Development of Hollow Cathodes for Electric Thrusters: Theoretical and Experimental Results

F. Paganucci, D. Pedrini, G. Becatti

- University of Pisa, Pisa, Italy
- SITAEL S.p.A., Pisa, Italy
- Jet Propulsion Laboratory, Pasadena, CA, USA

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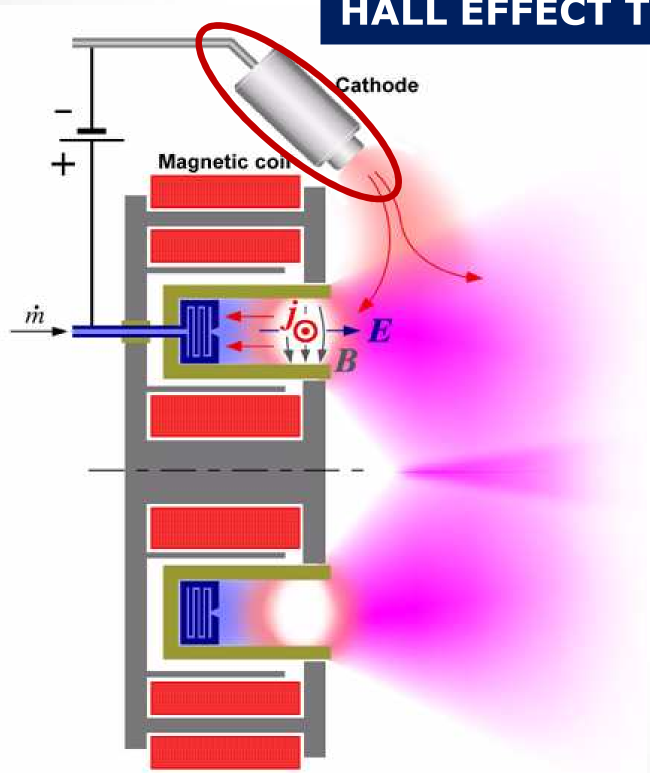
Basics of a Hollow Cathode

HOLLOW CATHODES are electron sources used to ionize the propellant and to neutralize the ion beam exhausted by ion and Hall thrusters.

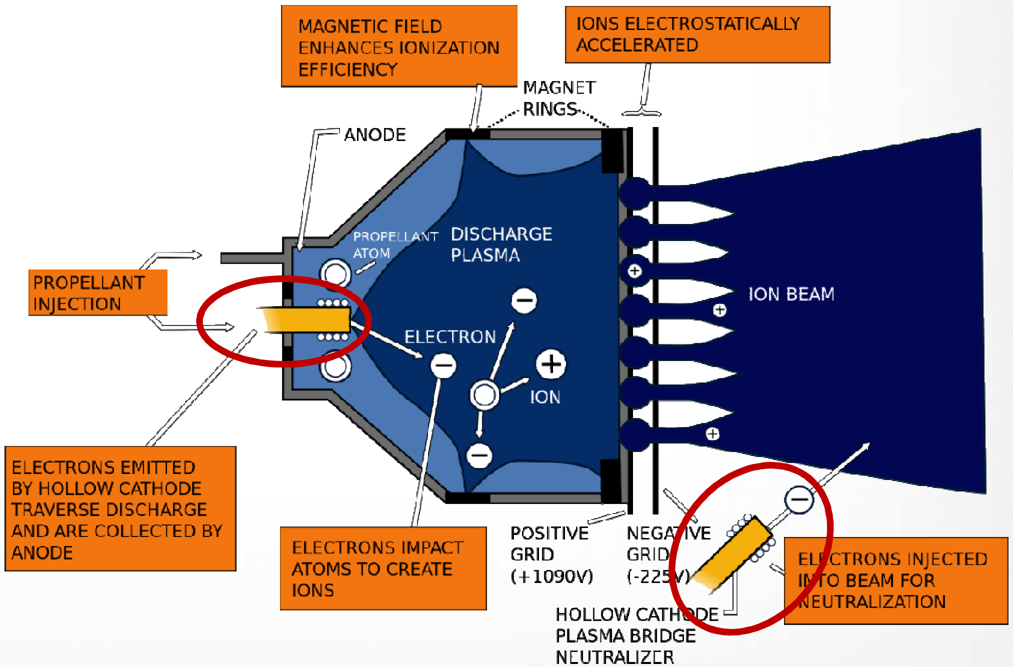
The operational **lifetime**, maximum **power**, and **performance** of these thrusters depend heavily on the capability of the cathode.

HOLLOW CATHODES are also used as plasma contactors.

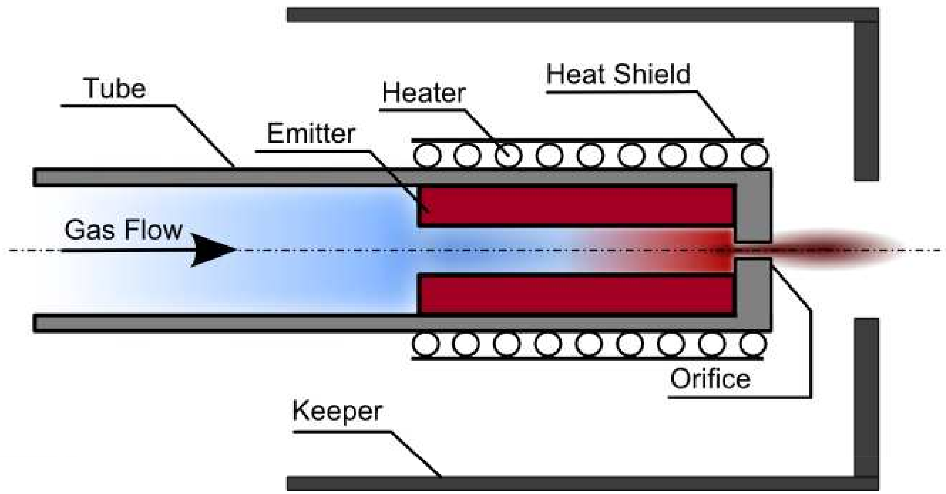
HALL EFFECT THRUSTER

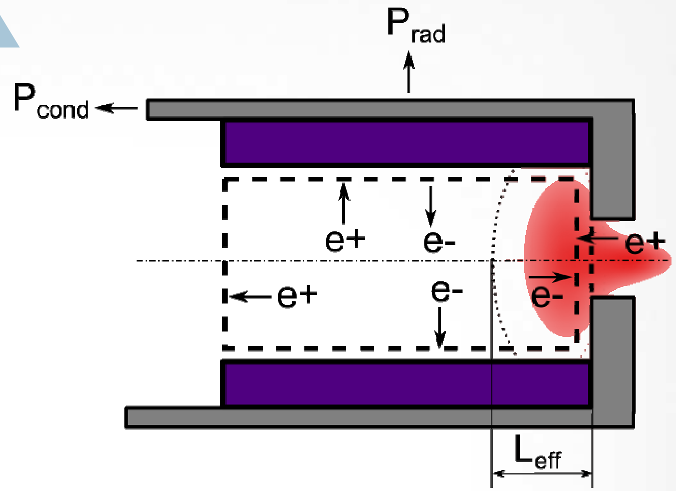


ION THRUSTER



Basics of a Hollow Cathode





- Conductive refractory **metal tube**;
- Neutral **gas** (e.g. xenon, krypton) feed;
- **Emitter** (or insert) made of low work function material which thermionically emits electrons;
- **Heater** used to increase the emitter temperature thus easing the discharge initiation;
- An **orifice plate** increases the internal pressure to efficiently ionize the propellant;
- A **keeper** electrode to start the cathode by applying a positive potential with respect to the inner tube. The keeper also protects the cathode interior parts from high-energy ion bombardment.

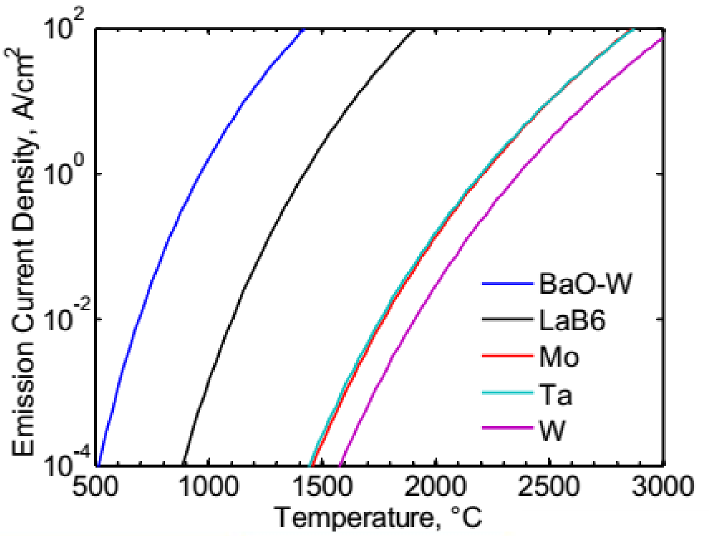
Basics of a Hollow Cathode

The cathode emits electron by **thermionic effect** from the emitter surface.

Richardson-Dushman equation (modified):

$$j = DT^2 e^{-\frac{e\varphi_0}{kT}}$$

(D: material specific modified R-D constant)



Type of emission	Cathode emitter type	Description	Work function
Oxide semiconductors	BaO	Superficial monoatomic layer of BaO over a nickel substrate	1.5 eV
Bulk material	Tantalum (Ta)	Thermionic emission from pure material	4.1 eV
	Tungsten (W)		4.55 eV
	LaB_6		2.4 – 2.66 eV
Chemically activated metallic surfaces	*Dispenser cavity reservoir*	Porous tungsten emitter over a reservoir of $BaCO_3$ or BaO	1.8 – 2.0 eV
	Dispenser impregnated	Porous tungsten matrix impregnated with $BaCO_3$:$CaCO_3$:Al_2O_3 (**4:1:1** in S-type cathodes)	1.8 – 2.1 eV
	Thoriated tungsten	Tungsten with ThO_2 (thoria), 0.5-1.5 %	2.6 eV

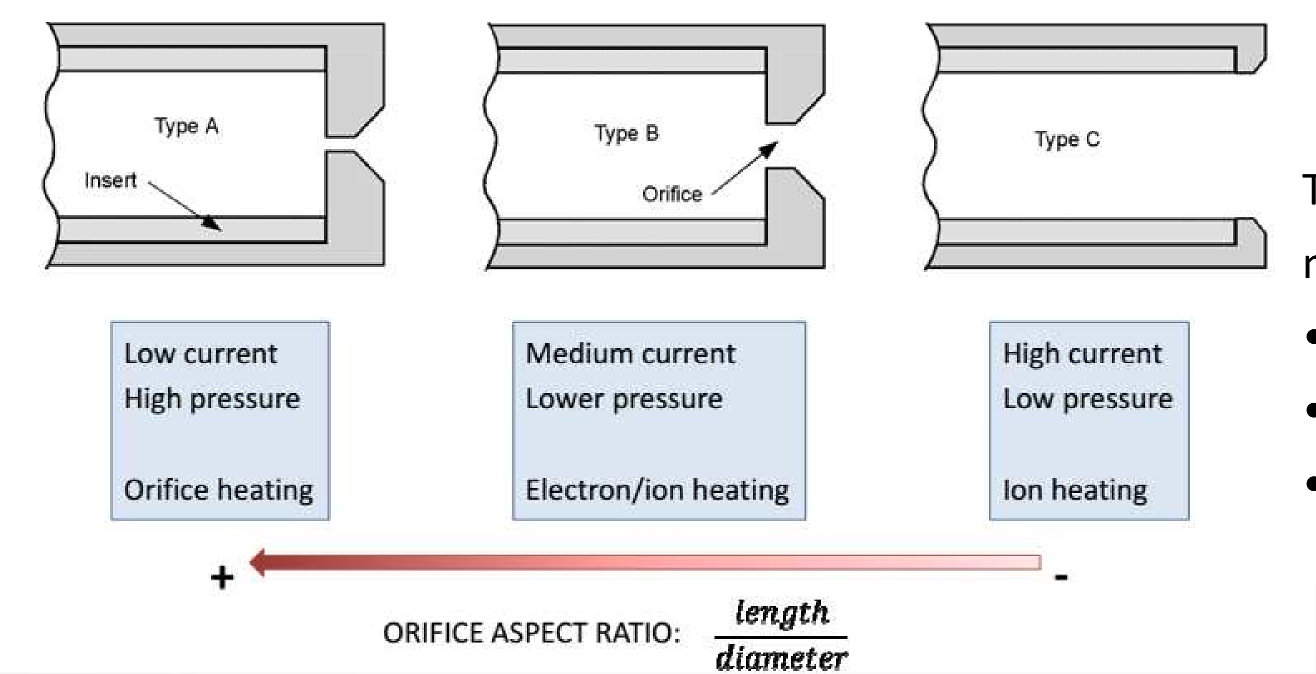
Basics of a Hollow Cathode

After the discharge ignition, the heater is switched off and the cathode operates in "self-heating" mode: the emitter is heated by plasma bombardment.

• **Orifice heating**: cathode with small orifice and high internal pressure. The high plasma power delivered to the orifice walls is transferred to the insert via conduction and radiation.

• **Ion heating**: classic heating mechanism due to ion bombardment of the insert.

• **Electron heating**: high internal pressure and high discharge current. The energetic tail of the Maxwellian electron distribution having sufficient energy to exceed the sheath potential and reach the insert surface.



The dominant heating mechanism depends on:

• **Cathode geometry**;

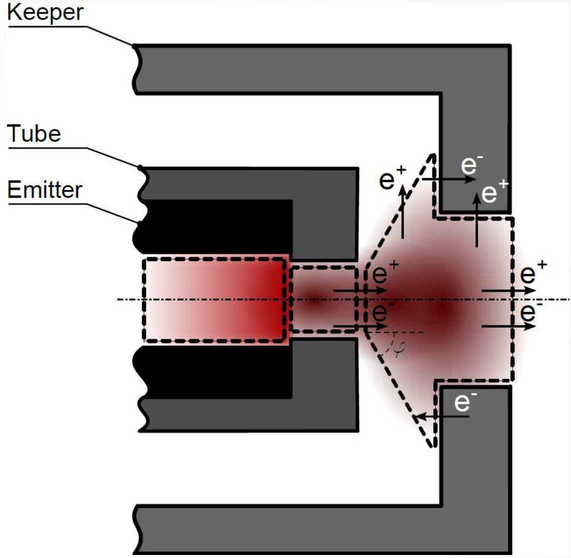
• **Internal pressure**;

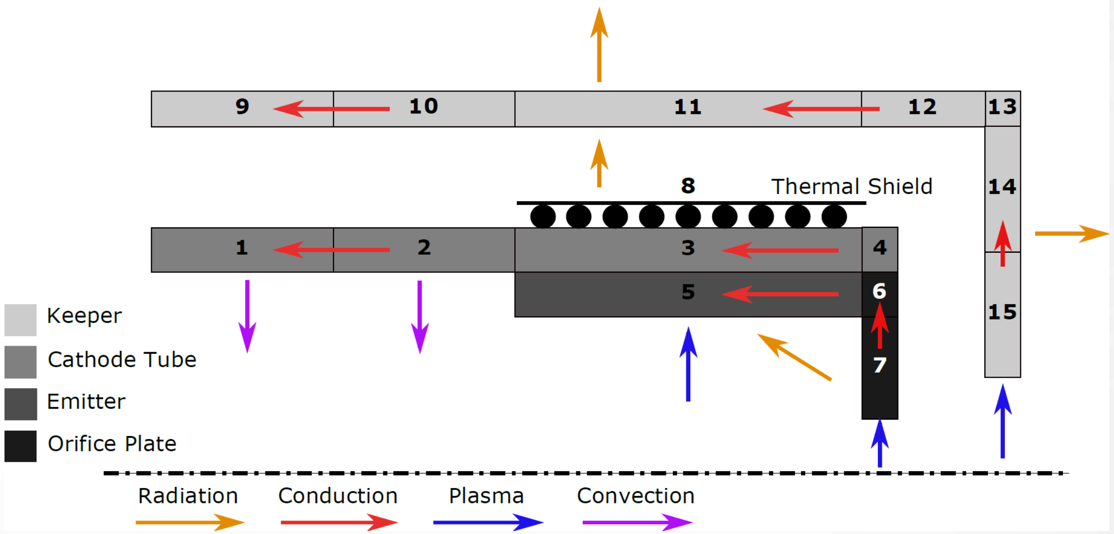
• **Discharge current**.

Cathode Model

Conceived as a flexible tool to guide cathode design

- **Reduced-order** model[1]
- **Plasma** divided in **three coupled regions**: emitter, orifice, cathode-to-keeper gap
- Dedicated **thermal** model including the keeper
- Pressure model based on a **Poiseuille flow** and **transitional** regime in the orifice
- **Step-wise ionization** included
- **Lifetime** estimation based on the emitter evaporation rate





[1] Pedrini, D., Albertoni, R., Paganucci, F., Andrenucci, M. ,"*Modeling of LaB_6 Hollow Cathode Performance and Lifetime*", Acta Astronautica, 106 (2015), 170-178.

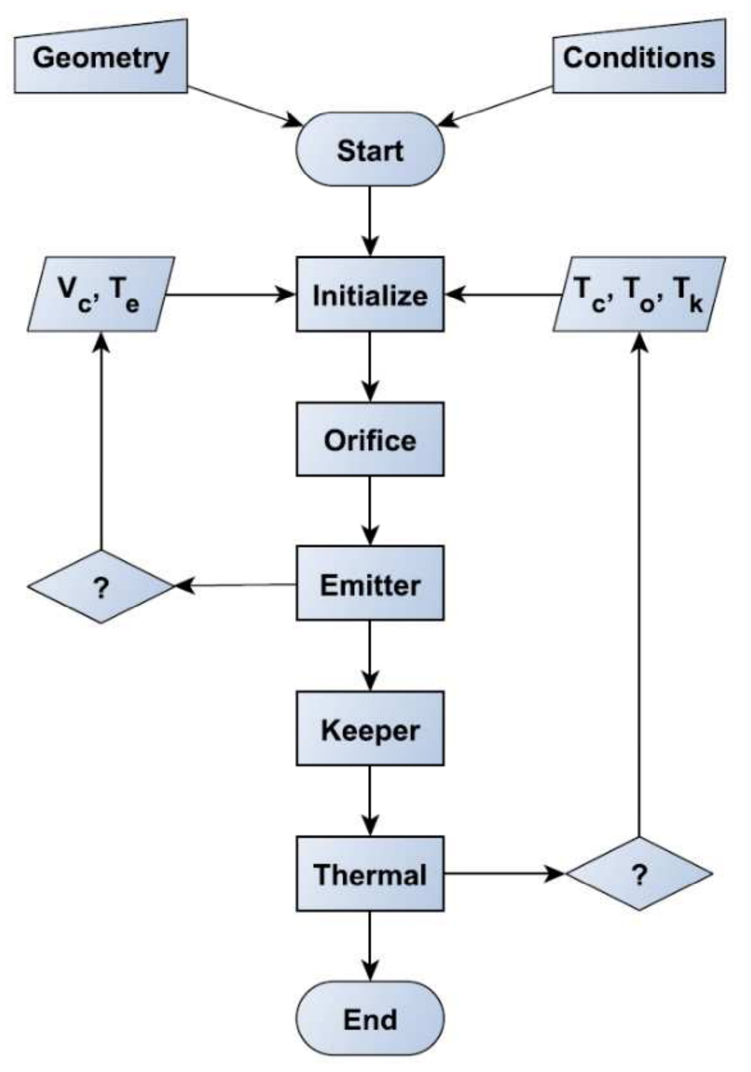
Cathode Model

Plasma and thermal sub-models combined in an iterative solution procedure.

Iteration variables:

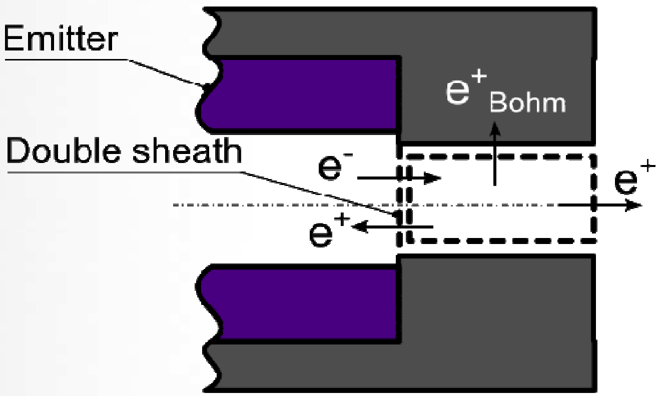
- V_c: voltage drop at the emitter sheath
- T_e: electron temperature in the emitter region
- T_c: emitter surface temperature
- T_o: orifice surface temperature
- T_k: keeper surface temperature

The effective emission length (L_{eff}) is obtained by applying the Steenbeck –Prigogine principle: (*the discharge power (and hence the voltage) is minimized for a fixed current).*



Cathode Model

Orifice



Unknowns: T_e, n, n_0

- **Ion balance:**

$$\underbrace{q\pi r_o^2 L_o n_0 n \boxed{K_i}}_{\dot{n}_{ion}} = \underbrace{j_i\left(2\pi r_o L_o + \pi r_o^2\right) + j_{th}\pi r_o^2}_{\dot{n}_{out}}$$

Ionization rate for single electronic impact and for multiple impact.

- **Plasma energy balance:**

$$\underbrace{RI_d^2}_{P_R} = \underbrace{\dot{n}_{ion}\langle\varepsilon_i\rangle}_{P_{ion}} + \underbrace{2\frac{k_B}{q} I_d\left(T_{e,o} - T_{e,e}\right)}_{P_{conv}} + \boxed{\cancel{P_{ds}}}$$

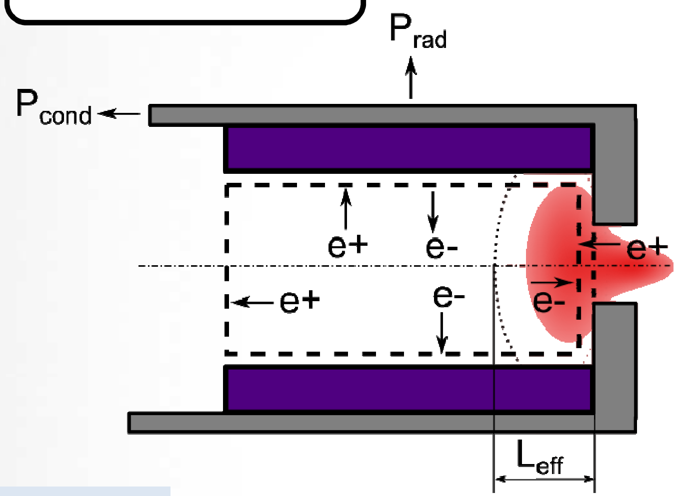
Double sheath approximation

- **Pressure equation (mass continuity + state equation):**

$$(n + n_0)k_B T_o\left(1 + \alpha\frac{T_e}{T_o}\right) = \frac{\dot{m}}{\pi r_o^2(1 + 8Kn)}\sqrt{\frac{R_g T_o}{\gamma}\left(1 + \alpha\frac{T_e}{T_o}\right)}$$

Cathode Model

Emitter



- **Current density:** $j = \dfrac{I_d}{A_{eff}} = j_i + j_{em} - j_{er}$

- **Ion balance:** $\dot{n}_{ion} + \dot{n}_{in} = \dot{n}_{out}$

- **Plasma energy balance:**

$$f(V_{ds}) \quad \boxed{P_{i,o}} + P_R + P_{em} = P_i + P_{er} + P_{conv}$$

Unknowns:

T_e

V_c

n

n_0

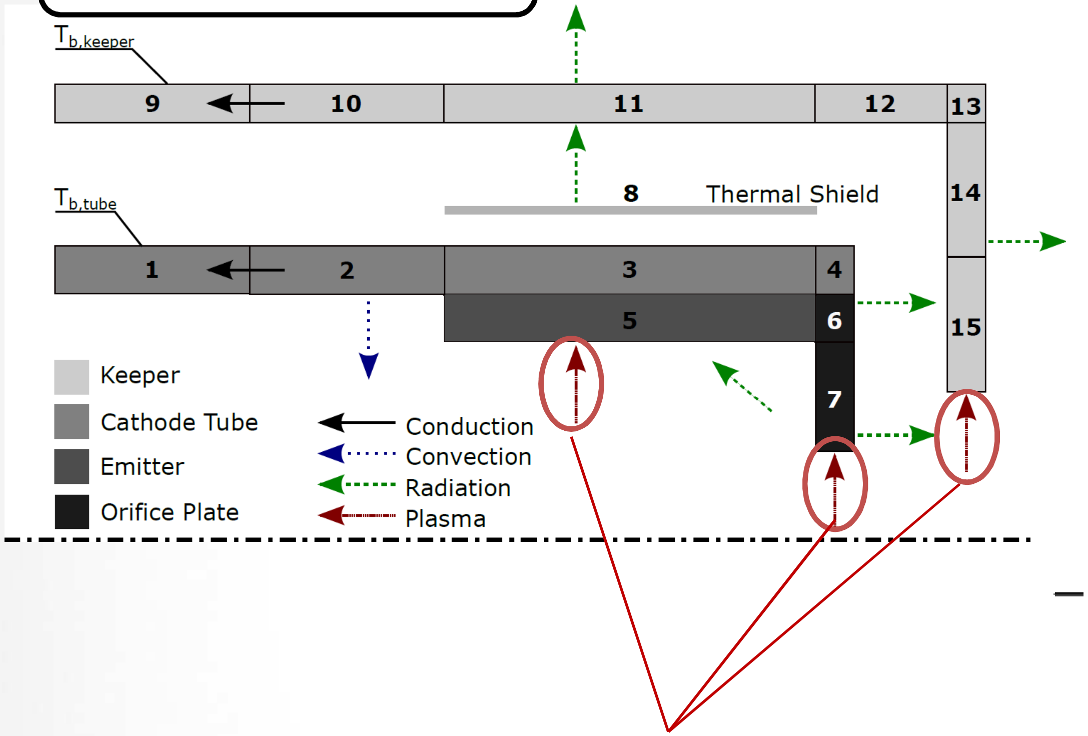
- **Pressure equation:**

$$(n+n_0)k_B T_c\left(1+\alpha\frac{T_e}{T_c}\right) = \sqrt{\dot{m}\frac{16\mu}{\pi r^4(1+8Kn)}R_g T_o L + p_o^2} + \frac{1}{2}\frac{p_o}{R_g T_o}\boxed{\bar{u}_o^2}(1+K_L)$$

Orifice average speed (Poiseuille flow)

Cathode Model

Thermal model



Thermal input from previous plasma model

Unknowns:

T_i, P_i

J_i

- **Power balance:**

$$-P_i + \frac{(\sigma_{SB} T_i^4 - J_j)}{R_i} + \sum_j \frac{(T_i - T_j)}{R_{cond,ij}} = 0$$

$$\sum_j \frac{(J_i - J_j)}{R_{ij}} - \frac{(\sigma_{SB} T_i^4 - J_j)}{R_i} = 0$$

Design Guiding Lines

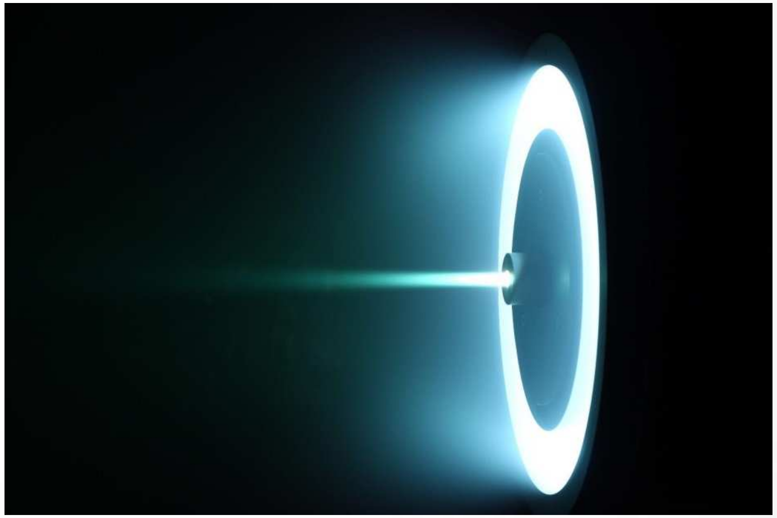
- An orifice diameter which minimizes the power exists;
- An increase of the emitter inner diameter yields a cathode lifetime increase;
- A reduction of the orifice length yields a reduction of the operation temperatures;

The theoretical model has been used for the development of hollow cathodes for HET of different power.

Tests carried out on the cathodes have allowed the model to be validated.

Cathodes developed at Sitael

Name	HC1	HC3	HC20	HC60
Emitter	LaB_6 / BaO-W	LaB_6	LaB_6	LaB_6
Current range	0.3 – 1 A	1 – 3 A	8 – 20 A	30 – 60 A
Mass flow rate (Xe)	0.08 – 0.5 mg/s	0.08 – 1 mg/s	1 – 4 mg/s	2 – 6 mg/s
Reference HET	HT100	HT100/HT400	HT5k	HT20k



HC1

Hollow cathode for the 100 W-class Hall thrusters

Discharge current	0.3 – 1 A
Mass flow rate	0.08 – 0.5 mg/s
Heater power	< 25 W
Cathode mass (w/o harnesses)	< 30 g
Expected lifetime	> 4000 h

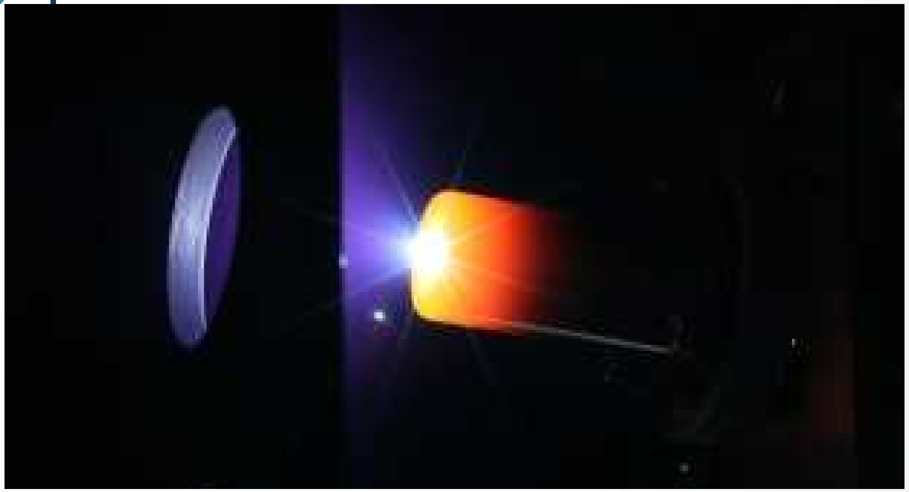
More than **200 hours** of continuous operation
More than **30 ignitions**

Cathode tested with and without a **heater**

- **Diode** mode with the keeper
- Diode mode with anode plate
- **Triode** mode with keeper and anode

Ignition parameter	With heater	Heaterless
Keeper voltage	300 V	700 V
Mass flow rate, Xe	0.5 mg/s	1 mg/s
Heater power	< 25 W	N.A.

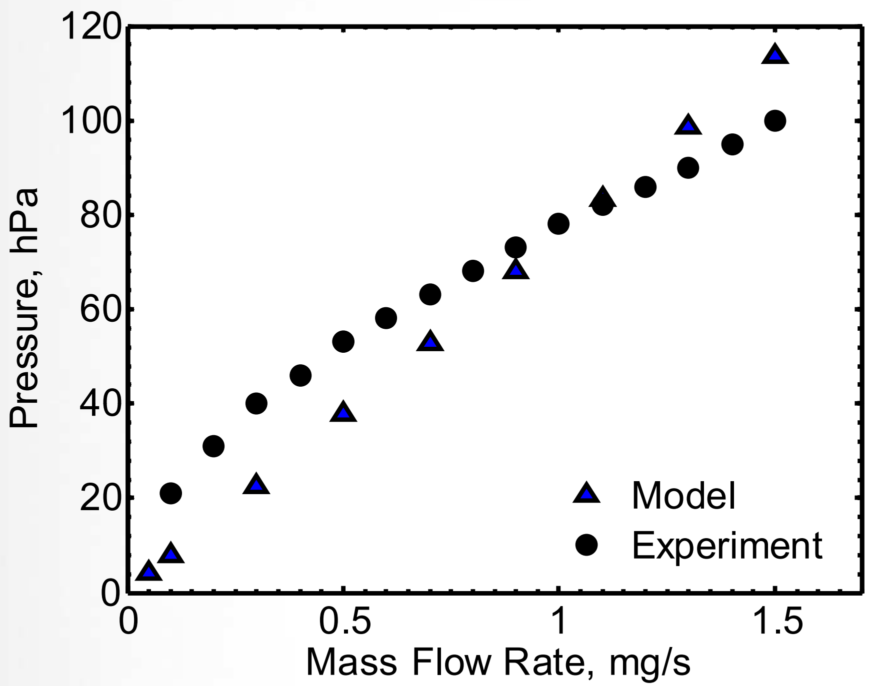
1 A keeper current, 0.1 mg/s Xe



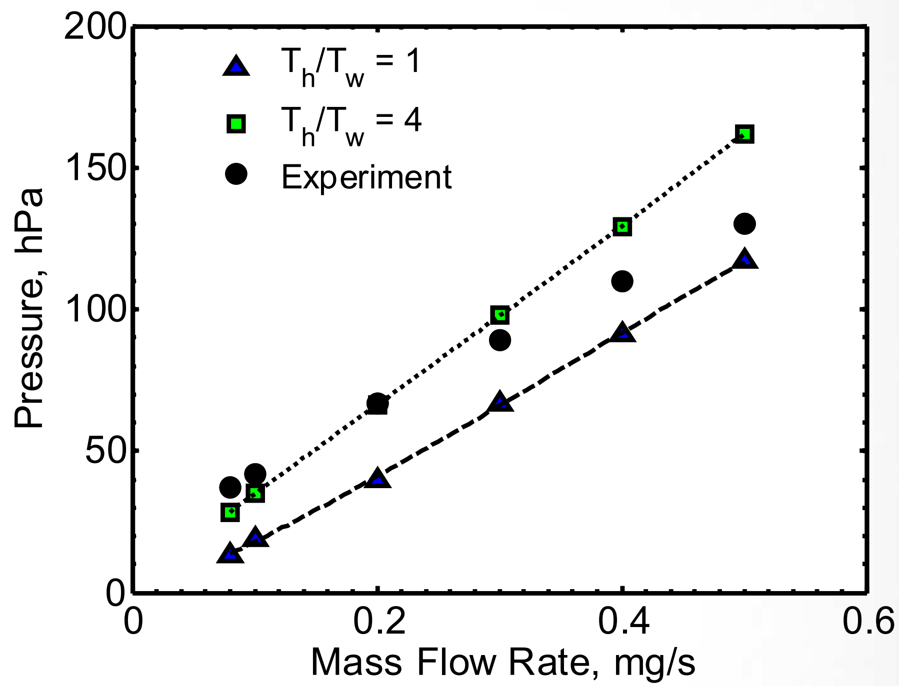
1 A keeper current, 0.9 A anode current, 1 mg/s Xe

HC1

Cathode Pressure



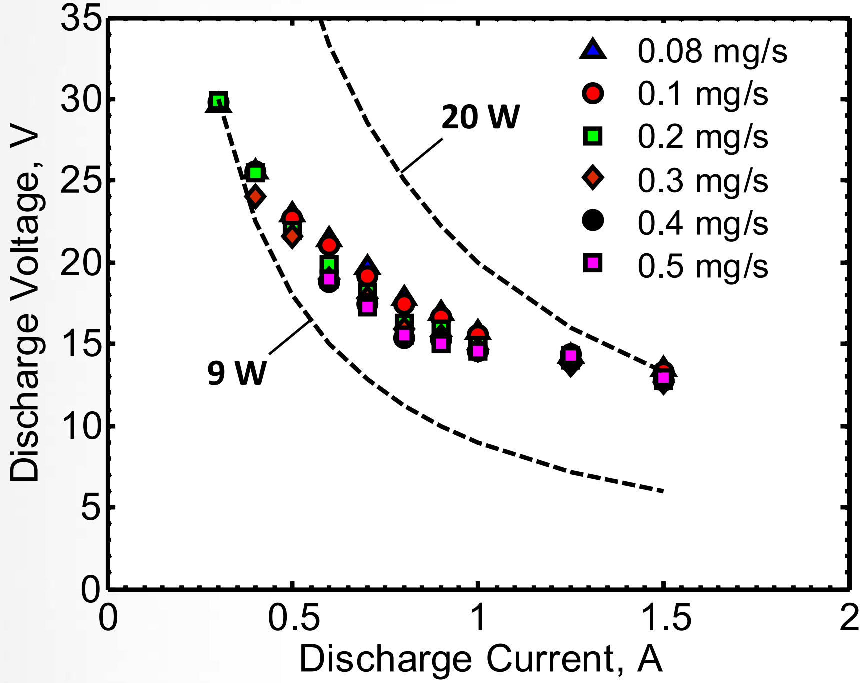
Comparison at **room conditions**



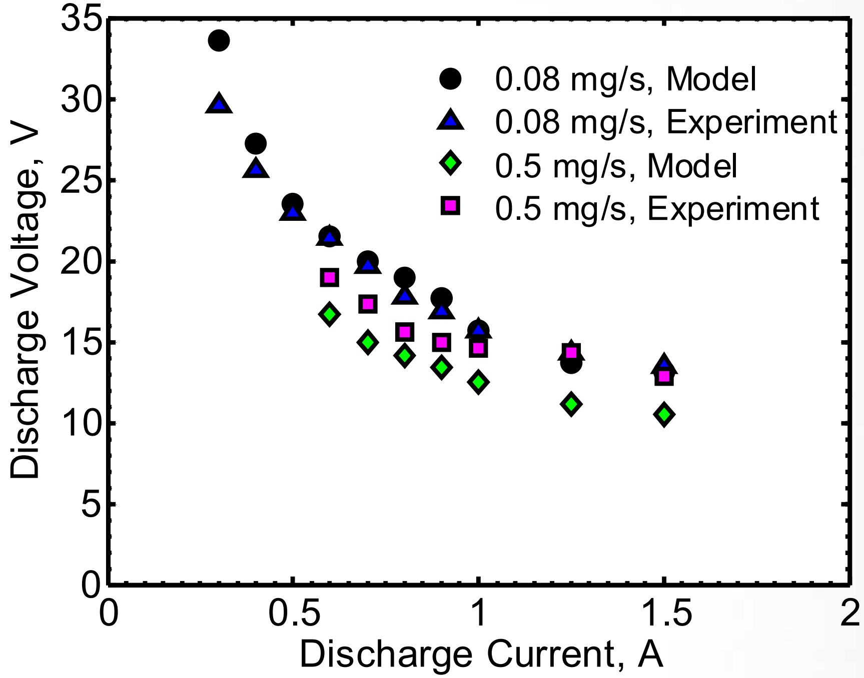
1 A keeper current, theoretical results for different ratios of the heavy particles temperature, T_h, to the wall temperature, T_w

HC1

Electrical Characteristics – Diode Mode with the Keeper



Electrical characteristics in diode mode with the keeper, xenon propellant



Discharge voltage comparison with the model results

HC3

Hollow cathode for 100-400 W Hall thrusters

Discharge current	1 – 3 A
Mass flow rate	0.08 – 1 mg/s
Heater power	< 50 W
Cathode mass (w/o harnesses)	< 100 g
Expected lifetime	> 10000 h

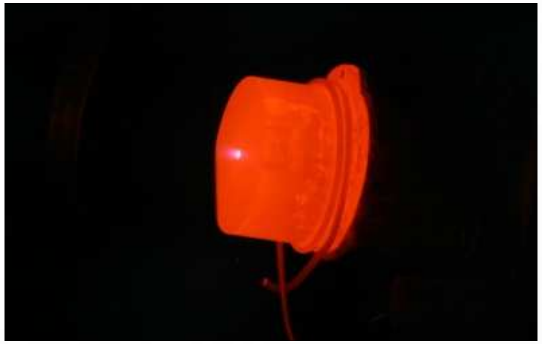
More than **120 hours** of continuous operation
More than **60 ignitions**

HC3 operating with the HT100D Hall thruster (Xe)

Cathode tested with and without a **heater**

- With **keeper** only
- With **anode plate**
- With Sitael **HT100D** 100 W Hall thruster

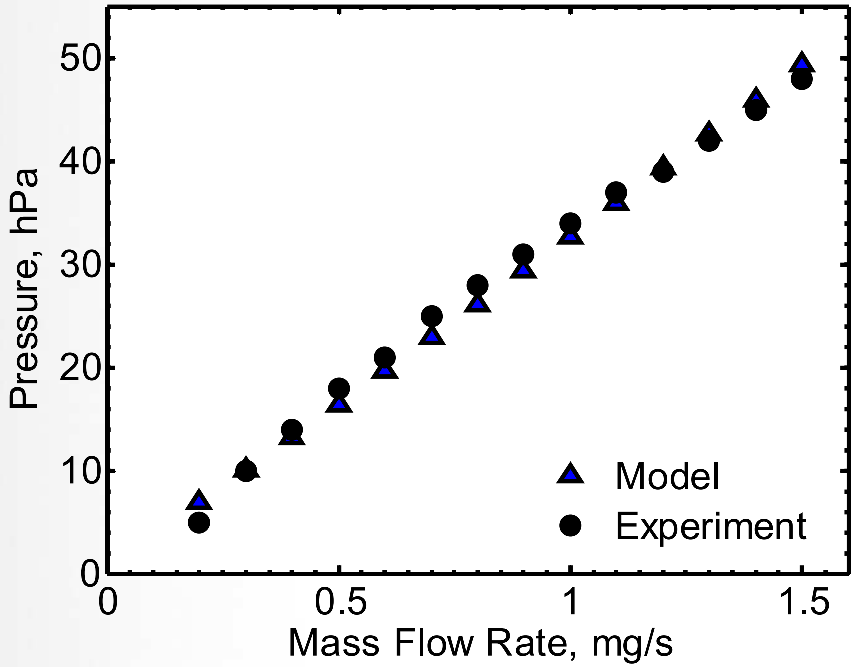
Ignition parameter	With heater	Heaterless
Keeper voltage	300 V	950 V
Mass flow rate, Xe	0.4 mg/s	1 – 2 mg/s
Heater power	< 50 W	N.A.



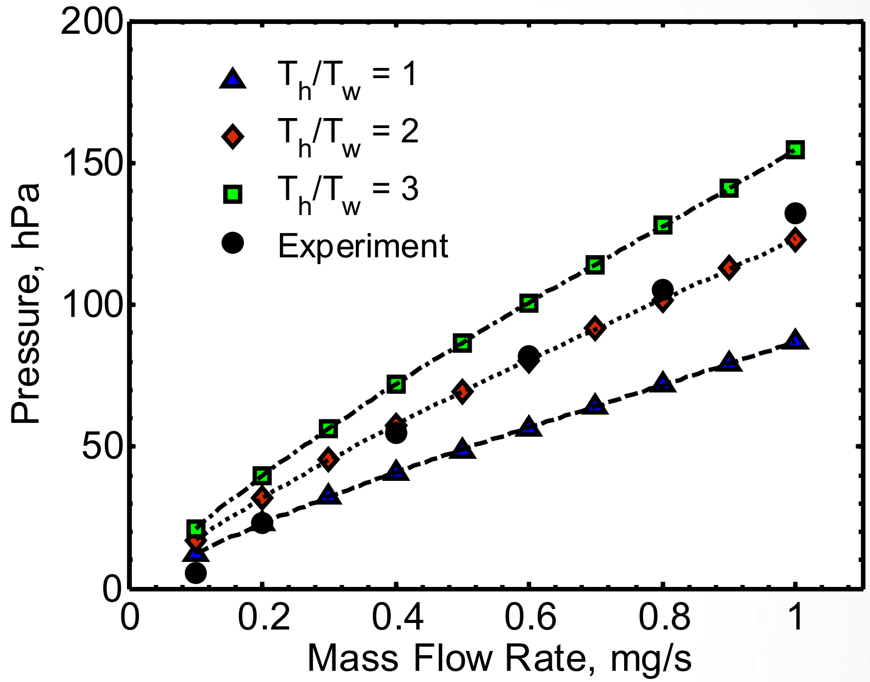
1.5 A keeper current, 1 mg/s Xe

HC3

Cathode Pressure



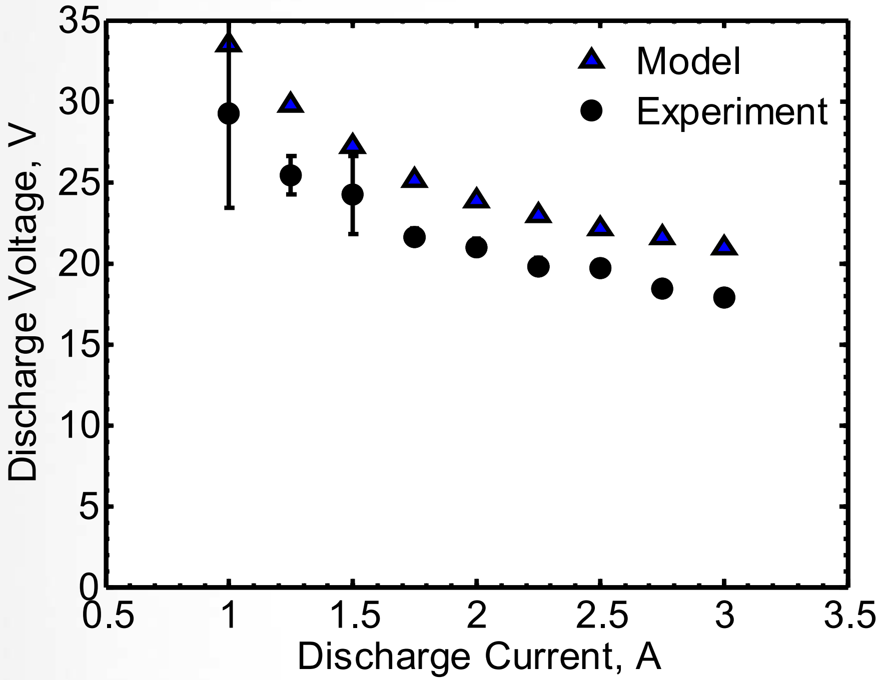
Comparison at **room conditions**



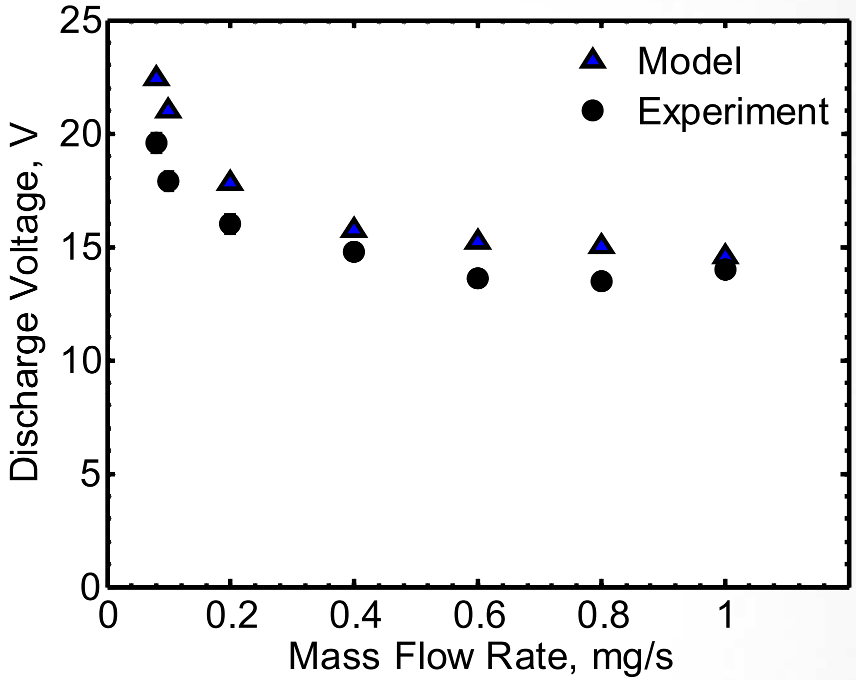
3 A keeper current, theoretical results for different ratios of the heavy particles temperature, T_h, to the wall temperature, T_w

HC3

Electrical Characteristics – Diode Mode with the Keeper



Discharge voltage comparison with the model results at **0.1 mg/s Xe**



Discharge voltage comparison with the model results at **3 A**

HC20

Hollow cathode for the 5 kW-class Hall thrusters

Discharge current	8 – 20 A
Mass flow rate	1 – 4 mg/s
Cathode mass (w/o harnesses)	< 300 g
Expected lifetime	> 10000 h

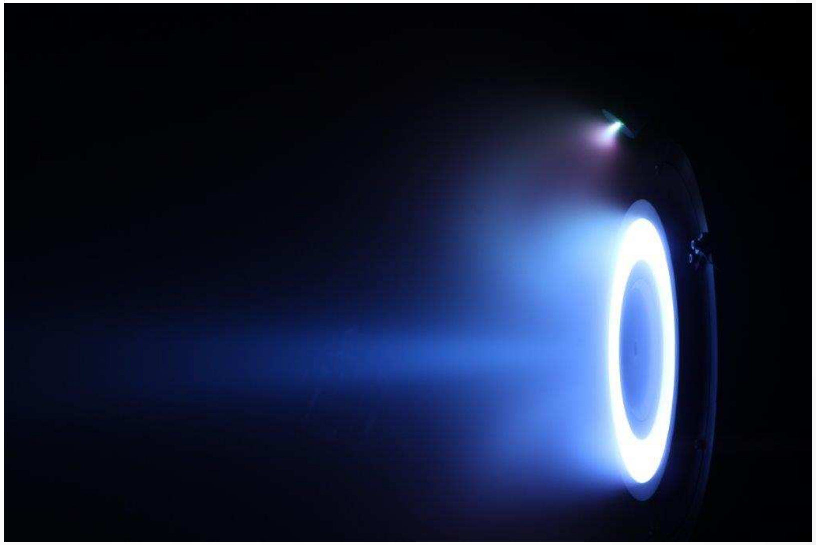
About **1000 hours** of continuous operation
More than **100 cold ignitions**

Heaterless cathode, tested with **Xe** and **Kr**

- With **keeper** only
- With **anode plate**
- With Sitael **HT5k** 5 kW Hall thruster

Ignition parameters

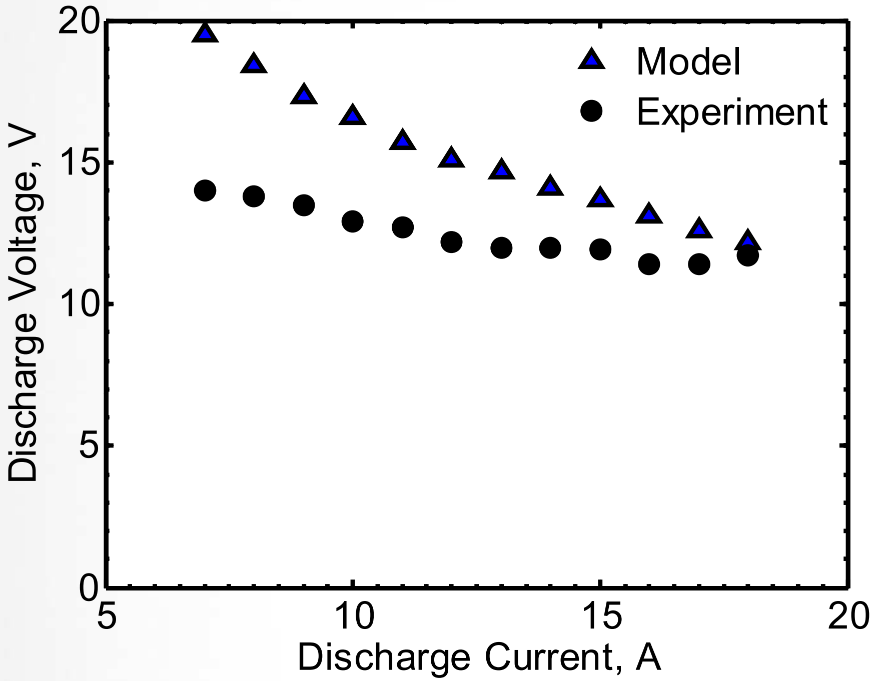
- **800 V** keeper voltage
- **5 mg/s** mass flow rate



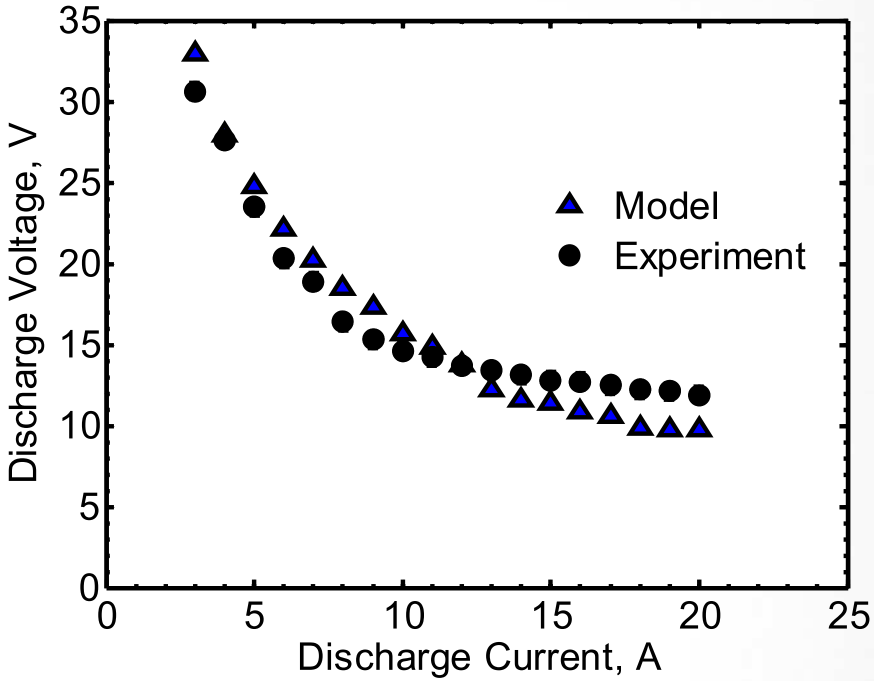
HC20 operating with the HT5k Hall thruster (Xe/Kr)

HC20

Electrical Characteristics – Diode and Triode Mode with Anode Plate



Discharge voltage comparison with the model results at **2 mg/s Xe**, floating keeper

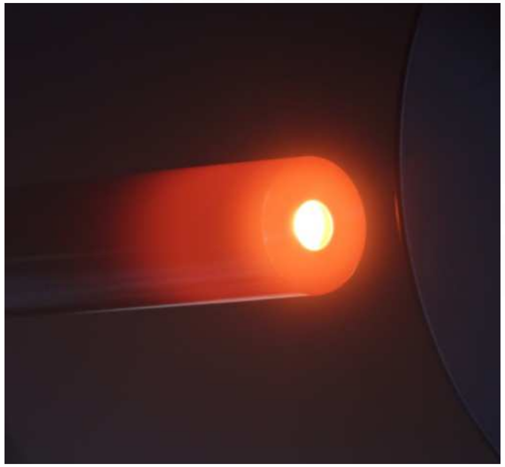


Discharge voltage comparison with the model results at **2 mg/s Kr**, 2 A keeper current

HC60

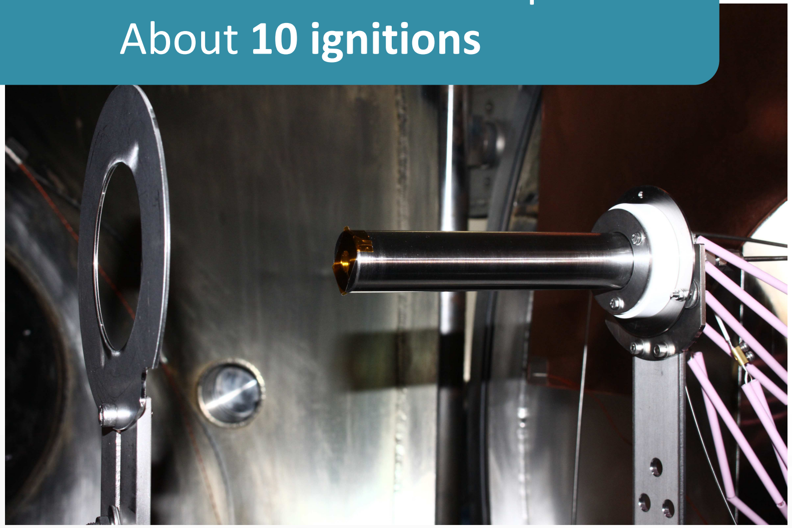
Hollow cathode for the 20 kW-class Hall thrusters

Discharge current	30 – 60 A
Mass flow rate	2 – 6 mg/s
Heater power	< 250 W
Cathode mass (w/o harnesses)	450 g
Cathode dimensions	ϕ 80 x 220 mm
Expected lifetime	> 10000 h



HC60 during the initial heating phase

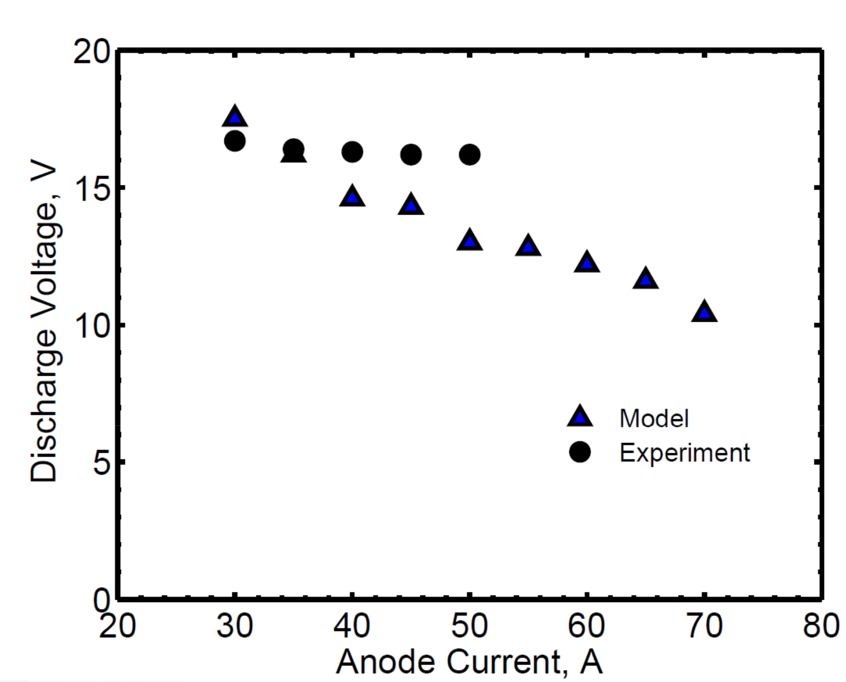
About **20 hours** of continuous operation
About **10 ignitions**



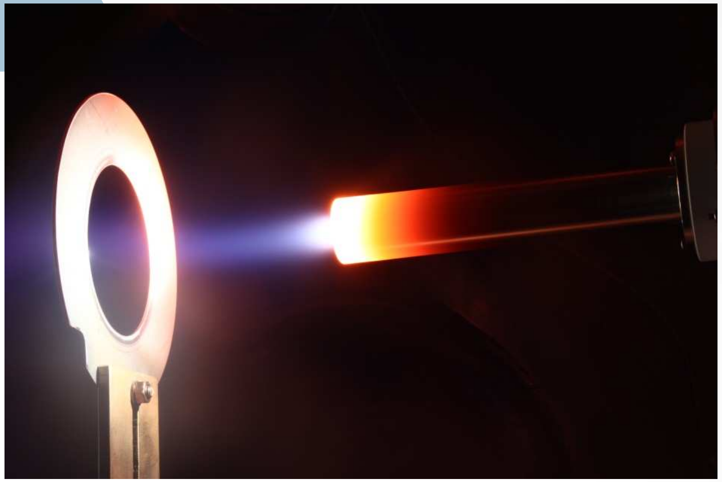
Setup of HC60 before the characterization tests

Ignition parameter	With heater	Heaterless
Keeper voltage	450 – 500 V	800 – 950 V
Mass flow rate, Xe/Kr	5 mg/s	12 mg/s
Heater power	< 250 W	--

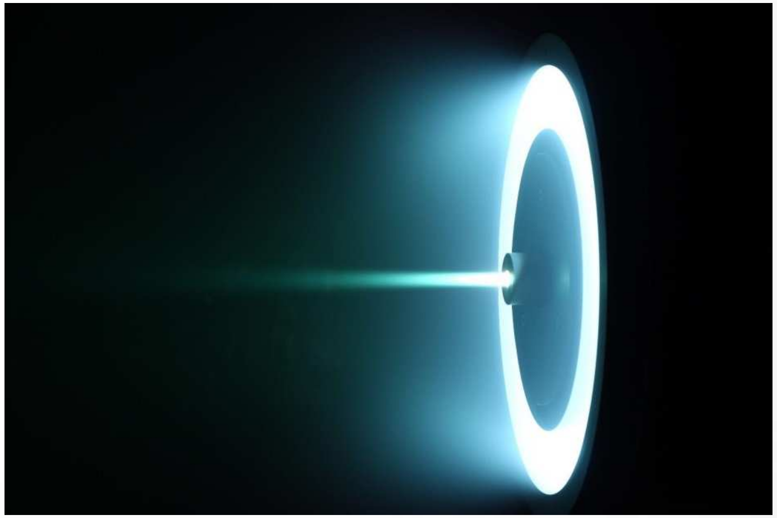
HC60



Discharge voltage comparison with the model results at **5 mg/s Xe**, floating keeper

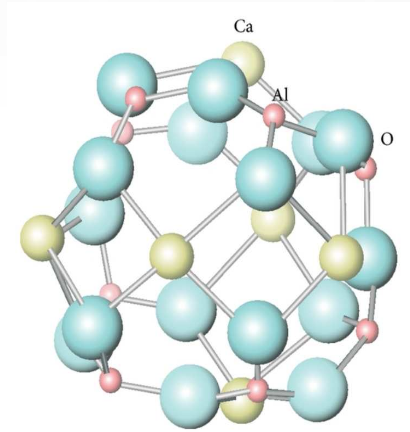


HC60 during the characterization test (10 A keeper current, 38 A anode current, 3 mg/s Xe)



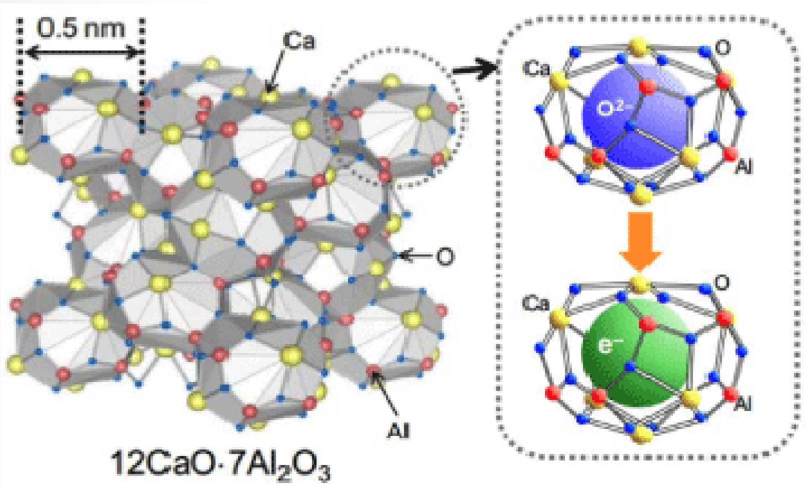
HC60 coupled with the thruster HT20k (xenon)

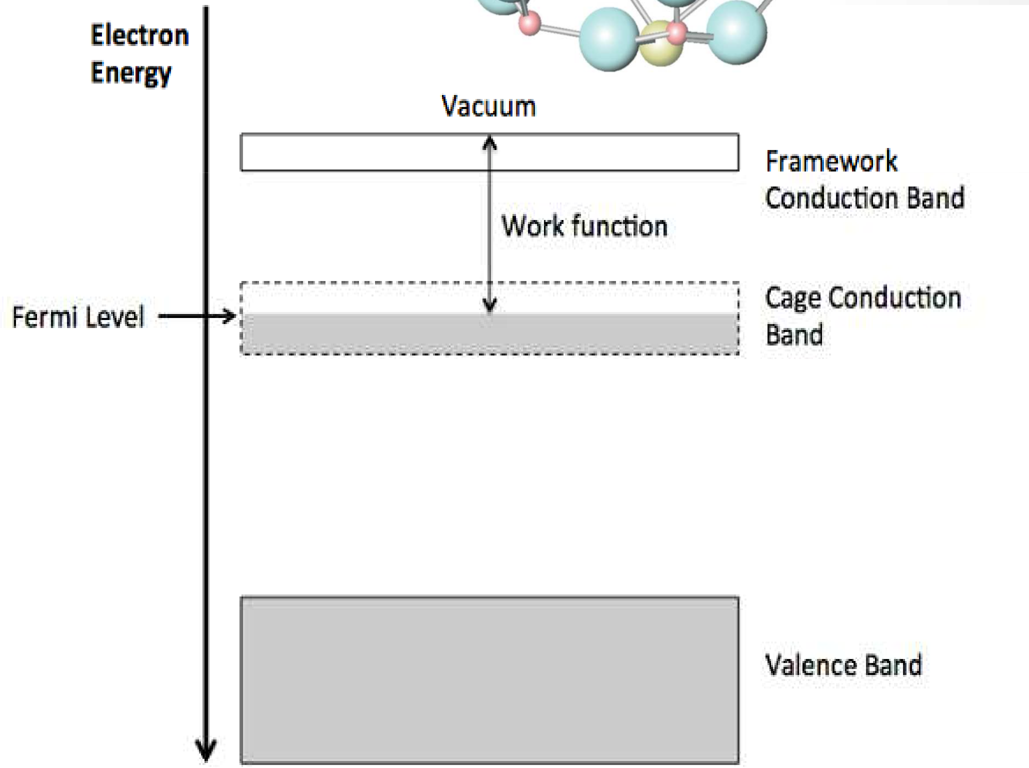
Further Developments



Development of emitter with a lower work function

(as the calcium aluminate compound 12CaO-7Al_2O_3, in **electride** form, with a measured work function of **0.76 eV**)



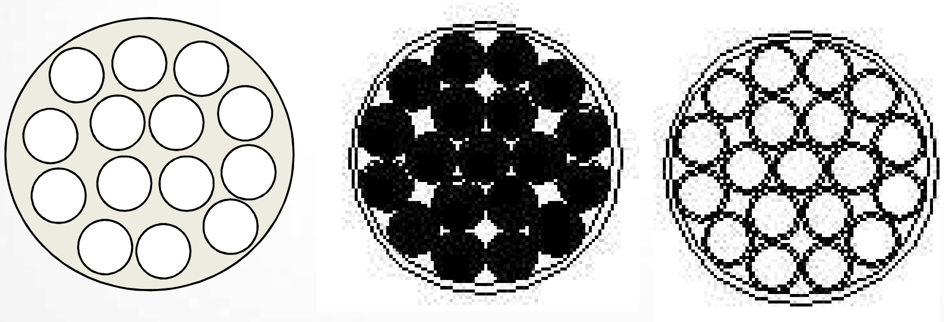


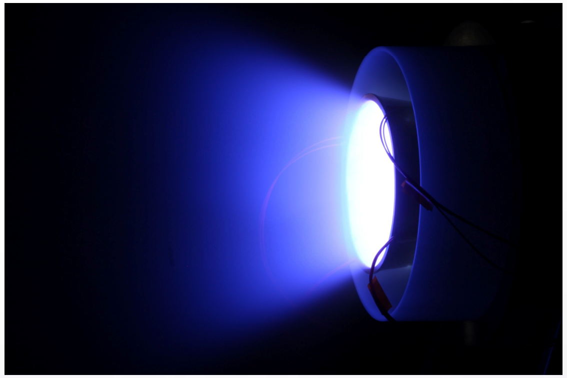
Further Developments

Operation with alternative propellant (iodine)

	Xenon	Iodine
Atomic mass [u]	131,3	126,9
First ionization potential [eV]	12,1	10,5
Storage	Supercrit./Cryo.	Solid
Storage density [g/cm³]	1,6-3,0	4,9
Cost [$/kg] (2016)	2200	83
Reactivity	No	Material dependent

Development of multichannel cathodes for kAs currents (MPDT)





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