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Development of a cathode for the PPS®5000 Hall Thruster Unit

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I. Introduction

Electric Propulsion (EP) devices tends to become the main propulsive system for earth orbit satellite. Since the late 1990's. Safran has concentrated on Hall Effect Thruster technology.

Among the 4 devices in Safran's product line, the PPS®5000 thruster unit vocation is to cover a large range of missions including orbit raising and/or station keeping. In the frame of its development and qualification, a hollow cathode equipped with a LaB_6 (Lanthanum hexaboride) thermoionic emitter able to provide a wide current range, from 5 A to 20 A, has been designed, manufactured and tested in house. A lifetime over 15,000 hours is expected in order to cover the whole specification of the PPS®5000 thruster.
The first ignition of the BBM1 cathode occurred during December 2014. This complete test heritage on PPS®5000 functional development model is significant.

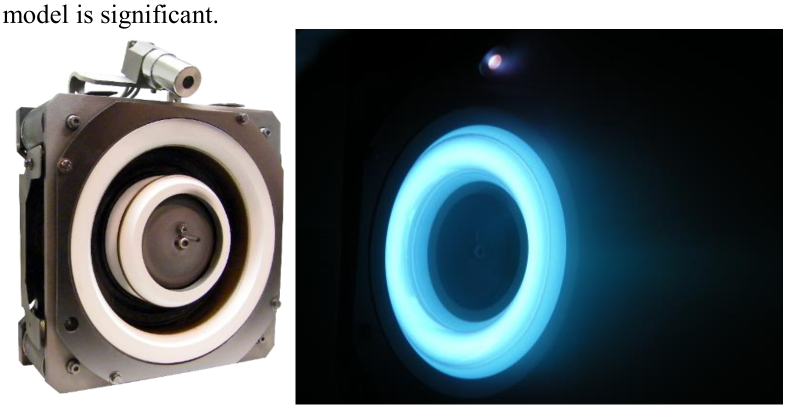


Figure 1 : first ignition of the BBM1 cathode mounted on PPS5000-EM model

The PPS®5000 Hall Thruster Unit is a propulsion system comprising a Hall Thruster and its Xenon Flow Controller (XFC), as represented in Figure 2.

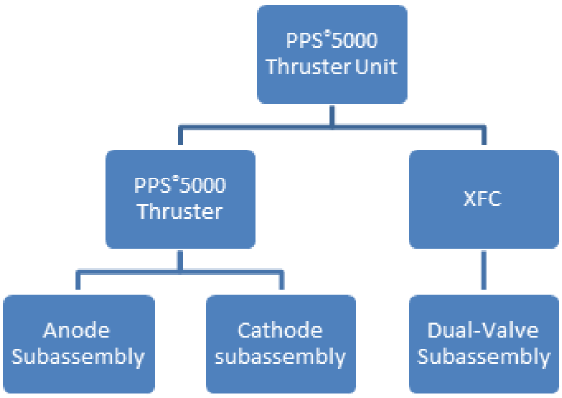


Figure 2 – PPS®5000 Thruster Unit product tree.

This paper will describe the development and qualification status of this cathode.

II. Cathode Design

A. Cathode requirements

This cathode has been designed on the PPS®1350 cathode heritage which performed a qualification life test of 10,500 hours. The PPS®5000 cathode has been designed in order to provide electrons to the thruster during its qualification (orbit raising, station keeping, deorbiting). The mission profile is present in the Figure 3.

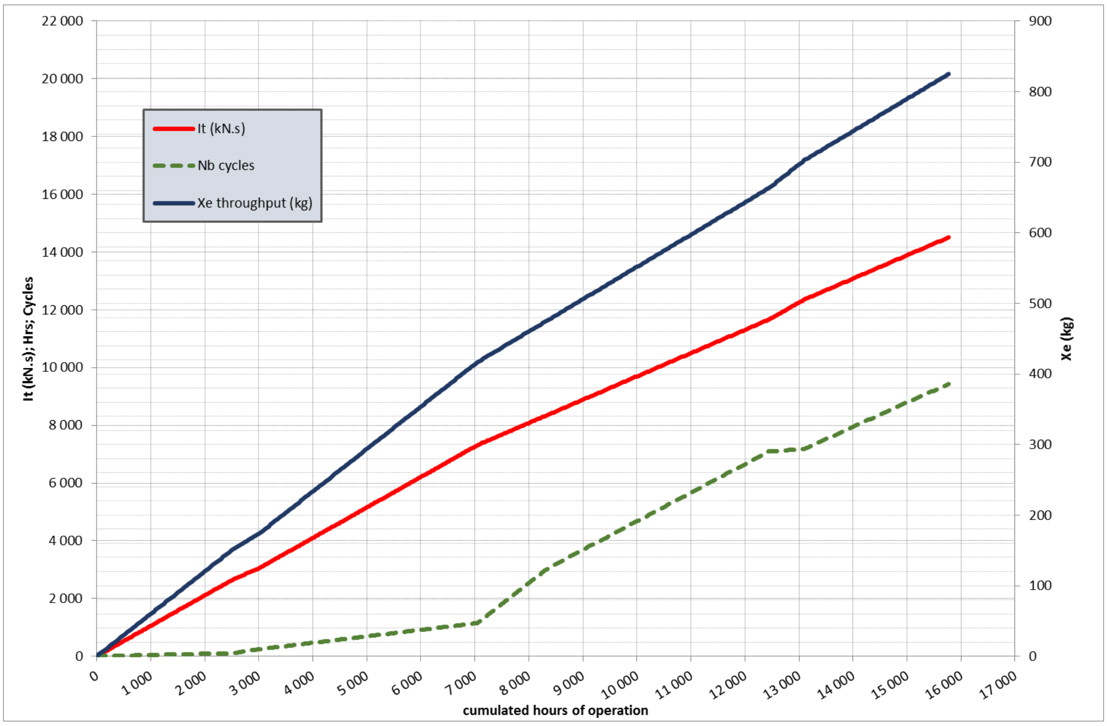


Figure 3 : PPS(R)5000 qualification profil

The main properties of the designed cathode are given in the following table:

Qualification environmental temperature	> -65°C
Pre-heating current	10 ± 0.45V
Preheating duration	< 240 s (including 60 s pulses)
Mass flow rate	[0.3 mg/s – 2 mg/s]
Discharge current range	[5 A; 20 A]
Lifetime	>15, 000 hours

The functional parts of the PPS®5000 cathode, presented in the Figure 4, has been designed thanks to a coupled thermal, fluid and plasma model. This model has been validated by a cathode equipped with thermocouples which has been tested on its whole functional range both in diode mode and on a 5 kW Hall thruster.

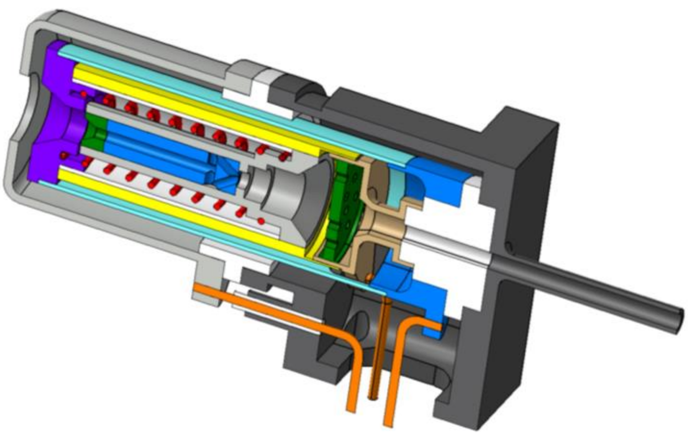


Figure 4 – Pricipal schematic Cathode

B. Modeling and functional tests

- **Preheating phase**

During this phase, the plasma is not ignited. The emitter is a thermoionic material that needs a minimum temperature in order to provide electrons. A heater filament is used so as to reach this temperature.
A thermal model is computed to define the temperature reached by each parts of the cathode. In order to validate and tune this model, an instrumented cathode is manufactured and tested in a vaccum chamber.

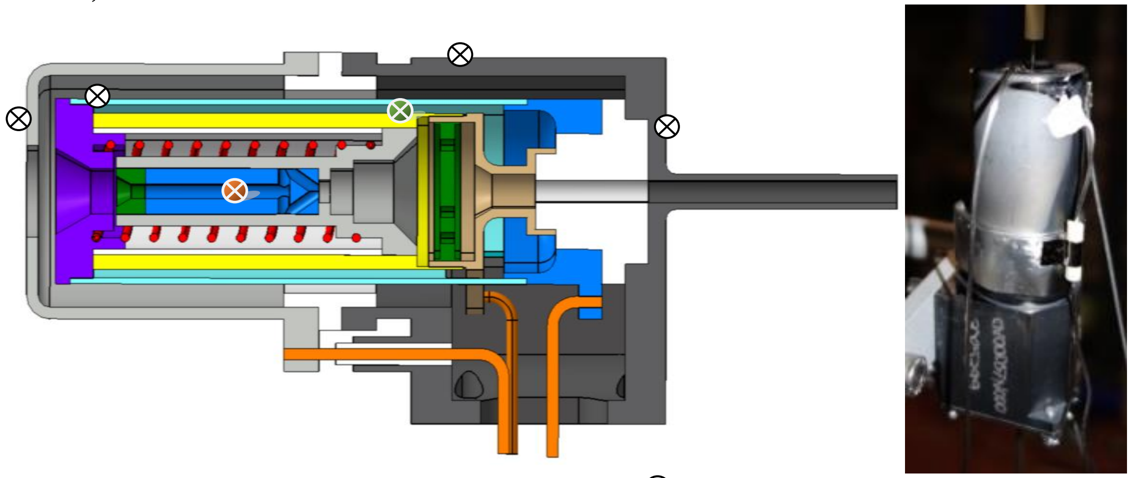


Figure 5 : instrumented cathode with thermocouples. ⊗ Represent the thermocouple positions

The results present a good prediction of maximum emitter temperature at emitter interface ⊗ and at the bottom of thermal shield ⊗ (with a phase difference) which are very important for the coupled model presented in the next paragraph. The results also helped to define the preheating delay.

- **Operating phase**

In house thermal/fluid/plasma coupled model has been developed using the thermal model validated during preheating phase. The model takes the assumption that the density and gas temperature are time independent.

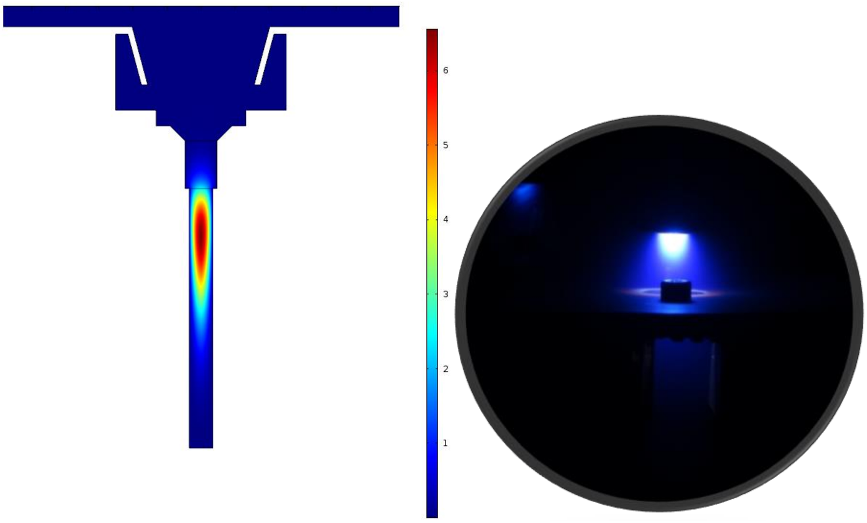
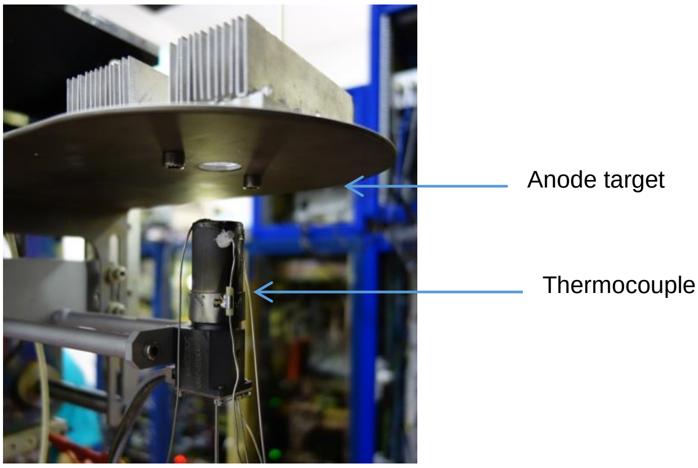


Figure 6 : plasma density inside the fluid vein (left), and the plasma discharge of the cathode

The same instrumented cathode is set inside a vacuum chamber and is operated on diode mode. The objectives of the tests are to analyze:

- Heater current influence ~[4A:11A]
- T_{off} influence ~[7min:22min]
- Influence of cathode flow rate [0.4 mg/s:2mg/s]
- Influence of discharge current [4 A : 25A]
- Measurement of minimum discharge current in diode mode
- Comparison of measurements with thermal model
- Tune of the model for a better predictive model



The self-heated behavior of the cathode is supposed when the coupled model present a convergence. The tests correlated to the model help to define the self-heated operating points of the cathode as well as the fluid vein inside the emitter to withstand the whole range of operating points of the PPS®5000 thruster.

C. Dimensions and electrical interfaces

The overall dimensions of the cathode as well as the global mass (excluding cabling) or the electrical interface are presented on the Figure 7.

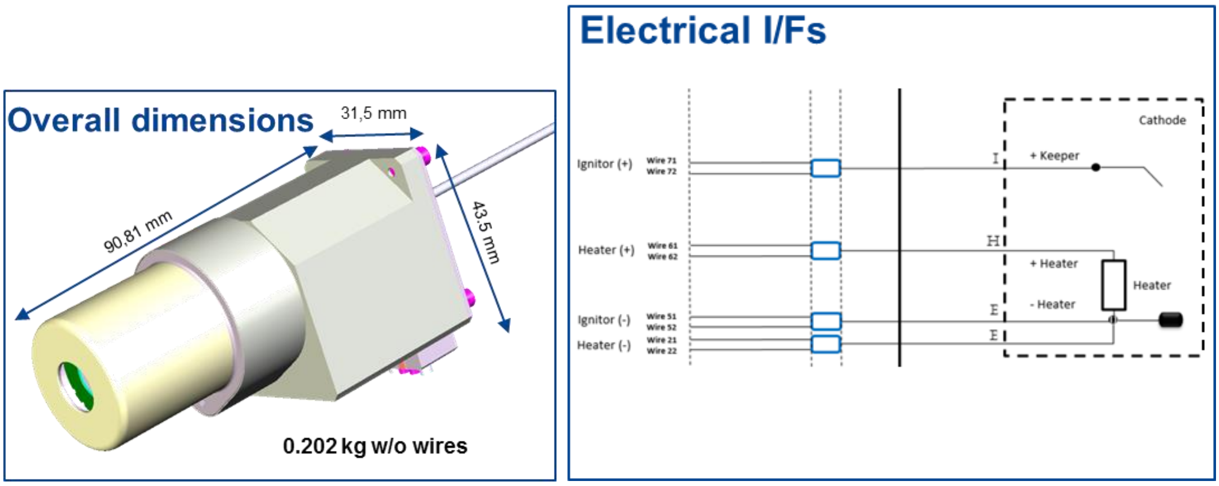


Figure 7 – Overall dimensions and mass (left), and électrical interface (right)

III. Development of the cathode

In order to meet the very stringent time-to-market constraints placed on the PPS®5000 and the lately start of the cathode development, an overlapping of the preliminary design, development and qualification phases has occurred as described on the Figure 8.

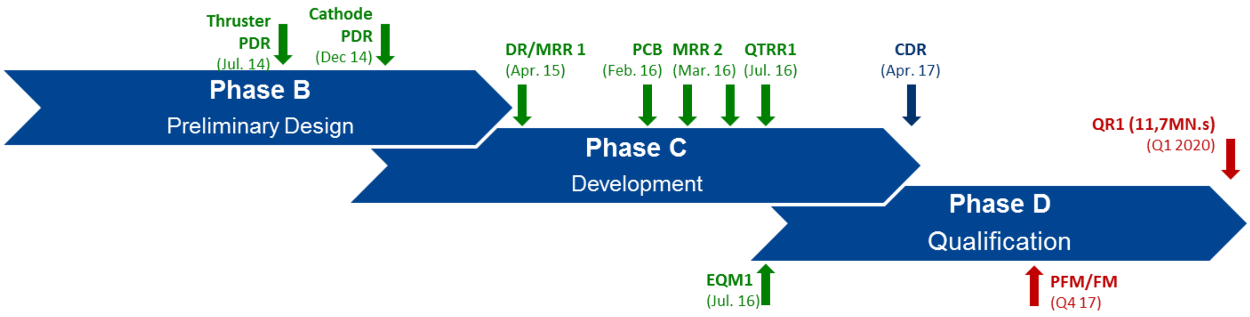


Figure 8 – development logic

In order to validate computed model as well as function aspects or mechanical stress, different structural or breadboard models have been manufactured to be used as forerunner. The tests logic for each model is presented in the Figure 9.

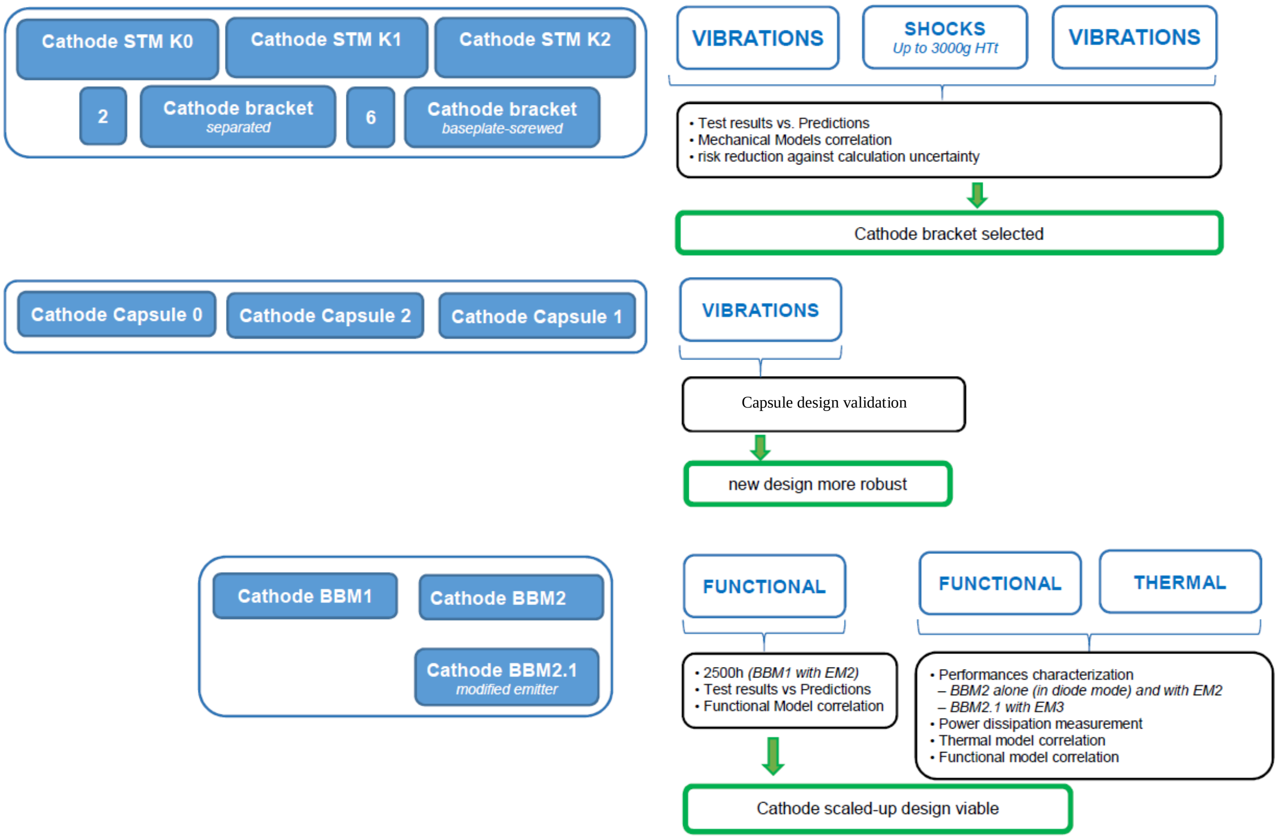


Figure 9 – cathode test logic

The qualification model takes into account all the improvement brought by each model. The qualification test campaign, gathering thruster unit and XFC, is now underway according to the Figure 10.

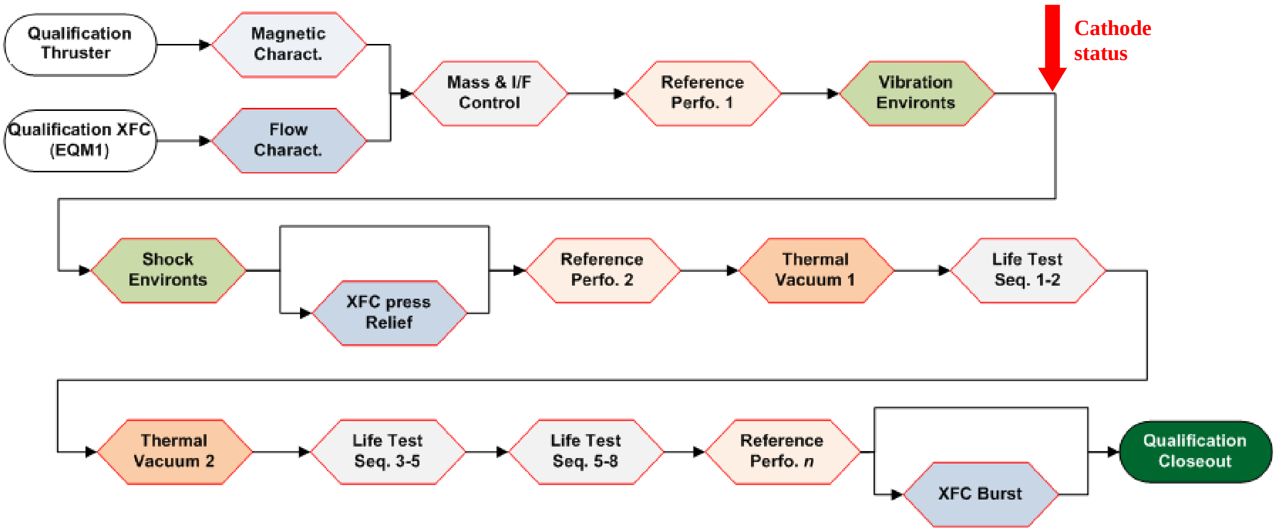


Figure 10 - Thruster Unit Qualification Test Sequence

IV. Qualification status of the cathode

The qualification model has already successfully complete 1600 h of run on a test bench with functionnal and thermal characterisation tests as well as vibration.

D. Functional behavior

The Figure 11 present the discharge current dépendance of stability of the cathode. for each discharge current. For one current, the mass flow rate down the cathode is displaced around the nominal mass flow rate until the cathode reference potential collapses. It is shown that the cathode has more than 50 percent of mass flow rate margin.

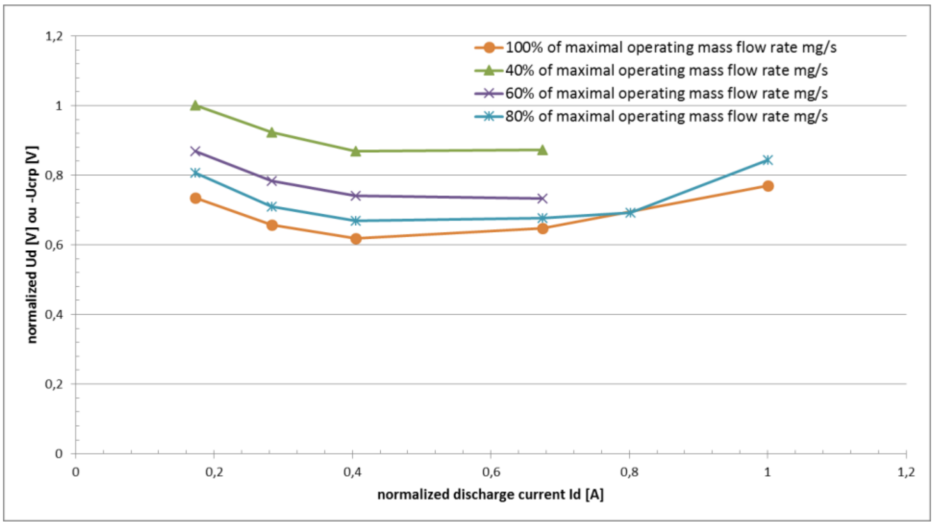


Figure 11 -- discharge current dépendance of stability of the cathode for different mass flow rates

E. Mechanical tests

The mecahnical stress are tested by :

1. Random vibration tests including high level sinus
2. Pyrotechnic choc tests

Qualification PSD (power spectral density) injected at the thruster level is a spectrum envelope that takes into account the customer's and launchers' specifications.

As described above, a simplified model but highly representative, version of the PPS®5000 Cathode is manufactured. The first mechanical tests were performed using a mock-up, see in picture Figure 12 composed with the structural Cathode model, the Bracket and a Baseplate.

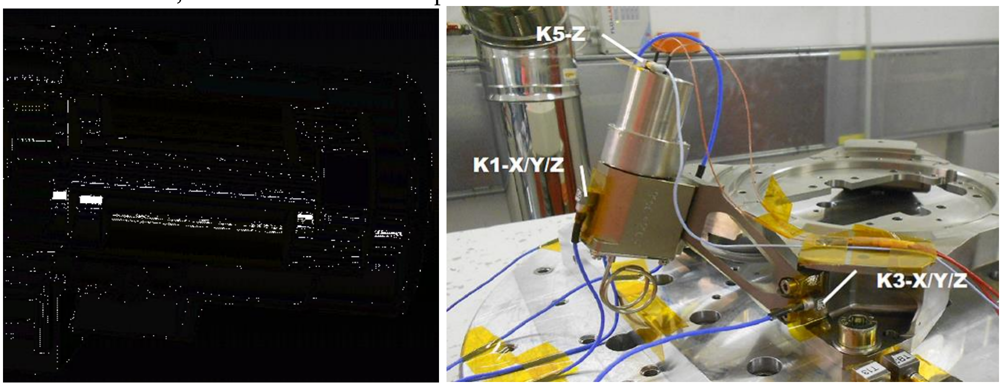


Figure 12. Pricipal schematic of the structural cathode model

The objective were to assess the cathode strength with respects to random vibrations. The full assessment has then been done on a complete qualification model testing.

The shock response spectrum (SRS), as the PSD, takes into account customer's and launchers' specifications. SRS defines the shock level at unit input. This test is only performed for the qualification model.

This test has been performed on a fully representative model of qualification design model. As a result, the cathode inner parts withstand the pyrotechnic shocks 3 times per axis and remains sound. The cathode retains nominal performances after being exposed to the shock conditions.
The cathode design is robust to mechanical loads.

V. Conclusion

The cathode has been design using heritage aquired from PPS®1350 cathode. It is an upscale including some evolutions necessary to meet the requirements as :

- ✓ Soft-start with sustain mode is stable at 5A
- ✓ the cathode covers all thruster operating points set at the qualification sequence
  - – Operating voltage 300 V and 375 V
  - – Operating current 5 to 17 A
  - – Lifetime over 15,000 h
- ✓ Ramp-up up to 10,45 A/s
- ✓ Pre-heat 180 s up to 240 s
- ✓ Mass flow rate
  - – Constant ratio between cathode and anode mass flow rate (frozen by XFC)
  - – Compliant with each mass flow rate at anode level

This cathode has also shown robustness in term of functionnal behavior as well as mechanical stress withstands.