsten/Osmium W/Os Mixed-Metal matrix impegrated with Barium Calcium Aluminate has been considered an optimum basis for being applied as emissive insert of a hollow cathode neutralizer. This is because of its reduced work function compared to a pure tungsten insert and because of its

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robustness and reliability proven throughout an impressive flight heritage in TWT electron guns of more than 200 million hours in space.

HKN 5000 neutralizers have been developed to breadboard (BB) and, since recently, to elegant breadboard model (EBB) level. The main cathode technological and neutralizer operational properties have been investigated in detail for HKN 5000 BB. HKN5000 EBB incorporates exclusively space-qualified material processing and production technologies as for TED's TWTs and is therefore an ideal basis for later engineering and qualification models.

This paper is divided in 5 chapters. In chapter 2, the neutralizer operational principle and technology are briefly reviewed, chapter 3 and 4 summarize the development status of HKN 5000 BB and EBB, and in chapter 5, a summary and outlook to future activities is given.

II. Neutralizer Operational Principle and Technology

A. Operational Principle

The operational principle of a hollow cathode neutralizer is shown schematically in figure 1. A discharge is ignited between a heated electron emitter insert through which the working gas (typically Xenon propellant) is passed and a so-called keeper. The emitter insert, which is terminated by a front plate with a small orifice, acts as hollow cathode, the low work function of which allows sustaining a high current discharge with a low voltage drop U_K to the keeper. This is due to a significant electron current contribution throughout Xenon ionization compared to solely thermal electron emission and due to the large positive ionic space charge such that electron current is drawn from a practically space-charge neutralized situation. Electrons for ion beam neutralization are drifting through the keeper bore to the positive space charge formed by the thruster ion beam, or, for testing issues, to an anode. In order to draw a given electron current drawn from the cathode, a so-called coupling voltage U_C is needed. U_C denotes the difference in electrical potential which adjusts self-consistently between the cathode and the anode or, when the ion propulsion system is operated in space or in floating configuration, between the cathode and the thruster housing, respectively. Since ion beam neutralization represents a loss mechanism for an ion propulsion system with respect to Xenon propellant and electrical power consumption, the main development goals are to minimize these losses and to assure full reliability over the entire life time and the number of cycles required. In addition, a calm discharge operation without strong current oscillations is mandatory. The following issues contribute to discharge stability, neutralizer efficiency and life time:

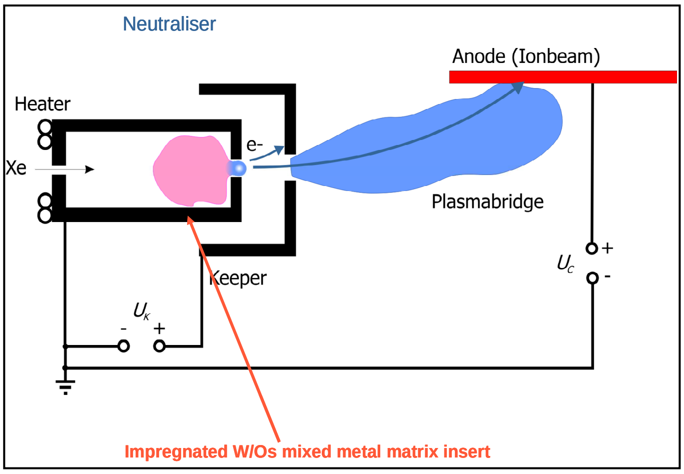

Figure 1: Schematic view of the operational principle of a hollow cathode neutralizer.

(i.) Insert and orifice disk properties: the higher the electron emissivity, the lower both the keeper and the coupling voltage and hence the power consumption[†]. For low voltages of typically below 15V for U_K and 20V for U_C, ionization is concentrated in the orifice and the front part of the hollow

[†] This is the case provided the cathode is self-heated by the discharge and there is no need of excessive cathode heater power.

cathode. Under this conditions, the neutralizer operates calmly in the so-called spot mode with a minimum of discharge current oscillations. In case the voltage drop increases, the ionisation front propagates outside the orifice towards the keeper. This leads to the so-called plume mode, which is characterized by high discharge current oscillations that can cause thruster instabilities and an interference with telecommunication signals of the satellite. In addition, high voltage drops above 17V cause Xenon ions impinging the cathode surfaces to deterioate the cathode due to sputtering reactions.

(ii.) Xenon gas flow and neutral gas density: the desired spot mode operation typically is facilitated at higher Xenon gas densities, i.e., at a higher Xenon gas consumption. Therefore, insert, orifice and keeper geometries, which determine the neutral gas distribution for a given gas flow, strongly influence both gas and electrical power consumption.

(iii.) Plasma properties in the plasma bridge region: the higher the density of slow ions in the plasma bridge region, the lower is the impedance for neutralizer electrons to reach the anode or to neutralize the thruster ion beam, respectively. This reduces the coupling voltage and hence the electrical power consumption. Higher neutral gas density is caused by a high gas flow through the neutralizer, which reduces the specific impulse of the ion propulsion system, however. Also insufficient pumping speed of the test environment leads to an artificial lowering of the coupling voltage and hence to an over-estimate of neutralizer performance. Typically neutralizer operation in vicinity of the thruster yields better performance due to the presence of slow charge-exchange ions at the thruster exit.

B. Cathode Physics and technology

TED's cathode technology incorporates a W/Os (70%/30%) matrix which is impregnated with Barium Calcium Aluminates in the molar ratio mixture of 5.6:2:1. At higher temperatures, Barium is evaporated and forms a Barium Oxide BaO dipole in front of the W/Os surface. As a consequence, a high electrical field is built up which facilitates electron emission due to a lowering of the Fermi level. This effectively lowers the work function. A comparison of the BaO orientation for different metal surfaces is given in figure 2. Lowest Fermi levels are obtained for Osmium, Iridium or Ruthenium surfaces, and the Fermi level is slightly increased in case of pure tungsten. For Platinum and other catalyst metals electron emission is strongly hindered, which means that Platinum contamination on a cathode surface would poison the cathode.

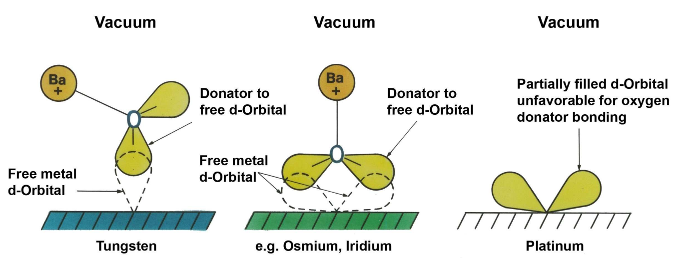

Figure 2: Orientation of the BaO dipole with respect to different metallic surfaces.

For continuous Barium evaporation via diffusion of the Ba-Ca-Aluminates to the cathode surface, a porous cathode body is needed, which is difficult to manufacture from Osmium, Iridium or Ruthenium. As an alternative, a porous Tungsten body can be coated with these favorable surfaces, but operation at high cathode temperature would lead to diffusion of the coating into the Tungsten body. Therefore, TED has developed a process to produce a mixed-metal W/Os porous cathode body with a relative mass ratio of 70%(W) to 30%(Os). As a result, the work function is lowered from 2.08eV in case of a pure Tungsten body to 1.98eV[‡]. This reduction of 0.1eV yields a reduction in cathode temperature of about 50K for the electron current density drawn from the cathode and a respective increase in cathode life time by a factor of 3.3. A detailed overview on life time considerations is given in reference[3].

‡ For comparison: a thoriated tungsten surface has a work function of about 3eV.

III. HKN 5000 BB

A. Design and production status

HKN 5000 BB is a breadboard model developed under support of German Space Agency DLR contract 50JR0342. The design goal was a neutralizing current up to 5A at minimum Xenon gas and electrical power consumption. In the framework of the project, 6 BB models have been set up and characterized. A drawing of HKN 5000 BB is given in figure 3.

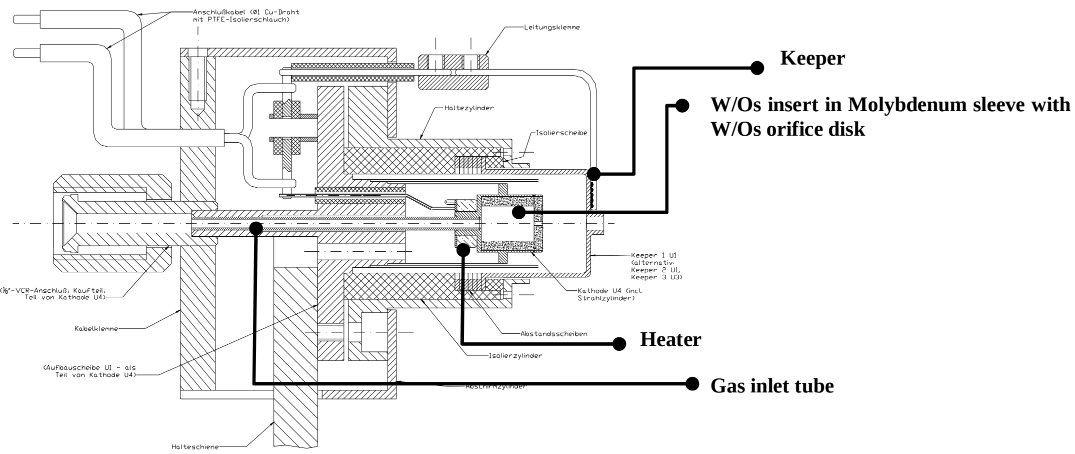

Figure 3: Drawing of HKN 5000 BB. The dimensions are not to scale.

The cathode of HKN 5000 BB is composed of an insert and an orifice disk, both made of an impregnated W/Os body imbedded in a Molybdenum sleeve. The inner diameter of the insert is 4mm, the thickness of the orifice plate is 0.5mm and the orifice diameter is 0.25mm. The latest HKN 5000 breadboard model, EBB-6, was equipped with a 1mm thick orifice plate for life time considerations[3]. Using the same low work function material for the orifice plate as for the insert, a low discharge ignition voltage is expected. In addition, in case the orifice plate surface was sputtered by ion impingement, the continuous Barium diffusion to the surface would maintain the emissive properties. The cathode is heated from the rear side by means of a space-qualified heater element derived from one of TED's TWT product lines. The 156µm thick heater wire is made from Tungsten-Rhenium. It is coated by alumina and imbedded with alumina paste into a coaxially shaped containment made from Molybdenum. The heater element is brazed to the Molybdenum sleeve of the cathode body. The gas inlet tube, which feeds Xenon to the hollow cathode is also made from Molybdenum and brazed to the cathode body sleeve. The connection to the gas feed system is made by means of a commercial 1/8"-VCR connector. The cathode is fixed to a central mounting disk through a thin walled 37µm thick cylinder made from Molybdenum-Rhenium. This assures minimum heat transport to the mounting disk and high mechanical stability. Two additional radiation shields made from Tantalum minimize radial heat transport from the cathode. The keeper assembly is screwed to the central mounting disk. It allows for variable positioning of the keeper to adjust an optimum distance to the cathode and to exchange keeper geometry. The keeper assembly design is not based on space-qualified technologies. In the BB design, the cathode is fixed to the ground potential of the neutralizer housing.

C. Operational and Performance Characteristics

6 HKN 5000 BB models have been set up with variations in cathode and keeper geometry and have been characterized in different testing environments. Tests were first performed in TED's neutralizer test stand, a 400mm diameter vacuum chamber with an effective pumping speed for Xenon of about 2,000l/s provided by means of a turbo molecular and a cryo pump. The testing set-up is shown schematically in figure 1 with an anode representing

the thruster ion beam. In figure 4, a photograph of HKN 5000 EBB-1 is shown while operated in triode-mode where the electron current is drawn to the anode.

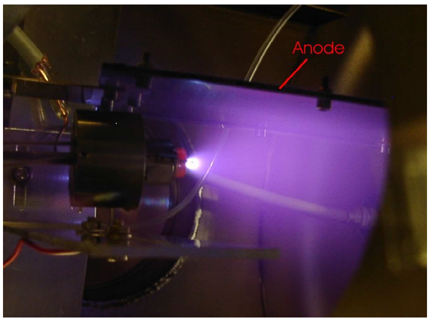

Figure 4: HKN 5000 EBB-1 operating in triode-mode in TED's neutralizer test stand.

It can be seen that the keeper is slightly glowing red due to the electronic power dissipation of the keeper discharge. The plasma bridge to the anode is characterized by a bluish light becoming bright towards the keeper bore.

HKN 5000 BB models were tested extensively in diode (keeper discharge only) and triode configuration and have been coupled to different thruster types. The main test campaigns and the performance characteristics results are listed in the following:

1. *Ignition properties:*

Typically, discharge ignition can be performed at voltages of as low as 12 to 15V, and it has been found that 30V represent a sufficient margin for safe ignition during cycling tests.

2. *Power consumption:*

HKN 5000 BB shows very low electrical power consumption: the heater power for cathode heating to emission temperature is about 27W. After discharge ignition the cathode is self heating via the keeper discharge with a typical power consumption of less than 30W.

3. *Gas consumption in diode mode:*

The gas consumption in diode mode for spot-mode operation is about 0.4sccm/A keeper current for currents above 1A.

4. *Gas consumption in triode mode:*

The gas consumption in triode mode in TED's neutralizer test stand for spot-mode operation is about 1.3 to 1.6sccm/A emission current to the anode for currents above 1A.

5. *Coupling test with RIT-22 grid ion thruster – comparison with state-of-the-art European neutralizer technology:*

A coupling test of HKN 5000 BB-4 with Astrium-ST's RIT-22 grid ion thruster was performed at Giessen University. The measurements essentially confirmed the values of gas and electrical power consumption obtained in TED's neutralizer test stand; however, coupling voltage was much lower presumably due to the presence of charge exchange ions at the thruster exit. Compared to the standard neutralizer used so far for the RIT-22 system, HKN 5000 BB-4 proved a relative reduction in gas consumption of up to 30%, which means an increase in specific impulse of the respective ion propulsion system of up to 5%. In addition, power savings of about 60W for the entire operational envelope of the thruster were observed. A photograph of HKN 5000 EBB-4 installed on the housing of RIT-22 and of neutralizer and thruster in operation is given in figure 5.

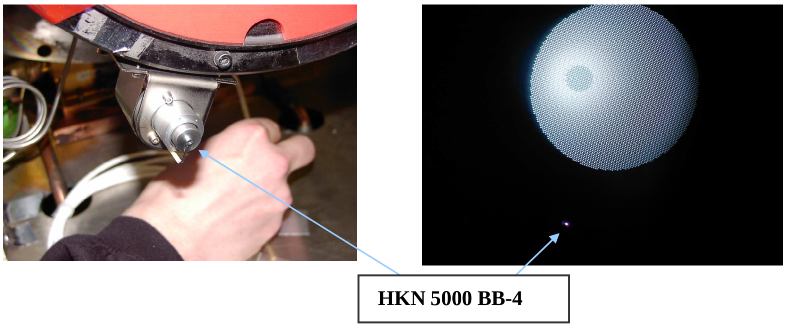

Figure 5: HKN 5000 BB-4 mounted on RIT-22 (left) and thruster and neutralizer in operation (right)

6. *Coupling tests with HEMP 3050 thrusters:*

Two coupling tests of HKN 5000 BB neutralizers have been performed, one with HKN 5000 BB-2 on HEMP-T 3050 DM7 for first short duration tests in floating configuration and one 250h endurance test with HKN 5000 BB-3 on HEMP-T 3050 DM8 in grounded configuration. The tests in floating mode showed a good compatibility with coupling voltages around 17V and a specific gas consumption of 1.5sccm/A neutralization current. The 250h endurance test showed very stable and reproducible neutralizer performance. A photograph of HKN 5000 BB-3 mounted on HEMP-T 3050 DM8 is given in figure 6.

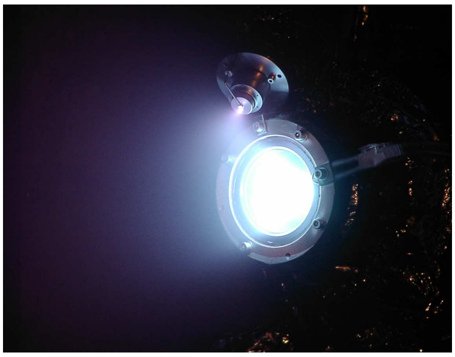

Figure 6: HKN 5000 BB-3 mounted on HEMP-T 3050 DM8 in operation during a 250h endurance test

7. Cycling tests:

Cycling tests have been performed with HKN 5000 BB-2 in TED's neutralizer test stand. The test sequence was as flows:

- 4,000 ignition cycles in diode mode operation
- 10,000 heater cycles
- 500 ignition cycles in diode mode operation
- 150h endurance test in triode configuration with 5A emission current to the anode

Although no degradation in neutralizer performance could be observed, a following destructive physical analysis (DPA) showed some technological problems which might affect long-term stability and life time.

8. Technology analysis:

A technology analysis was performed on all HKN 5000 BB models. It included X-ray examinations and a destructive physical analysis (DPA). Two main issues which were believed to have a negative influence on life time and reproducibility have been identified:

(1) Brittle material structure and partially cracks in the brazing joint at the gas inlet tube to the cathode body: these could lead to Xenon gas losses and increase neutralizer gas consumption with time.
(2) Gaps in the brazing joint from the heater to the cathode body: this could cause an undefined heat transition and a potential overheating of the heater element with time.
(3) Brittle and partially broken radiation shields caused by oxygen diffusion into the Tantalum.

As a result, a complete re-design of HKN 5000 BB has been performed towards an elegant breadboard model, HKN 5000 EBB, which addresses the technological issues and forms the basis for a HKN 5000 product line.

IV. HKN 5000 EBB

A. Design and Production status

HKN 5000 EBBs are elegant breadboard models developed under support of German Space Agency DLR contract 50JR0342. Their design serves as direct basis for further engineering and qualification models. The main design changes compared to HKN 5000 BB are listed in the following:

- Isolated mounting of cathode and gas inlet: this allows for mounting the neutralizer housing directly to the thruster housing being on satellite secondary star ground and to measure directly the neutralization current and the coupling voltage.
- Gas inlet tubing and heater body machined from one Molybdenum part to eliminate thermal stress.

- Implementation of a high temperature cycle proved bellows in the upstream end of the gas inlet tube to reduce thermo-mechanical stress.
- Increased thermal conductivity from the heater element to the cathode body and along the cathode body itself to minimize temperature gradients.
- Increased heater wire diameter of 200µm at slightly increased heater resistance to allow for higher heater powers to compensate for the increased cathode mass.
- Reduced thermal conductivity from the gas inlet tube to the central mounting disk to reduce heater power consumption.
- Radiation shields made from Tungsten-Rhenium which is not sensitive to air exposure as is Tantalum.
- All isolating joints are made from Alumina-to-Nickel-Cobalt-alloy junctions as in case of TED's space-qualified TWTs.
- All electrical connections are fed inside the neutralizer body to avoid short circuits during handling and to improve mechanical stability with respect to vibration and shock loads.
- Possibility to exchange the keeper to allow further optimization of keeper geometry and keeper-to-cathode distance.
- Possibility to vary cathode geometry on sub-assembly level.

Twenty part sets of the HKN 5000 EBB have been produced with the goal to set up 6 EBB models in total. The remaining parts and sub-assemblies are being used to perform technological studies such as, e.g., thermal cycling tests, studies of the heater stability or DPAs on the cathode assemblies.

So far, three HKN 5000 EBB assemblies have been set up: EBB-1 has an orifice diameter of 0.45mm, a thickness of the orifice plate of 1mm, a keeper-to-cathode distance of 2mm and a keeper bore of 3mm. The reason for the increase in both orifice and keeper bore diameter was to study in how far this configuration could yield lower gas consumption in triode mode operation compared to the BB models. EBB-2 incorporates the typical dimensions of the BB models and has an orifice diameter of 0.28mm, a keeper-to-cathode distance of 2mm, a keeper bore of 2mm, but a thickness of the orifice plate of 1mm. EBB-2 has an orifice diameter of 0.28mm with a conical edge downstream, the keeper properties will be fixed after the tests with EBB-1 and EBB-2 are accomplished.

D. Operational and Performance Characteristics

HKN 5000 EBB-1 has been characterized with respect to heater parameters, cathode emission behavior, performance characteristics in diode and triode configuration, degradation due to cathode poisoning effects and technological properties. At the time this paper has been written, coupling tests to the HEMP-T 3050 BB are being performed. In addition, EBB-2 has undergone a first activation and has been characterized with respect to its cathode emissive characteristics.

The test sequence performed on EBB-1 has been as follows:

1. *First activation and characterization of cathode emission properties:*

For this purpose, EBB-1 was first put in a glass diode evacuated on a pump stand with a base pressure of 10^{-10}mbar and baked at 350°C for 6h. Then the cathode was activated by continuously heating to 1200°C, which was kept for 2h. During that time, the keeper voltage was set to 25V to study the emissive properties. The emission current adopted a steady-state value of about 5mA, which is considered to correspond to full activation and which is by far sufficient for hollow cathode discharge ignition (typical limit: 0.2mA). A photograph of HKN 5000 EBB-1 in the glass diode is given in figure 7. In course of cathode activation, also the temperature of the orifice disk and inside the hollow cathode has been measured as function of the heater power by using a pyrometer. It has been observed that in order to reach 1200°C inside the hollow cathode a heater power of 21W is sufficient. For comparison, this value amounts 27W in case of the BB design. In addition, the temperature gradient between hollow cathode and orifice disk was only about 40K, whereas in the BB design, this was 60K.

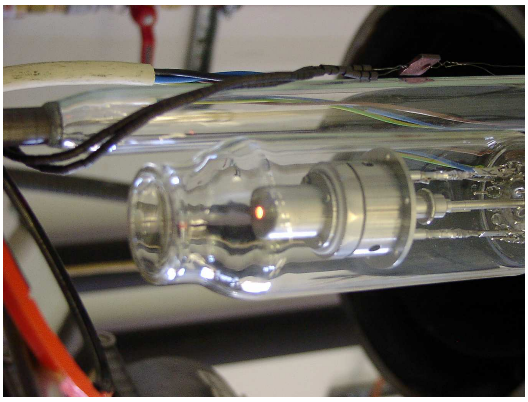

Figure 7: HKN 5000 EBB-1 in glass diode during first activation of the cathode. The glowing orifice disk can be seen through the keeper bore.

2. *Tests in the neutralizer test stand – basic characterization:*

Operating EBB-1 in diode configuration it was found, that, compared to the BB design, higher keeper currents had to be applied to keep the cathode in a self-heated mode with reasonable keeper voltages. However, in triode configuration, the keeper voltage was reduced and high emission currents to the anode (represented by the vacuum chamber – the cathode is biased negatively through the coupling voltage). Since HKN 5000 EBBs are to be optimized for operation with a HEMP-T 3050, nominal anode currents of 1 to 2A have been drawn. In this regime, the specific gas consumption is about 1sccm/A, which represents a clear reduction compared to the BB performance. Typical values for 1.3A emission current are a gas flow of 1.25sccm, a keeper voltage and current of 12.7V and 3.5A and a coupling voltage of 15.5V. Under these conditions, EBB-1 was operated very calm in the spot mode with a discharge current amplitude for both keeper and anode current of below 20mA. For further comparison with the BB performance, the anode current was set to 2.3A corresponding to the nominal working point of the RIT-22 thruster. Here, a gas consumption of 2.3sccm was needed compared to 3sccm with the BB model, which represents a relative improvement of 25%. However, the electrical power consumption with EBB-1 is much higher (92W compared to 49W). Nevertheless, for a high power, high specific impulse ion propulsion system with a nominal power of about 6kW, the reduction in neutralizer gas consumption is a much more important feature. In addition, operating EBB-1 in vicinity of RIT-22, an improvement in neutralizer efficiency can be expected due to the presence of charge exchange ions at the thruster exit.

3. *Tests in the neutralizer test stand – 250h endurance test:*

A 250h endurance test was performed at an anode current of 1.3A and a Xenon gas flow of 1.25sccm and a keeper current of 3.5A. Throughout the entire running time, the discharge operated completely stable in spot mode with variations in the keeper voltage from 12.6V to 12.8V and in the coupling voltage from 14.8V to 15.3V, respectively.

4. *Test inspection via X-ray examination:*

After the 250h endurance test, EBB-1 has been expected via X-ray examination. No degradation of the mechanical joints has been found.

5. *Cycling tests:*

A cycling test has been performed with 750 switching on cycles in diode mode to establish the conditions for reproducible and stable ignition. It has been found, that EBB1 ignited reliably throughout the entire test.

6. *Coupling tests to HEMP-T 3050 BB:*

At the time this paper is written, coupling tests with HEMP-T 3050 BB thruster are being prepared. Those will include optimization of neutralizer position and observation of long term stability and reproducibility.

7. *Exposure to air and re-activation*

During the tests performed so far EBB-1 has been exposed to air followed by re-activation of the cathode for 7 times. Though activation time got slightly prolonged (up to 3h for the latest activation compared to 2h for first activation), full cathode emission could be regained.

V. Summary and conclusions

THALES Electron Devices TED has started hollow cathode neutralizer development based on its W/Os mixed-metal cathode technology, which has demonstrated a large and successful space flight heritage applied in traveling wave tubes TWTs, and on experiences made through neutralizer development for the RIT-10 ion thruster system for the EURECA mission. In course of a study supported by German Space Agency DLR, HKN 5000 neutralizer models have been developed, produced and characterized on breadboard BB and elegant breadboard EBB level.

HKN 5000 BB models exhibit very low power and moderate gas consumptions. In comparison with the neutralizer used for Astrium-ST's RIT-22 ion thruster, HKN 5000 BB would lead to a clear improvement in propulsion system efficiency. Since recently, HKN 5000 EBB models have been developed and manufactured, and are currently being characterized in different testing configurations. EBB models are based exclusively on space-qualified material and manufacturing processes derived from TED's TWT production and represent the basis for further engineering and qualification models. First tests on EBB-1 show a further reduction in gas consumption, but an increase in electrical power needs. Current efforts are directed towards an optimized adaptation of HKN 5000 EBB models to HEMP-T 3050 thruster models and towards a further improvement in neutralizer efficiency.

Acknowledgements

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