DEVELOPMENT & TEST STATUS OF THE THALES W/OS MIXED METAL MATRIX HOLLOW CATHODE NEUTRALISER HKN5000

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Abstract: Based on well proven W/Os mixed metal matrix cathode technology for long life space Travelling Wave Tubes, Thales developed a low power hollow cathode neutraliser, HKN5000, providing nominally up to 5A neutralisation current to the ion beam. Made of bulk tungsten/osmium material the cathode is less sensitive to sputtering than a M-type cathode and provides lower work function and thus lower operational temperatures and power requirements compared to standard B-type dispenser hollow cathodes. Two unique features could be verified:

- Ignition starts at keeper operating voltage around 10V (no additional 200V to 300V ignition power supply required).

- Total power consumption (heater-, keeper- and coupling power) measured with a RIT 22 thruster of EADS-ST for 2.5 A neutralisation current was only 40 W at 3 sccm Xe cathode flow.

Nomenclature

Ba/Ca/Al	=	Barium Calcium Aluminates in the 5.6:2:1 molar ratio mixture, respectively
BB	=	Breadboard
$°C_b$	=	Centigrade brightness
HEMP	=	High Efficiency Multistage Plasma thruster
HKN	=	Hollow cathode neutraliser
Φ	=	Cathode electron emission workfunction
TWTA	=	Traveling Wave Tube Amplifier
TEDG	=	Thales Electron Devices GmbH, Söflingerstr. 100, Ulm, Germany
W/Os	=	70% Tungsten / 30% Osmium powder mixed and sintered porous cathode material
Uk	=	Keeper voltage
Uc	=	Coupling voltage

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I. Thales Background in Hollow Cathode Neutralisers

THIRTY years ago, Thales Electron Devices GmbH Ulm, Germany, formerly AEG-Telefunken, developed with the University of Giessen [1] and the RIT 10 thruster group of EADS-ST (formerly MBB) a dispenser hollow cathode neutraliser for the RIT 10 ion thruster. Though working already at that time with good results on a neutraliser using impregnated tungsten dispenser cathode material for the front cathode disk, the selected approach used the more standard thoriated tungsten disk on top of the W-dispenser hollow cathode (see figure 1). This neutraliser approach was space qualified within the RIT 10 EUREKA program [2]. The small amount of business and lack of funding then led to a stop of this activity in the early eighties.

In 2002, Thales restarted the activity in order to get access to an effective neutraliser for its HEMP thruster family [3-6]. Based on the W/Os mixed metal matrix dispenser cathode technology, which was developed in the early nineteeneighties and space qualified at Thales Electron Devices GmbH for their long life space Traveling Wave Tubes, the German DLR supported since 2003 this new development for neutraliser application. First BBs of this HKN 5000 neutraliser were very successfully tested for 250 h with a Thales HEMP 3050 thruster in December 04 and in April 05 with the RIT 22 grid ion thruster of EADS-ST, both at the Giessen University Jumbo thrust test stand.

II. Neutraliser Design

Looking to the original design as shown in figure 1, one can see the double cylindrical heater externally surrounding and directly touching the thoriated cathode disk. This design was required by the relative high workfunction (around 3 eV) of this material in order to achieve sufficiently high temperature for electron emission at neutraliser ignition. In steady state operation of the neutraliser, electron emission is mainly provided from the W-dispenser cathode insert which operates already at lower temperature due to its lower workfunction (about 2.08 eV at 1000°C_b).

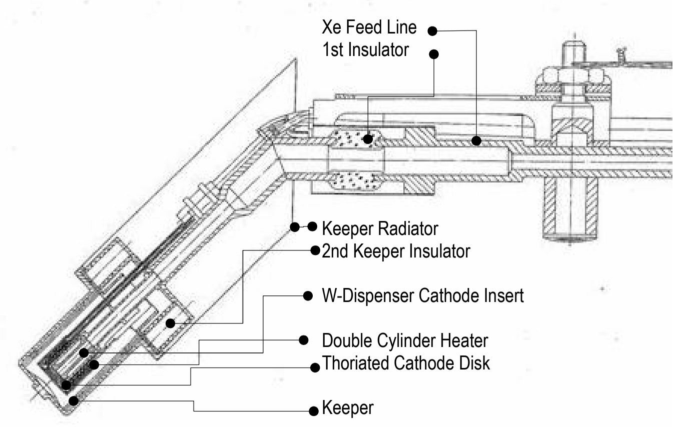

Figure 1. RIT 10 Neutraliser of AEG Telefunken in 1979

There were three design guidelines for the development of the new neutraliser.

1. Employ for both, emissive front disk and cathode insert the Thales W/Os impregnated cathode material to reduce workfunction and thus ignition and operating temperature and to enhance lifetime.
2. Use a standard Thales space qualified cathode heater assembly design verified to pyroshock levels up to 10.000 g and 100.000 heater switch on/off cycles.
3. Make an as compact as possible Xe feed supply to reduce radiation losses and to save heater power and mass.

As a result we obtained a 30 g lightweight neutraliser shown in figure 2 below.

A compact bifilar, toroidally wound W/Re heater wire, cataphoretically alumina coated and potted with alumina in a can of molybdenum is braced to the back of a molybdenum cathode holder. The W/Os insert and cathode disk are directly pressed and impregnated into this holder. This is the typical configuration of the Thales cathode/ heater assemblies for space TWT cathodes. The only exception is the added thin walled Mo Xe-supply tube assembly directly braced to the cathode/heater assembly. On its other side the tubing is connected to a 1/8" VCR flange. The keeper is mounted on isolating coaxial ceramic tubing. Several coaxial heat shields between cathode /heater assembly and keeper minimize the thermal losses. Its dimensions are 19.5 mm in diameter and 30 mm in length. The orifice in the cathode front disk has a diameter of 0.2 mm to maintain optimal discharge pressure conditions while operating at low Xe flow between 2 and 3 sccm.

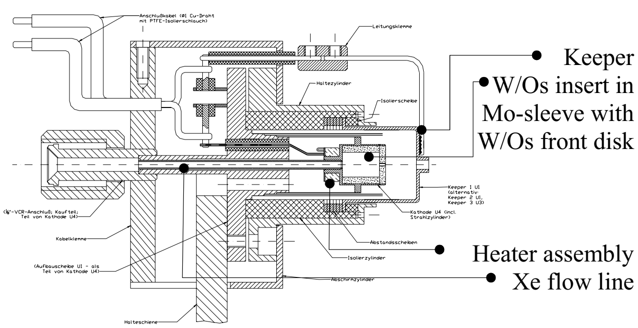

Figure 2. Thales W/Os mixed metal hollow cathode neutraliser, BB HKN 5000 design

III. Physical properties of the W/Os mixed metal cathode

In the late seventies and eighties of the last century it became apparent that tungsten is not the best base metal for dispenser cathodes. Other materials like Osmium, Iridium, and Ruthenium provide a cathode surface leading to even lower workfunction for electron emission. The electrochemical reason for this behavior is the more favorite orientation of the BaO dipole molecules due to the covalent binding orbits on those metal surfaces, as shown in figure 3.

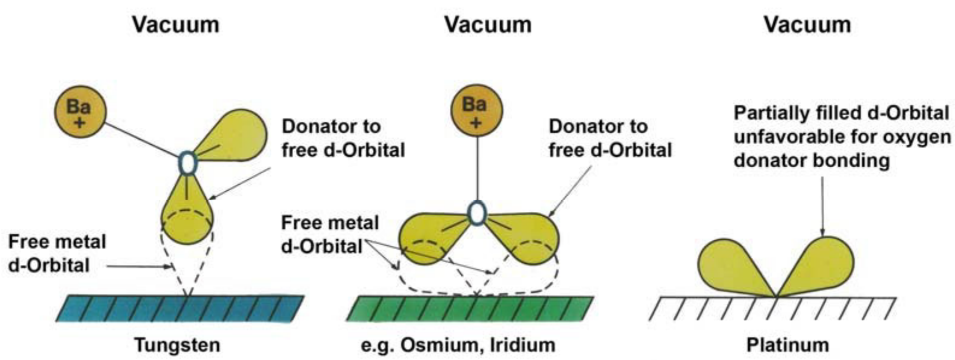

Figure 3. Comparison of covalent bonding structure Tungsten / Osmium, Iridium, Ruthenium etc. and some catalyst materials like Platinum. The latter become due to the lack of bonding capability to the BaO dipole even poisoning when present on a cathode surface.

Since it is quite difficult to produce porous bodies of pure Os, Ir or Ru metals with stable porosity at high temperatures, most dispenser cathode manufacturers chose to coat a tungsten surface with thin layers of these materials. For operation at low current density and low cathode temperature (<1050 C_b) this is advantageous. For high temperature operation as required for high current density cathodes, it is less favorable since the layer then diffuses into the tungsten and disappears leading to emission degradation. Another possibility to loose the layer is due to sputtering induced by ion impingement when operating at higher residual gas pressures. To avoid these risks for a broader application range TEDG decided in the late 1970s to improve their cathodes by a powder mix of the best suited combination of tungsten and osmium for the pellet production. In extensive test series under DLR, ESA and Intelsat contracts, the lowest workfunction was found at a mass ratio W to Os of 70% to 30%. The reduction in workfunction was about 0.1 eV from 2.08 to 1.98 eV. Though this amount looks small it leads to a possible operation temperature reduction of about 50 K for the same cathode current density. This temperature reduction allows a life time increase of an approximate factor of 3.3. For the useful cathode life time **L** of such cylindrical pellets with only one open surface face, three essential dependencies were found:

1. On cathode operating temperature **T**: $\mathbf{L} \propto \mathbf{exp\,(AE/kT)}$, (Arhenius Law) where **AE** = activation energy of Ba, Ca-Aluminates decomposition in the pellet pores and **k** = Boltzmann constant.
2. On the cathode pellet thickness **d**: $\mathbf{L} \propto \mathbf{d^2}$
3. On the open porosity **p** of the mixed metal matrix: $\mathbf{L}\downarrow$ **if** $\mathbf{p}\uparrow$. (For higher porosity, the arrival rate of Ba at the surface is increased and thus, the supply is thus faster evaporated and exhausted).

Using the severe life end criteria of 10% degradation from the initial cathode current, for the selected standard open porosity of about 25% and the standard pellet thickness of 1mm of the Thales W/Os cathode it was found that its life lasts typically about 200 000 h at 1000°C_b and 20 000h at 1100°C_b cathode temperature.

Whereas the reliability and life of this cathode type has been rock solid demonstrated with more than 3000 TWTs in orbit accumulating more than 100 million hours of operation and up to 100000 individual heater switching cycles, its respective long life in use for as hollow cathode neutralisers can so far be concluded only from the following similarity considerations.

IV. Life considerations of the W/Os mixed metal hollow cathode neutraliser

The life time of a hollow cathode neutraliser depends on the same dispenser mechanisms of Ba to the cathode surface as in cathodes operating in an ultra-high-vacuum environment. For the neutraliser we have to guarantee the emission in two distinct areas: Firstly from of the cathode front disk, required for the neutraliser ignition and secondly from the interior insert surface of the hollow cathode during operation. Since both area use in our case the same cathode material and both are due to its close contact on almost the same operating temperature, it should be assumed that the insert will last longer since it can loose Ba only through the very small orifice area whereas the cathode front disk is in a similar open situation as the open cathode surface of a TWT cathode. Assuming that, we are neglecting the Ba feeding from the backside insert and the Ba re-evaporation from the keeper. Assuming further that the presence of Xe species has no impact on the Ba evaporation rate from the surface, we can derive from our space cathode results a sort of worst case life estimation for our hollow cathode neutraliser. This estimation depends only on operating temperature T and the front disk thickness d for given pellet porosity p. Here we again imply that a drop of 10% of space charge emission capability is already a life end criteria. For the neutraliser ignition this might be a far too severe assumption but it is in any case a very save limit. Figure 4 plots the expected minimum life time vs temperature and disk thickness as a consequence

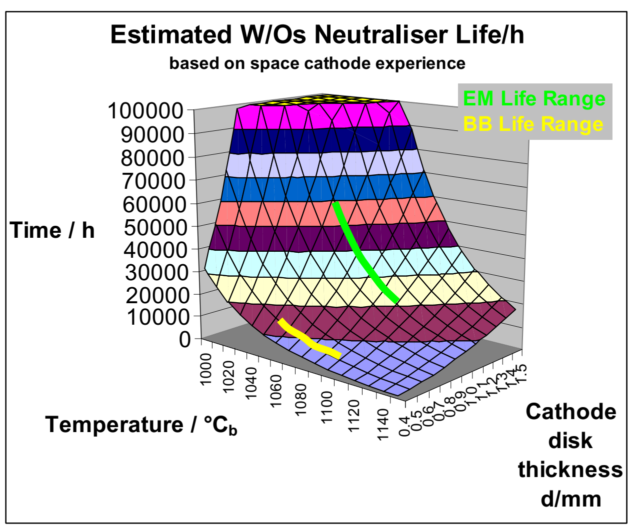

Figure 4. Neutraliser ignition life estimation as function of cathode disk temperature and thickness

of the Arhenius law for the Ba exhaust and the quadratic dependence on disk thickness. Since we know only roughly from heater resistance the operating temperatures of our BB model HKN 5000 front disk to be between 1050°C_b to 1100°C_b, we could estimate its life at a disk thickness of 0.5 mm between 15000 and 5000 hours, respectively. For the planned EM design, with a disk thickness of 1mm, this would lead to a minimal life expectation of 60 000 h to 20 000 h for the same operating temperature range, respectively.

V. Results of Performance Testing on HKN 5000 BB Neutralisers

A. Diode and Triode Testing

Figure 5 describes the test configuration: In the diode test configuration the emission current is completely drawn on the keeper at a given keeper voltage Uk. In the triode mode an additional anode representing the ion beam is introduced. Its potential Uc is simulating the coupling voltage of the plasma bridge to the ion beam. In a configuration isolated from ground the coupling voltage is self adjusting according to the emission properties of the neutraliser and the plasma density in the plasma bridge. Better emission properties and higher neutraliser gas flows support a low coupling voltage in the spot mode. At reduced Xe flow conditions the plasmabridge is not well established and its impedance and the coupling voltage rise (see figure 8). This condition is called plume mode. Reliable performance with low current noise is limited to the spot mode of the neutraliser. In figure 6 photographs are shown of the BB1 neutraliser and BB1 operated in the triode mode. The diode and triode test results are summarized in figures 7 and 8. Figure 7 gives the self adjusting keeper voltage for given selected keeper current and Xe flow. Note the heater is switched off in this condition and the neutraliser cathode is heated by the keeper power. One can see that with increasing keeper current the keeper voltage is dropping because the powers heating the cathode surface increases and emission capability increases with higher cathode insert temperatures. Also a strong reduction of the keeper voltage with higher Xe flow can be noted. This reflects the energetically more favorable hollow cathode discharge emission mode and the lower plasma impedance given at higher neutral gas density inside the cathode insert and cathode to keeper gap, respectively. A similar observation is made in the triode mode as shown in figure 8: The self-adjusting keeper voltage drops with increasing emitted electron current (anode current). On the other hand, at a given Xe flow the emitted electron current can not exceed a certain Xe flow related critical current limit

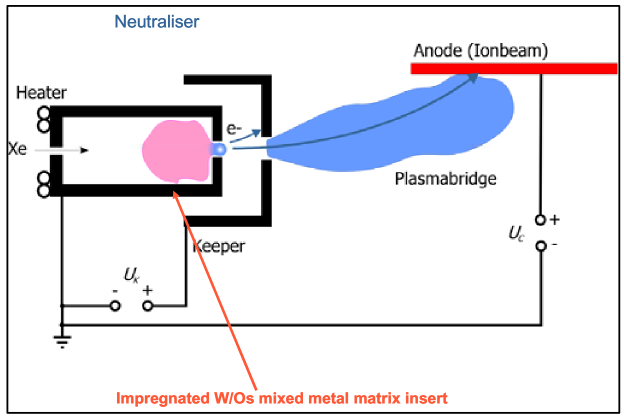

Figure 5. Neutraliser diode or triode test configuration

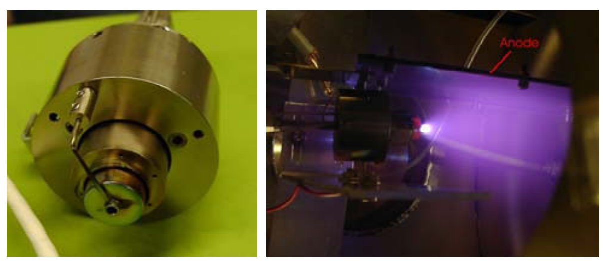

Figure 6. Neutraliser HKN 5000 BB (left), operating in triode mode in vacuum (right)

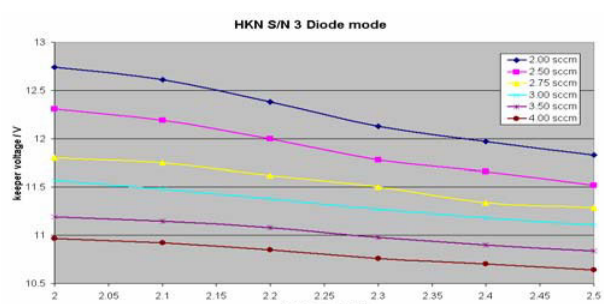

Figure 7. Neutraliser HKN 5000 BB1 performance in the diode mode. Keeper voltage vs current

without increasing suddenly the coupling voltage. This transition in the coupling voltage is the well known transition from the spot mode into the less favorable and less stable plume mode. For the triode mode we can sum up the power consumptions of keeper and anode power supply (heater is switched off) and introduce a neutralization cost (power/neutralization current) measured in eV. This is shown in figure 9.

Though it is difficult to compare the triode results with other data, because they always depend on the geometrical layout of the anode (perveance) and the residual gas pressure in the test chamber, the data looked very promising. This was confirmed by the neutraliser performance together with the HEMP 3050 or RIT 22 thrusters. There, it seemed that the presence of an ion beam could lower the neutralization costs, especially for the low current and low Xe flow case.

Another item of interest has been the neutraliser ignition capability. This was covered in an **ignition cycling test.** One cycle was characterized as follows:

- Heater on for 135 s then
- keeper (discharge) on for 20 s with only 1 s overlap with heating phsae
- 125 s keeper and heater off (cool down phase)

The total cycle time was 280 s. Three out of the first 4000 cycles are shown in figure 10. All cycles were electronically recorded and show no significant degradation. After 4.000 initial ignition cycles, 10.000 heater cycles were performed with no ignition, followed by additional 500 ignition cycles. After the cycling, the performance of the neutraliser was verified by a constant emission current test performed for 1 week at 5 A.

Already on BB level, the cycling tests demonstrated that typical neutraliser cycling specifications will be met.

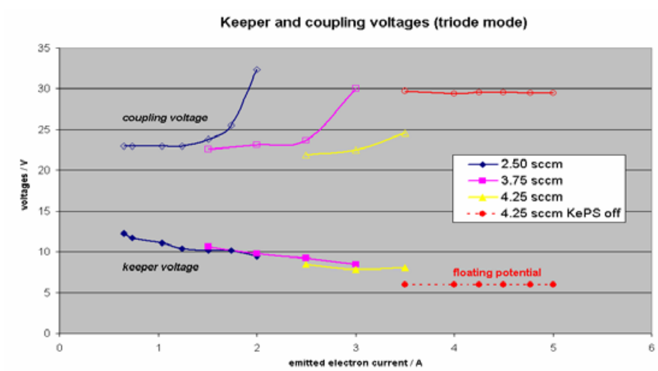

Figure 8. Neutraliser HKN 5000 BB1 performance in the triode mode. Keeper and coupling voltage vs emitted electron (anode) current.

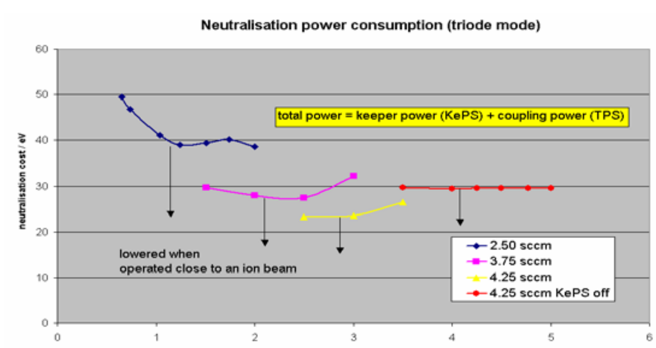

Figure 9. Neutralisation cost vs anode current of HKN 5000 BB1 neutraliser in triode mode.

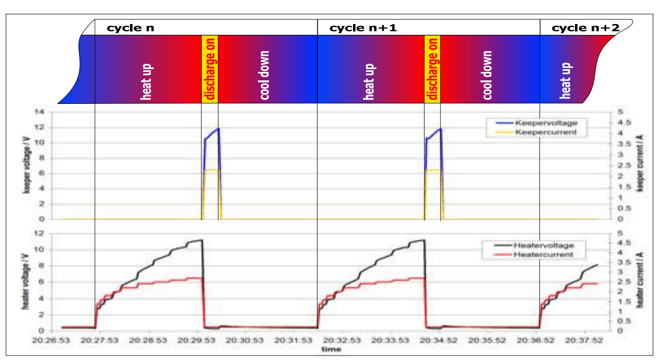

Figure 10. Three out of totally 4500 ignition cycles in diode mode of HKN 5000 BB1 neutraliser

B. 250 h Endurance Test of BB HKN 5000 with HEMP 3050 DM8 thruster

Operating at 3 sccm Xe flow and around 10 V keeper voltage, the neutraliser provided over the planned test period of 250 h a current of about 1.8 A. The thruster was operated at a thrust level of 57 mN at 2620 s specific anode impulse [4 and 5]. During the full operational period the thruster and neutraliser were running stably and free of interruptions. A visual inspection at the end of the 250 h test period verified the erosion free operation of the orifice of the neutraliser. It is believed, that this is due to the very low keeper voltage operation around 10 V, where ions impacting on the cathode disk remain energetically below the sputter threshold level of the cathode disk material. Figure 11 shows the assembly of thruster and neutraliser as prepared for the endurance test. Figure 12 shows both during nominal operation.

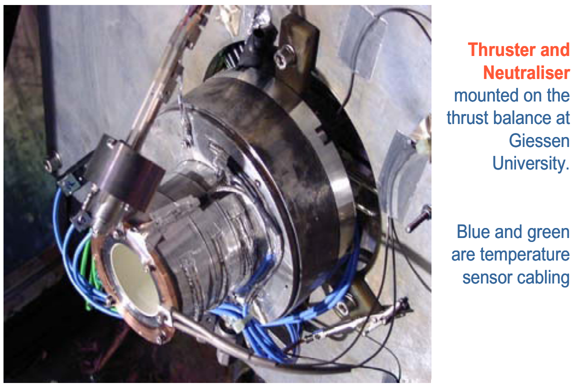

Figure 11. HEMP 3050 thruster and neutraliser mounted on thrust balance

Figure 12. HEMP 3050 DM8 thruster in operation with neutraliser HKN 5000

C. Compatibility Test of BB HKN5000 with RIT 22 thruster of EADS-ST

The compatibility of the BB HKN 5000 with the RIT 22 thruster of EADS-ST was verified at Giessen University. Assembly and operational views are shown in figures 13 a and b respectively.

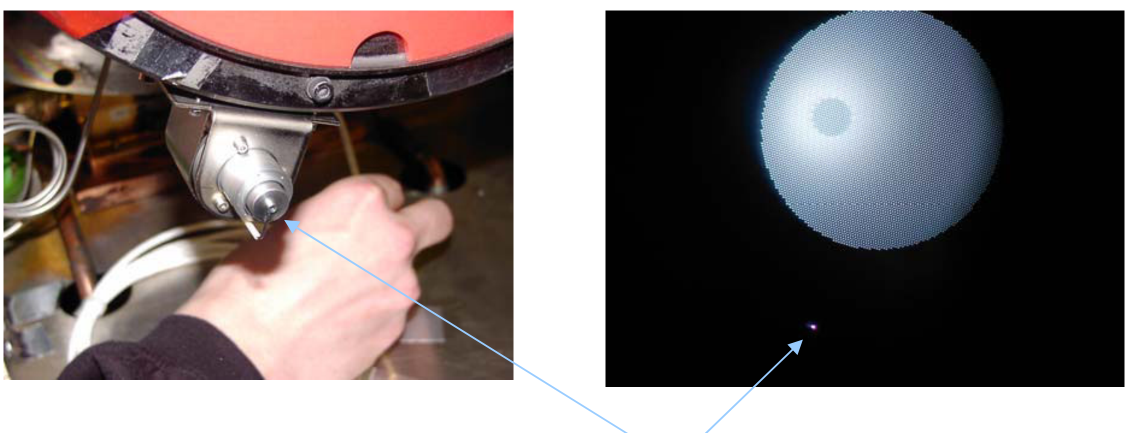

Figure 13 a, b. BB2 model of the HKN 5000 neutraliser mounted to RIT 22

The tests aimed to characterize the neutraliser performance and to compare it with other designs. Again the neutraliser showed absolute stable operation and visual inspection after the 4 days test campaign showed a completely clean and erosion free appearance of the neutraliser and its orifice area. In the tested parameter range, the neutraliser has demonstrated superior performance compared to a competitor neutraliser normally used for RIT22 operation. This can be seen for the total power consumption of the neutraliser in figure 14. A further example was the very low keeper ignition voltage. As in all previous tests, the ignition of the preheated HKN 5000 neutraliser spontaneously starts when the operational keeper voltage of about 10V is applied. No separate keeper ignition voltage supply was required. Also keeper and coupling voltage were running typically several V lower even when operated at only 3 sccm instead of 4 sccm Xe flow. For the same neutralization currents, the total power consumption (keeper + coupling power, heater off) was only about 40% required by the competing neutraliser design.

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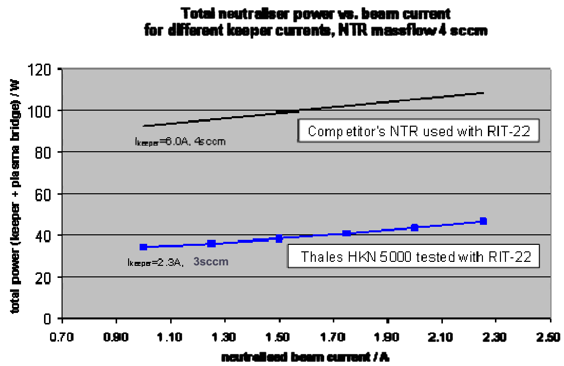

Figure 14. Total neutraliser power consumption of the Thales HKN 5000 and a competitive design

VI. Conclusion

The application of Ba/Ca-aluminates impregnated W/Os mixed metal cathode material as insert and front disk of hollow cathode neutralisers promises interesting performance advantages and simplifications of the required supply and control lines. The BB status of the HKN 5000 neutraliser, based on existing space proven cathode technology at TEDG, allowed performing already essential portions of a qualification program, indicating further straightforward development and full qualification of the neutraliser concept.

Acknowledgement

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