# MEDIUM AND HIGH CURRENT CATHODES FOR ELECTRIC PROPULSION: REVIEW OF RECENT DEVELOPMENTS AT LABEN/PROEL

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**Abstract**

The Cathode/Neutralizer or Hollow Cathode Assembly (HCA) is a "key" component of an Electric Propulsion (EP) System, and can significantly affect the performances and reliability of the whole EP system, especially if high thrust/power applications are at stake.

The paper addresses in particular two HCA models successfully developed and tested at LABEN/Proel: respectively the medium current NccA 5000 (discharge current 2 -5 A) and the high current NccA 15000 (discharge current 5-20 A), the former also qualified for operation at thruster level. Both the devices have been developed in the frame of ESA ARTES 5 contracts, financed by ASI. NccA 5000 and NccA 15000 models are proposed to the market for applications on both HET (Hall Effect Thruster) and GIE (Gridded Ion Engine), respectively, of the 1-2 kW class (e.g. SNECMA PPS 1350) and of the 2-6 kW class (e.g. the SNECMA PPS X000 and the Astrium RIT-XT).

**Introduction**

Electric Propulsion (EP), thanks to its intrinsically high specific impulse (up to 10 times higher than the one provided by the conventional chemical propulsion) and to its great flexibility in use, is nowadays recognized by the International Space Community as a mature technology available to the Spacecraft designers and manufacturers for fulfilling a variety of spacecraft missions. These missions being targeted to the achievement of a favorable cost-effectiveness or to pursue innovative and challenging mission scenarios (not excluding the possibility to address both targets).

For what concerns the Telecom satellite market EP, other than for performing orbit maintenance/control maneuvers (satellite station-keeping), will be proposed in the next future for the orbit transfer/orbit topping maneuver starting from the parking orbit (for example GTO, super GTO or MEO). Considering the masses (above 5 tons) and the power available (above 20 kW) of the near future (around 2006-2007) Telecom platforms, very powerful engines, capable to provide thrust level of at least 200 mN have to be developed and qualified (and possibly flight demonstrated).

In particular for medium/high power applications, the most critical component of an EP system (either based on a HET or GIE) is the cathode/neutralizer (HCA), which, in the current HET technology based on Russian heritage, is often adopted in redundancy for reliability reasons.

The HCA device in fact significantly affects the performances and reliability of the thruster, especially if high thrust/power applications are at stake (not neglecting the HCA role also for the economic competitiveness of the whole EP system).

In addition, the development and qualification of the HCA devices, in particular targeted to medium/high power EP applications, has to be conceived having also in mind " versatility" issues. This to make available to the EP manufacturers/integrators HCA components (as far "off-the-shelf" as possible) that can be easily integrated and used on different EP systems either based on the HET or on the GIE technology.

**Background & Achievements**

LABEN/Proel has ripened a wide heritage and experience [3] for what concern neutralizers/cathodes for EP applications. Currently 3 types of HCA products do exist, with different qualification status achieved, namely:

- NccA 1000 model (discharge current up to 1A, extracted electron current up to 700 mA): This device has been developed and qualified as a neutralizer for low thrust GIE and in particular has been finalized for the RIT-10 on ARTEMIS. The NccA 1000 has been fully qualified at component level (lifetime in excess of 20,000 hrs) [1], [2] and at thruster level (Joint lifetime with RIT-10 in ESTEC achieved more than 15,000 hrs). This model is currently flying on ARTEMIS satellite [6], supporting the RIT-10 operation in the attempt to raise the final orbit to GEO, after the failure of the ARIANE 5 3rd stage.

- NccA 5000 model (discharge current up to 5 A): This device as been developed and qualified as a cathode for HET thrusters of the 1.5 kW class (ref. SNECMA PPS 1350). This model has been qualified both at component level and at thruster level (joint test with PPS 1350 thruster). The “Emitter Sub-Assembly” has been manufactured by PLANSEE on the basis of design requirements provided by LABEN/Proel.

- NccA 15000 model (discharge current up to 20 A): This device is currently under development. At the time of the writing of this paper 2 Breadboard models have been designed, manufactured and functionally tested in view of being used on HET (e.g. PPS X000) and GIE (e.g. RIT-XT) thrusters of power level up to 5-6 kW. This model will be described in detail in the following. The “Emitter Sub-Assembly” of this model has, as well, been provided by PLANSEE.

The main characteristics and performances HCA models (see Fig. 1)

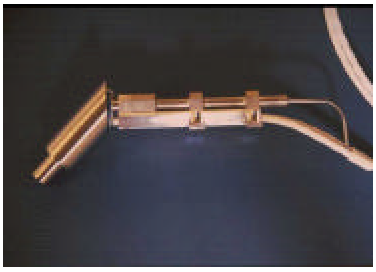
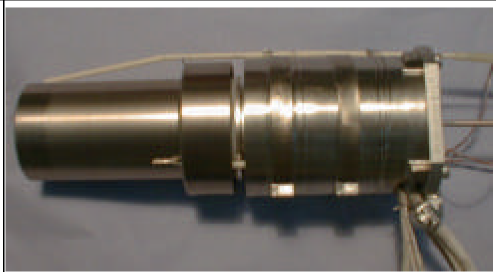
| ***NccA 1000 model<br>(RIT-10, RMT application)*** | ***NccA 5000 Model<br>(PPS 1350, SPT 100 application)*** | ***NccA 15000 Model<br>(PPS X000 and RIT-XT application)*** |
|---|---|---|
|  |  |  |
| ***Main Features of NccA 1000*** | ***Main Features of NccA 5000*** | ***Main Features of NccA 15000*** |
| Heating power: < 20 W | Heating power: < 60 W | Heating power:< 100W |
| Heating-up time: < 3 min | Heating-up time: < 6 min | Heating-up time: < 10 min |
| Gas flow rate: 0.02-0.1 mg/s | Gas flow rate: 0.1-0.5 mg/s | Gas flow rate: 0.3-0.8 mg/s |
| Discharge current: 0.5 to 1 A (cathode-to-keeper) | Discharge current: 2 to 5 A Nominal 4.3 A | Discharge current : 5 to 20 A (towards an external anode); nominal 15A; cathode-to-keeper discharge 10 A max |
| Ext. Electron current: up to 800 mA | Ext. Electron current: up to 4 A (neutralizer operation mode) | Ext. Electron current: up to 8 A (neutralizer operation mode) |
| Ignition voltage (also pulsed) | Ignition voltage (pulsed) | Ignition voltage (pulsed): 100-300 Vdc |
| Lifetime: > 15,000 (verified by test) | Lifetime: > 15,000 expected | Lifetime: > 15,000 expected |
| $H_2O/O_2$ absorber external to the device body | $H_2O/O_2$ absorber incorporated in the device mechanical body | $H_2O/O_2$ absorber incorporated in the device mechanical body |
| Mass: 60 g without cable | Mass: 100 g, without cables | Mass: 120 g without cable |
| Dimensions: 105x 37 x 37 mm | Dimensions: 82 x 32 x 32 mm | Dimensions: 90 x 42 x 42 mm |

***Fig.1: HCA Models developed at LABEN/Proel***

**HCA tasks within an EP system and most significant parts/elements**

The HCA can significantly affect the overall performances and reliability of the whole HET sub-system and therefore its design should pursue the following objectives:

- Lifetime capability at component level sufficiently higher than thruster operating time required by the mission: this can allow an increase of the overall reliability figure of the EP sub-system and avoid the adoption of cathode redundancy.
- Provide the required electron current at a lower propellant mass flow rate (into the cathode) and minimizing the "floating potential" which affects the net accelerating voltage. This feature affects the performance of the EP sub-system in terms of efficiency, thrust-to-power ratio, and specific impulse.
- Reduce heating power allowing the decrease of the complexity and cost of the Power Supply & Control Unit (PSCU) which is a fundamental part of an EP sub-system .
- Last, but not least, reduce manufacturing cycle, simplify the hardware complexity, in terms of number of sub-assemblies and parts necessary for the component realization, with the objective of increasing the intrinsic reliability of the component and of containing, as much as possible, the costs of the recurring production which, in turns, impact the overall EP system competitiveness.

The basic sub-assemblies composing the HCA design are shown in the following principle scheme of Fig. 2

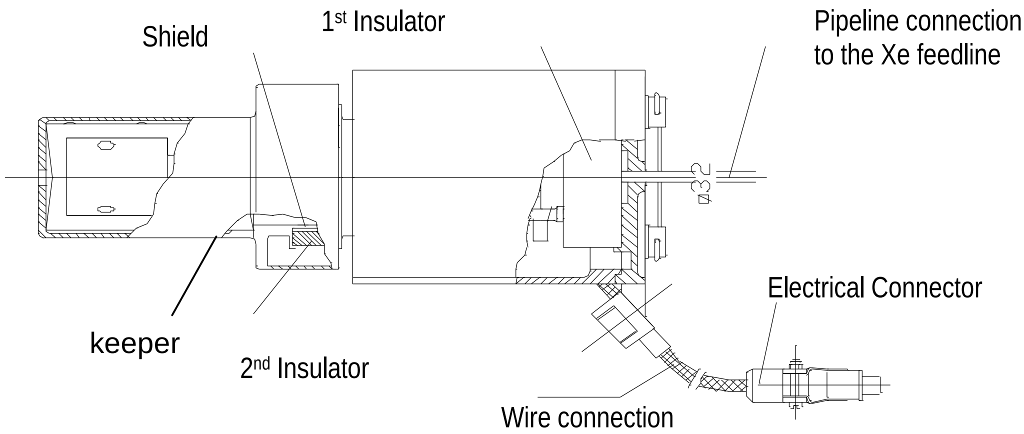



***Fig. 2: Main parts/sub-assembly of a typical HCA***

*Emitter sub-assembly*

The emitter sub-assembly (manufactured by PLANSEE starting from LABEN/Proel drawings and specifications) is an impregnated hollow cathode emitter (see Fig. 3 and Fig. 4), able to deliver a current of electrons (thermionic current) suitable to ignite and maintain the plasma discharge. During the heating-up phase the heating filament wound around the cathode tube is powered to bring the low work function insert to thermionic emission temperatures (1100÷1200 °C). When the HCA operates in the steady-state condition the heater can be switched off and the temperature of the emitting material can be maintained at suitable level for thermionic emission (around 900 °C) by impinging ions from the discharge.

the HCA Emitter sub-assembly includes:

- *the heater (heating filament embedded in $Al_2O_3$ insulating material*
- *the orificed disk*
- *electron emitting material (impregnated Tungsten)*
- *the support tube enabling the mounting.*

The electron emitting material of the HP HCA emitter is  Tungsten impregnated with chemicals BaO + CaO + $Al_2O_3$ in the molar ratio 4:1:1.

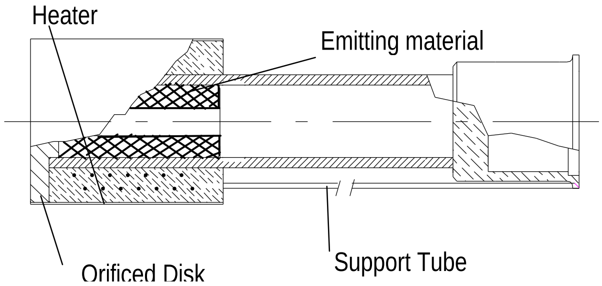



*Fig. 3: Cross-Section of the emitter sub-assembly for the PPS 1350 HCA manufactured by PLANSEE*

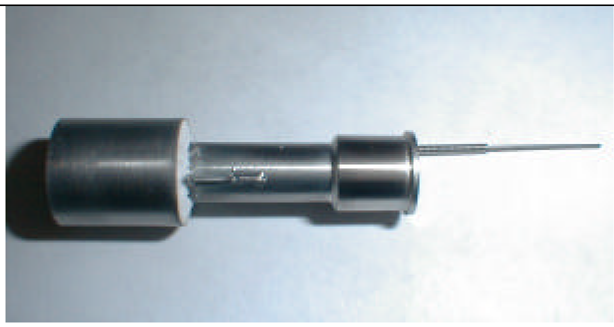


*Fig. 4: Photo of the emitter sub-assembly for the PPS 1350 HCA manufactured by PLANSEE*

*Keeper sub-assembly*

- keeper (discharge sustaining electrode) mechanical structure with heat shielding and sputtering erosion provisions
- keeper insulator (keeper electrode w.r.t. the hollow cathode).

*Frame body*

– hollow cathode insulator (hollow cathode w.r.t. the frame body)
– frame body, i.e. the mechanical structure which provides the support for the hollow cathode, keeper, wire connections; this structure is mechanically interfaced to the xenon feedline through a tubing connection.

*Mechanical interface*

The mounting interface flange with four fixing holes provides the mechanical interface between the cathode frame body and the thruster external case.

*Electrical interface*

Four cables provide the electrical contacts between the HCA electrical terminals and a connector. Two of these wires are used to power the heater and the other 2 to power the keeper. The keeper and heater circuits have a common point which is connected to the hollow cathode. This latter is electrically insulated from the HCA frame body which is usually at the thruster case ground potential.

**Development Status achieved for the NccA 5000 Model**

This HCA Model [7] has been developed on the basis of requirements provided by SNECMA, targeting the application on the PPS 1350 thruster (see Fig. 7). The development has been performed in the frame of an ESA ARTES 5 contract, within which LABEN/Proel acted as sub-contractor of SNECMA. LABEN/Proel activities were funded by ASI and by Company internal investments. The design of this device has been tuned in co-operation between LABEN/Proel and SNECMA. The NccA 5000 HCA FEM and thermal modelization are respectively shown in Fig.5 and Fig.6 below.

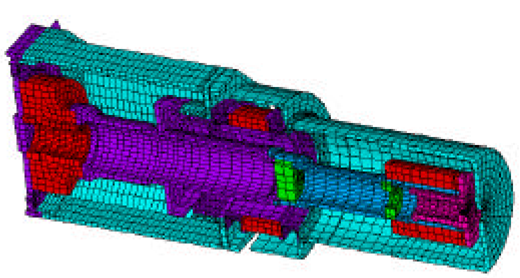


*Fig. 5: NccA 5000 FEM with Ansys 6.1 code*

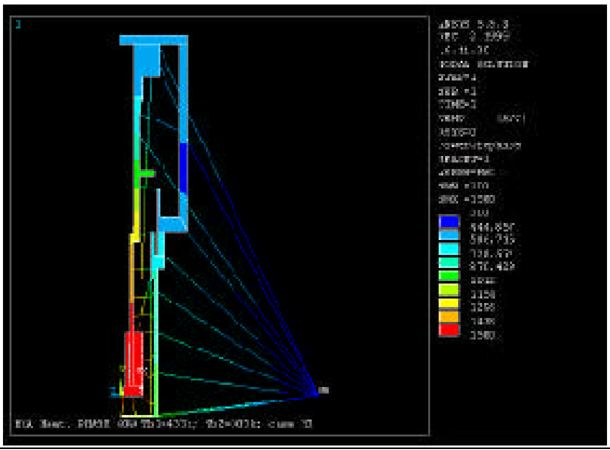


*Fig. 6: Thermal Modelization of the NccA 5000 EM Model*

The HCA design, in function of the customer requirements, has been carried out by using both modelling [4] and experimental activities [5]. The model has been tuned, exploiting the results of the experimental activity, till a satisfactory matching is achieved between numerical and experimental results. The issues that have been addressed to tune the design have been:

| Identification of the correct thermal regime | Geometry identification | Optimization of operating parameters |
|---|---|---|
| ▪ *achieve a stable emission in the identified current range*<br>▪ *avoid overheating and then thermal stresses*<br>▪ *minimize electrical power for discharge maintenance* | ▪ *orifice diameter*<br>▪ *insert geometry*<br>▪ *keeper geometry* | ▪ *optimum gas flow regime versus emitted current*<br>▪ *discharge voltage versus discharge current*<br>▪ *temperature versus discharge current*<br>▪ *gas flow rate versus floating (reference) potential* |

For the NccA 5000 engineering and qualification achievement the test campaign according to the following test matrix has been accomplished:

| | | |
|---|---|---|
| ▪ Electrical Checks<br>▪ Weight and Dimensions<br>▪ Activation & Functional Test<br>▪ Start-up from cold temperature (-60)<br>▪ Functional test coupled with PPS 1350<br>▪ Sinus Vibration at EP sub-system level | ▪ Discharge Voltage: 350 V<br>▪ Discharge Current: 4.28 A<br>▪ Mass flow rate to thruster: 4.9 mg/s<br>▪ Mass low rate to the HCA: 0.3 mg/s<br>▪ HCA Reference Potential: -16 ± 3 V<br>▪ Thrust: 88 ± 3 mN<br>▪ Specific Impulse: 1725 ± 50 s<br>▪ Thruster Efficiency: 49.7 ± 5% |  |
| *Performed tests within the NccA 5000 HCA engineering / qualification Campaign* | *Main parameters and results of Functional Tests at thruster level* | ***Fig. 7: Test of NccA 5000 HCA with the SNECMA PPS 1350 thruster*** |

**Additional Test Activity on NccA 5000 model**

In order to confirm the NccA 5000 design viability in view of possible application of EP on scientific and commercial satellites additional experimental data relevant to the operation of the HCA with other HET EP systems have been accumulated.

In Orleans (France), at the CNRS EP Laboratory a HCA EM has been characterized [8] in conjunction with a SPT 100 ML HET (see Fig.8). The operation of the LABEN/Proel NccA 5000 HCA has been also compared with the operation of a $LaB_6$ cathode provided by MIREA (Russia). For what concerns the reference (floating) potential investigation the collected experimental data are shown in Fig. 9.

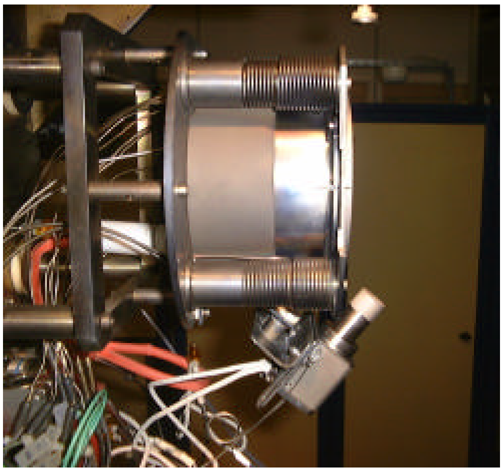


*Fig.8: NccA 5000 HCA assembled together the SPT 100 ML thruster at CNRS labs*

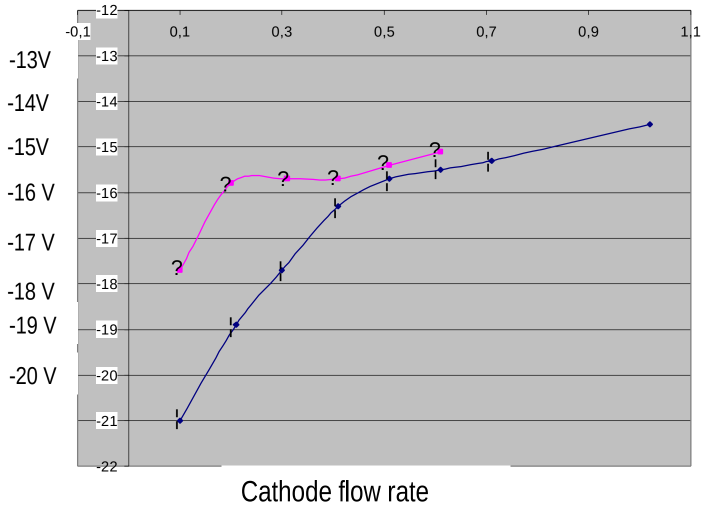



*Fig. 9: Reference cathode potential vs. cathode flowrate for NccA 5000 (? ) and for the MIREA LaB6 cathode (¦ )*

The LABEN/Proel HCA has shown a cathode reference potential more "stable" according to the cathode's flow rate than that of MIREA.

In addition to the test campaign at Orleans, a functional test of the NccA 5000 model has been performed together a HET of the TAL (Thruster with an Anode Layer Type)(see Fig. 10, 11, 12), at TsNIIMASH in Moscow (Russia). In particular the NccA 5000 has been performance tested joined to the TAL D-55 Model (in its flight version WSF).

*Fig. 10: TAL D-55 WSF (Courtesy of TsNIIMASH)*

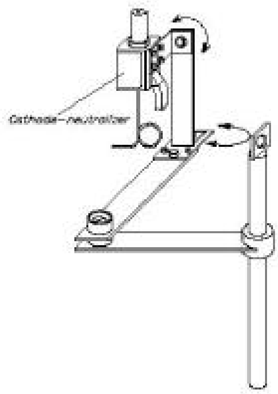



*Fig. 11:Mechanical Arm for supporting the HCA*

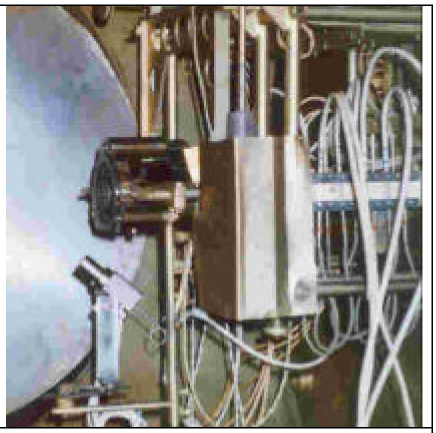


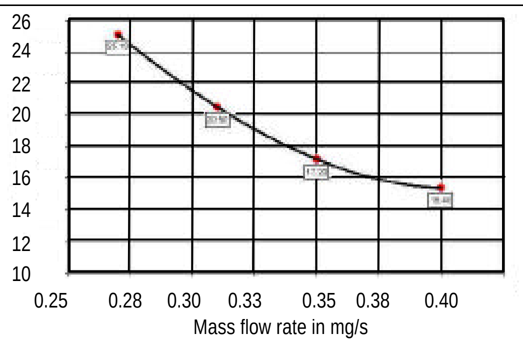
*Fig. 12: Test set-up arranged for the joint test NccA 5000 + TAL D-55*

The test parameters and the main test results are summarized in the following tables.

Parameters variation of the thruster:
- Mass Flowrate: 2.9 to 4.9 mg/s
- Discharge Voltage: 150, 200, 300 V

Parameters variation of the HCA
- Mass Flowrate: 0.2 to 0.5 mg/s
- Keeper Voltage: up to 15 V

***Tab. 1: Test Parameter variations***




***Tab. 2: HCA floating potential (V) variation versus mass flowrate***

Selected Operating Point
- Disch. Voltage: 300 V
- Disch. Current: 4.5 A

Achieved test results:
- Thrust: 82.3 mN
- Power: 1347 W
- Spec. Impulse: 1722 s
- Efficiency: 51.9%
- HCA Floating Potential: 17.3 V

***Tab. 3: Results at the selected operating point***

**Development Status of the NccA 15000 Model**

The HP_HCA (High Power Hollow Cathode Assembly) development and qualification, at current levels between 5 and 20 A, is currently underway at LABEN/Proel in view of applications within HET (Hall Effect Thruster) propulsion systems operating between 2 and 6 kW generation and also within GIE of the 3 to 10 kW class

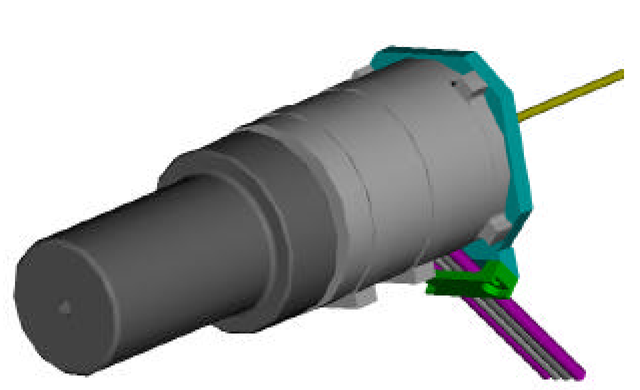
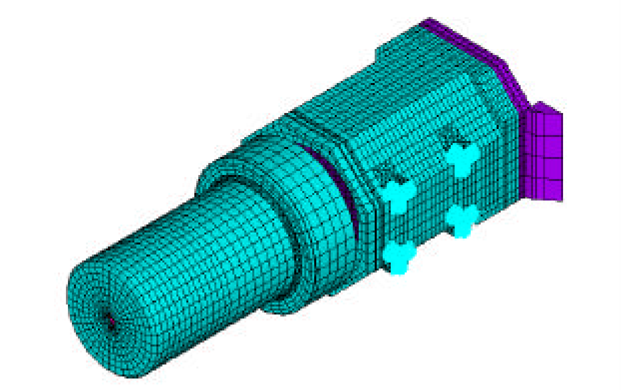
The proposed cathode, referred as HP-HCA or NccA 15000 model can be retained as a scaling-up and an upgrading/improvement of the lower current (5 A) device whose development and qualification has been successfully completed (HCA for the PPS 1350 thruster contract).

At the moment the reference HET thruster considered for finalizing the HP-HCA technology is the PPS X000 (by SNECMA). Applications on RIT-XT GIE (by Astrium GmbH) for the Alphabus platform will be furthermore pursued.

The design of the HP HCA has been conceived according to the following guidelines:

- Scaling up of the already developed and qualified HCA (NccA 5000 model) with the strong support of thermal/mechanical modelization and plasma processes modelization
- Scaling-up of the Emitter Sub-assembly and relevant design optimization (reduction of complexity, manufacturing reproducibility, heater geometry and potting, porosity of the W matrix, composition of the active material)
- Review of processes for joinings (brazings) of HP-HCA critical parts and choice of materials versus manufacturing simplification and reliability issue.

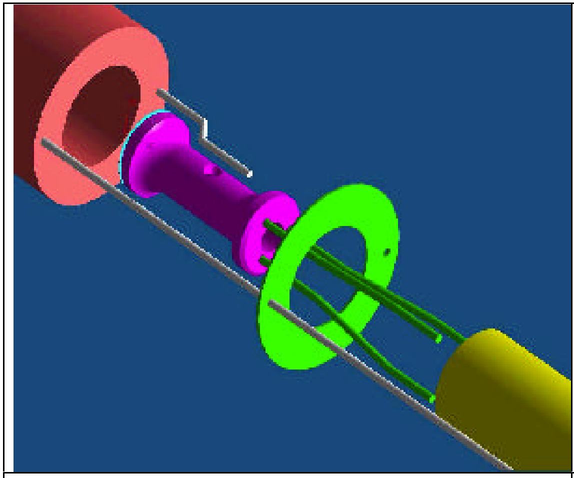
Fig. 13 and 14 below show the HP HCA Design Modelization used for verifying by analysis the design effectiveness (from the thermal and mechanical standpoints).

|  |  |
|---|---|
| ***Fig. 13: HP HCA 3D solid Modelization*** | ***Fig. 14: HP HCA FEM (Finit Element Modelization)*** |

Results obtained from the thermal simulation are satisfactory as they give the required picture of the temperature profiles in the HP HCA head for heating-up and steady-state operation. The simulated data show a good agreement with preliminary experimental data and demonstrate that the device operates in a safe temperature range for what concerns materials and critical joining (brazings).

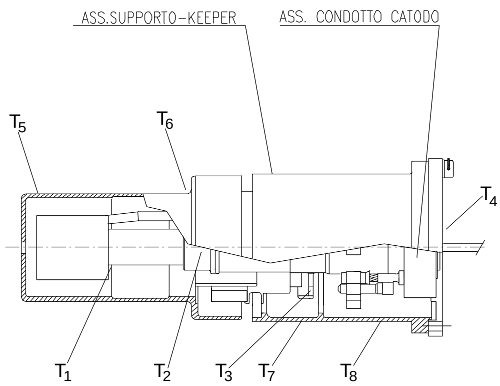
With reference to mechanical analyses, random vibration, sinus vibration and shock analyses have been performed. In the frame of the assumption used for the FEM model development, the obtained results indicate that the current design (prototype design) is reliable with respect to load data.

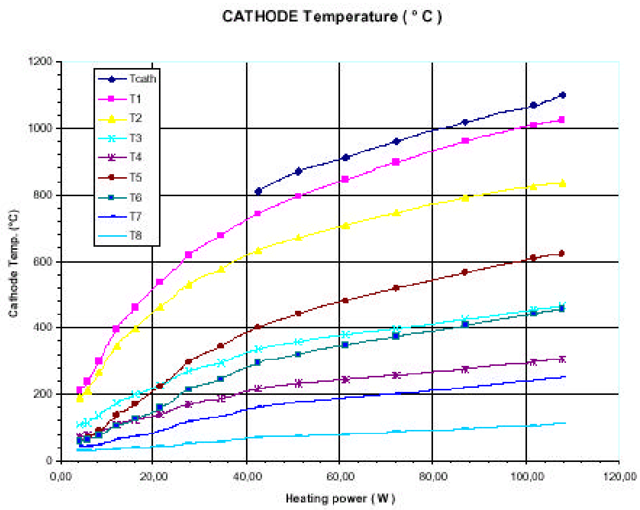
Fig.15 here below shows details of the Emitter Sub-assembly design and realization (PLANSEE activity). The HP HCA Emitter sub-assembly has been realized (see Fig. 16) on the basis of the requirement and preliminary drawings provided by LABEN/Proel to PLANSEE, who has prepared the detailed manufacturing drawing and processes procedures for the Emitter fabrication.



| *Fig. 15: 3D representation of the HP HCA emitter parts (PLANSEE)* | *Fig. 16: HP HCA Emitter Prototypes* |
|---|---|

The first Prototypes of the HpHCA (NccA 15000) have been successfully characterized at component level at LABEN/Proel. For what concerns the thermal characterization (see Fig. 17 and 18) the operating temperatures were collected by using thermocouples located in the points shown in the left figure below. The right figure below shows the temperatures at the location identified versus the heating power.




| *Fig. 17: Location of thermocouples for HP HCA prototype thermal characterization* | *Fig. 18: HP HCA Prototype temperatures versus the heating power* |
|---|---|

For what concerns the performance/functional characterization at component level the extracted discharge current towards an external target, versus the target bias voltage and versus the gas flow rate have been measured. The results of this test are summarized in Fig. 19 below. Fig. 20 shows a photo of the HP HCA operation inside the vacuum chamber:

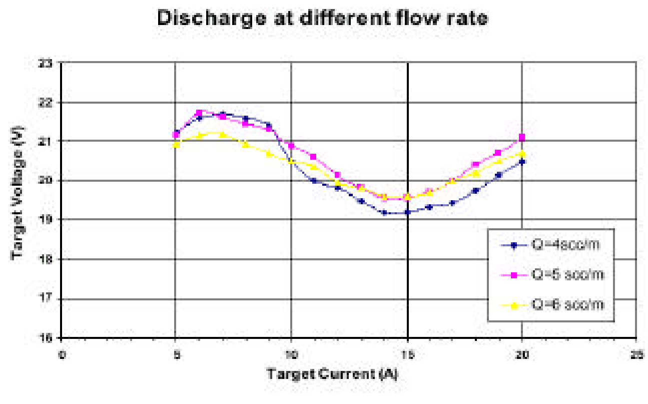



*Fig. 19: HP HCA prototype I-V characterization at different inlet mass flow rates*

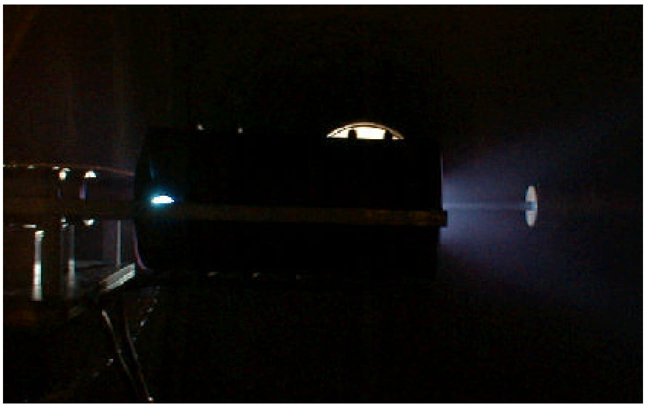


*Fig. 20: HP HCA in operation within the vacuum chamber*

It has to be pointed out that when the minimum in the target voltage is achieved around the discharge current on the basis of which the HP HCA design gas been developed (14-15 A): the current value for which a minimum in the target voltage is verified is practically independent from the inlet mass flow rate.

**NccA 15000 prototype test at thruster level**

The HP HCA prototype design from the functional viewpoint has been validated during a test session at thruster level with the SNECMA PPS X000 thruster. The test session has been performed in December 2002 at the vacuum plant of QinetiQ (Farnborough, UK) where SNECMA had dislocated part of the PPS X000 validation test campaign.

Fig. 21 and 22 below show respectively the accommodation of the thruster within the vacuum chamber HP HCA prototype mounted close to the PPS X000 beam exit.

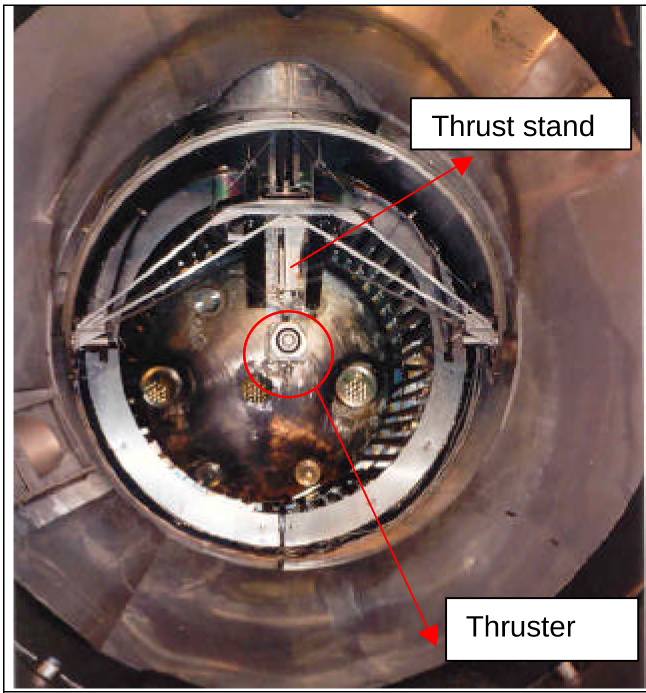



*Fig. 21: Accommodation of the thruster within the vacuum chamber*

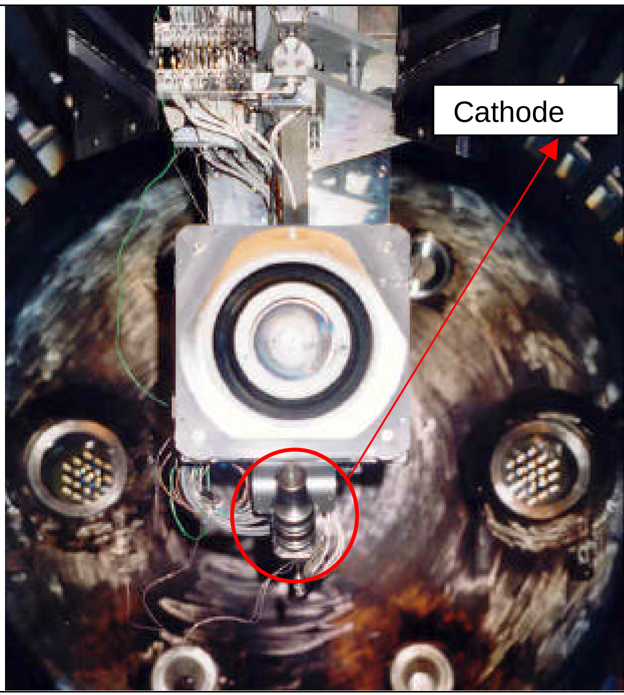



*Fig. 22: HP HCA mounted close to the PPS X000 beam exit*

The following Tab. 4 provides a summary of the joint thruster + cathode functional test parameters and results.

| $\dot{m}$ in the cathode | $\dot{m}$ in the thruster | $V_D$ (Disch. Volt.) | $I_D$ (Disch. Curr.) | Floating potential | Power to thruster |
|---|---|---|---|---|---|
| 0.58 mg/s | 7.45 mg/sec | 301 V | 6,5 A | -21,6 V | 1957 W |
| 0,68 mg/s | 10.05 mg/sec | 550 V | 9,1 A | -29,91 V | 5005 W |
| 0,68 mg/s | 9,47 mg/sec | 581 V | 8,8 A | -23,64 V | 5113 W |
| 0,78 mg/s | 10.24 mg/sec | 450 V | 11,1 A | -31,68 V | 4995 W |
| 0,88 mg/s | 13.86 mg/sec | 375 V | 13,3 A | -31,9 V | 4988 W |
| 0,98 mg/s | 15.91 mg/sec | 300 V | 16,6 A | -38 V | 4980 W |
| 0,98 mg/s | 15.91 mg/sec | 300 V | 18 A | -50 V | 5400 W |

***Tab. 4: Summary of test results of the joint NccA 15000 (HP HCA) + PPS X000 functional test***

## Conclusions

The cathode/neutralizer (HCA) is identified to be critical component of an Electric Propulsion (EP) sub-system based on both Hall Effect Thruster (HET) and Gridded Ion Engine (GIE) technology, in particular for what concerns applications on large Telecom Platforms. A family of hollow cathodes/neutralizers has been successfully developed and qualified at component level at LABEN/Proel. These devices range from the NccA 1000 model (discharge current up to 1A), developed for the RIT 10 on ARTEMIS and currently flying on the satellite, to the NccA 15000 model (discharge current up to 20A), dedicated to the multi-kW Ion/Plasma thrusters (e.g. SNECMA PPS X000 and Astrium RIT XT), whose development and qualification is under finalization within an ESA/ARTES 5 contract. In addition to these models the NccA 5000 (discharge current 5 A) device has been successfully qualified for operation together plasma thrusters of the 1.5 kW class (ref. PPS 1350 of SNECMA). In the paper technical aspects relevant to the HCA manufacturing, test and qualification are addressed with presentation of obtained experimental results with particular reference to the NccA 5000 and NccA 15000 models. These models will be offered as off-the-self EP components to the European EP manufacturers for the market applications.

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