Innovative Technologies Development for High Power Electric Propulsion Systems

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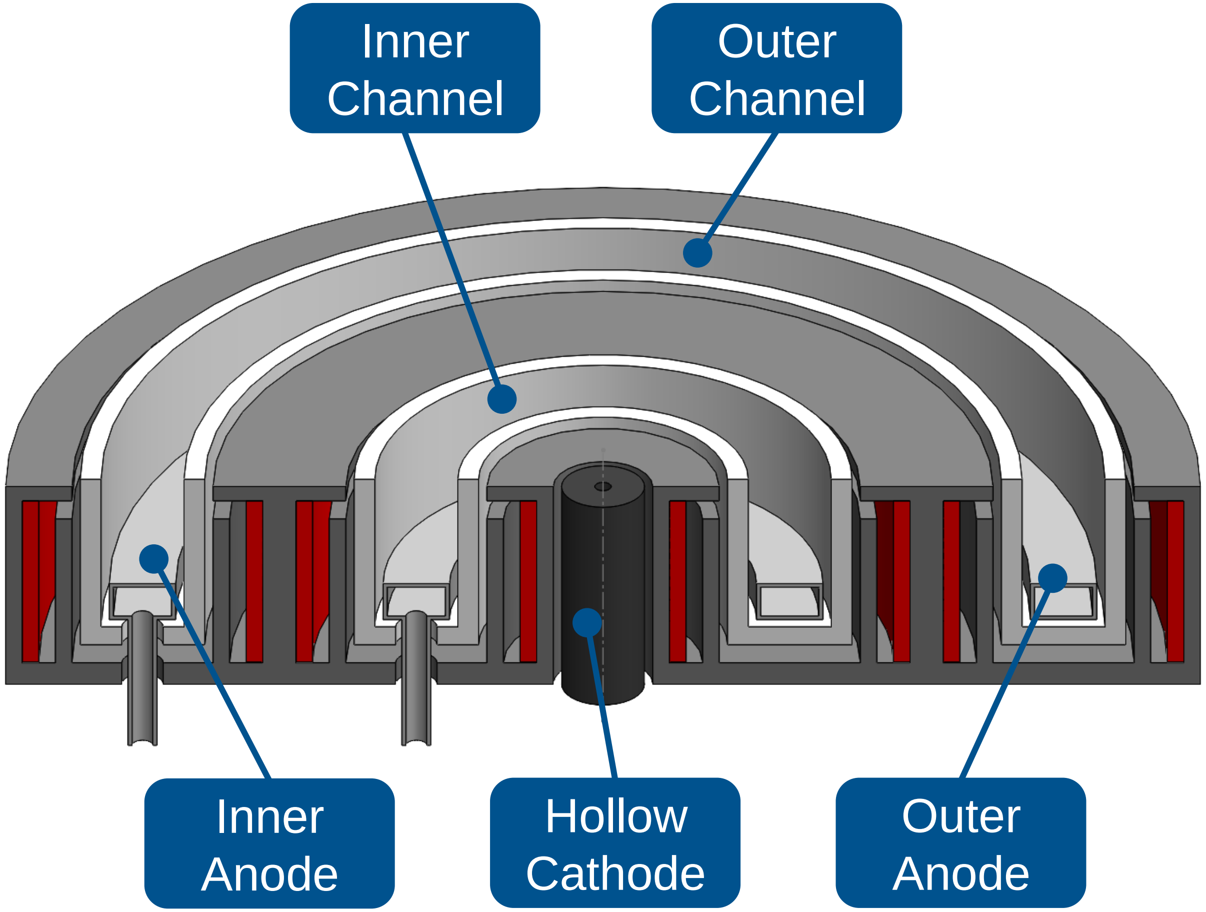
Nested Hall Thrusters

Nested Hall Thrusters are obtained integrating coaxially two or more discharge channels (possibly around a hollow cathode).

PROS	CONS
• Higher power density • Greater throttleability • Shared cathode • Better performance	• More scaling constraints • Added Complexity • More thermal issues



Possible causes of better performance:

- Reduction of the beam divergence due to an upstream shift of the acceleration region.
- Increase of mass utilization efficiency due to neutral ingestion.

The TANDEM project

Result of the collaboration between University of Pisa and Aerospazio Tecnologie S.r.l. in the framework of an ESA-TDE (Jan 2021).

Main objectives:

Designing, manufacturing, assembling and testing a high-power dual-channel magnetically shielded Hall thruster prototype.

Requirements from ESA	
Nominal discharge power	20 kW
Maximum discharge power	>25 kW
Maximum thrust	>1.25 N
Nominal thrust efficiency	>60%
Nominal specific impulse	>2000 s
Total impulse	>60 MNs

Thruster Overview

Components and materials:

- 2 boron nitride channels, magnetically shielded.
- Shared magnetic structure with circumferential coil.
- Specially designed high current hollow cathode, centrally mounted.
- Specially designed anodes-distributors.
- Graphite covers for the magnetic poles.
- Rear copper structure for thermal management.

Main features:

- Nominal discharge power of 20 kW (6 kW + 14 kW).
- 3 operating modes.
- Envelope: Φ380 mm x 160 mm.
- Mass: < 50 kg.
- State of the art expected performances.

Rendering of the TANDEM thruster

Thruster Overview

The expected performance and dimensions are compliant with requirements and comparable with those of other 20 kW class thrusters.

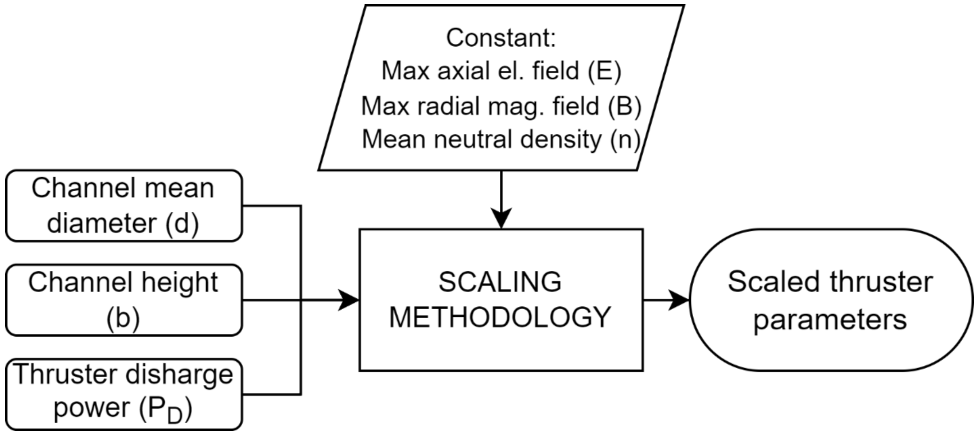
NOMINAL PARAMETERS (Xe)	I MODE	O MODE	IO MODE
Outer diameter of the outer channel [mm]		~ 300	
Discharge Power P_D [kW]	6.00	14.0	20.0
Discharge current I_D [A]	15.0	34.7	49.7
Discharge voltage V_D [V]	400	400	400
Anodic mass flow rate $\dot{m}_a$ [mg/s] (Xe)	13.8	31.9	45.6
Thrust T [mN]	340	792	1130
Anodic specific impulse $I_{sp,a}$ [s]	2500	2500	2500
Anodic thrust efficiency $\eta_{T,a}$	0.69	0.69	0.69

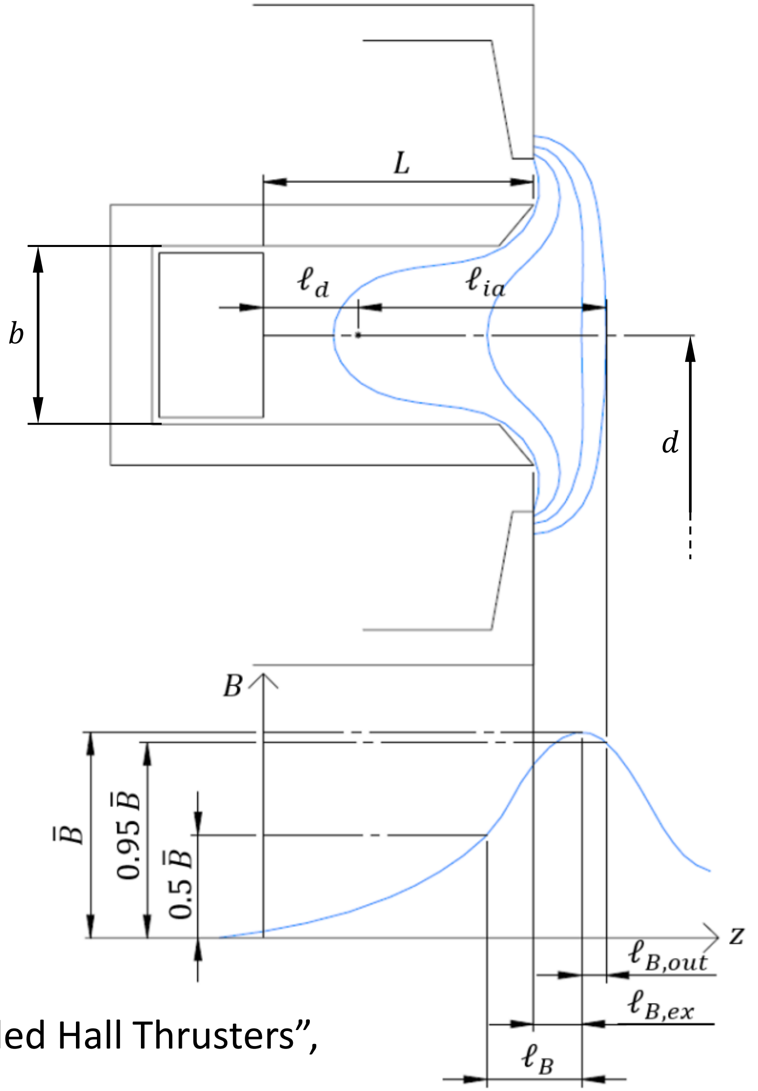
Scaling Methodology

A new scaling methodology for high power magnetically shielded Hall thrusters was developed for the preliminary design of the TANDEM thruster.

Main features:

- Revisited scaling formalism.
- New reference thruster: H6MS (6 kW, magnetically shielded).
- Phenomenological model adapted for magnetically shielded thrusters.
- Scaling criteria: maintain constant main plasma intensive parameters.





G. Giammarinaro, F. Marconcini, et al., "A Scaling Methodology for High-power Magnetically Shielded Hall Thrusters", Journal of Electric Propulsion, 2023, doi: 10.1007/s44205-023-00049-8.

Magnetic Circuit Design

Requirements

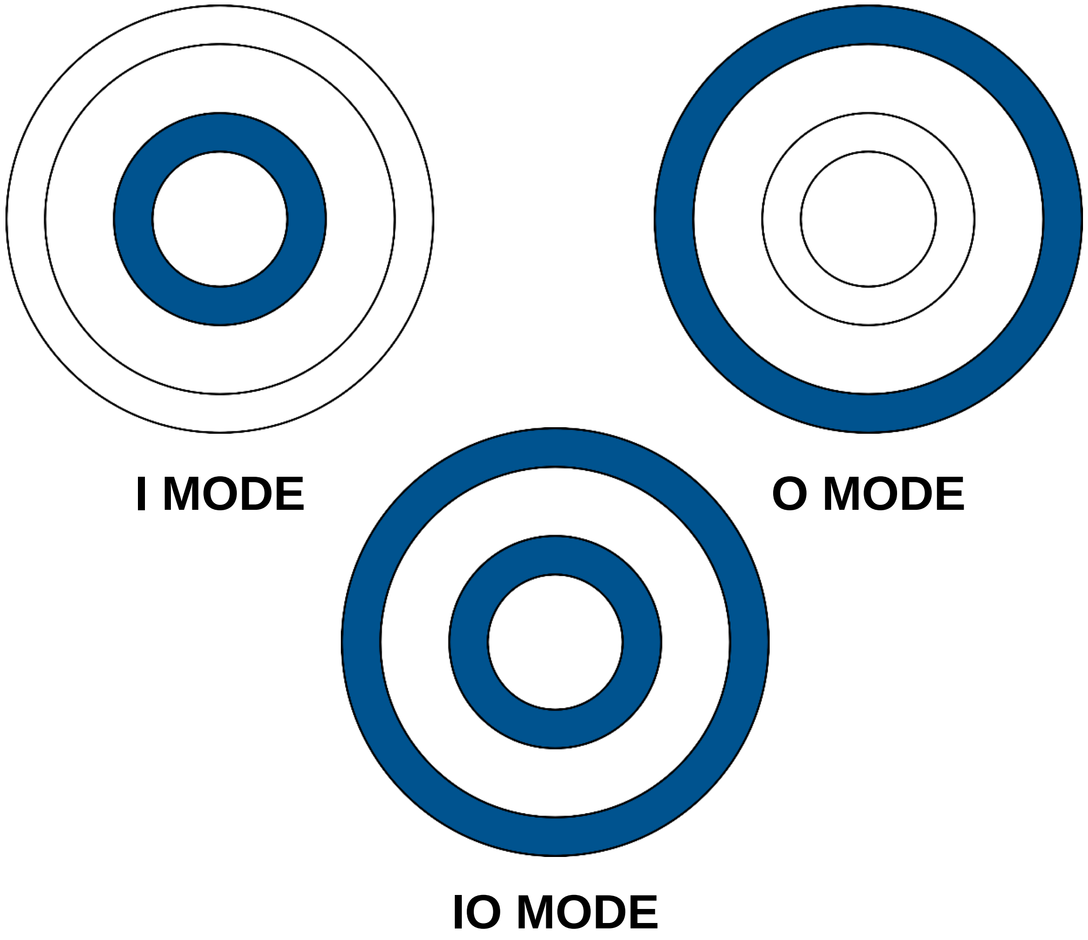
- High axial gradient of B_r.
- Symmetric magnetic lens.
- Avoid magnetic saturation.
- Adaptable to **3 different modes** (I, O and IO).
- **Magnetic shielding**.

Design Process

- Iterative optimization process via FEM simulations
  (MATLAB > OctaveFEMM > FEMM).

Materials and Coils

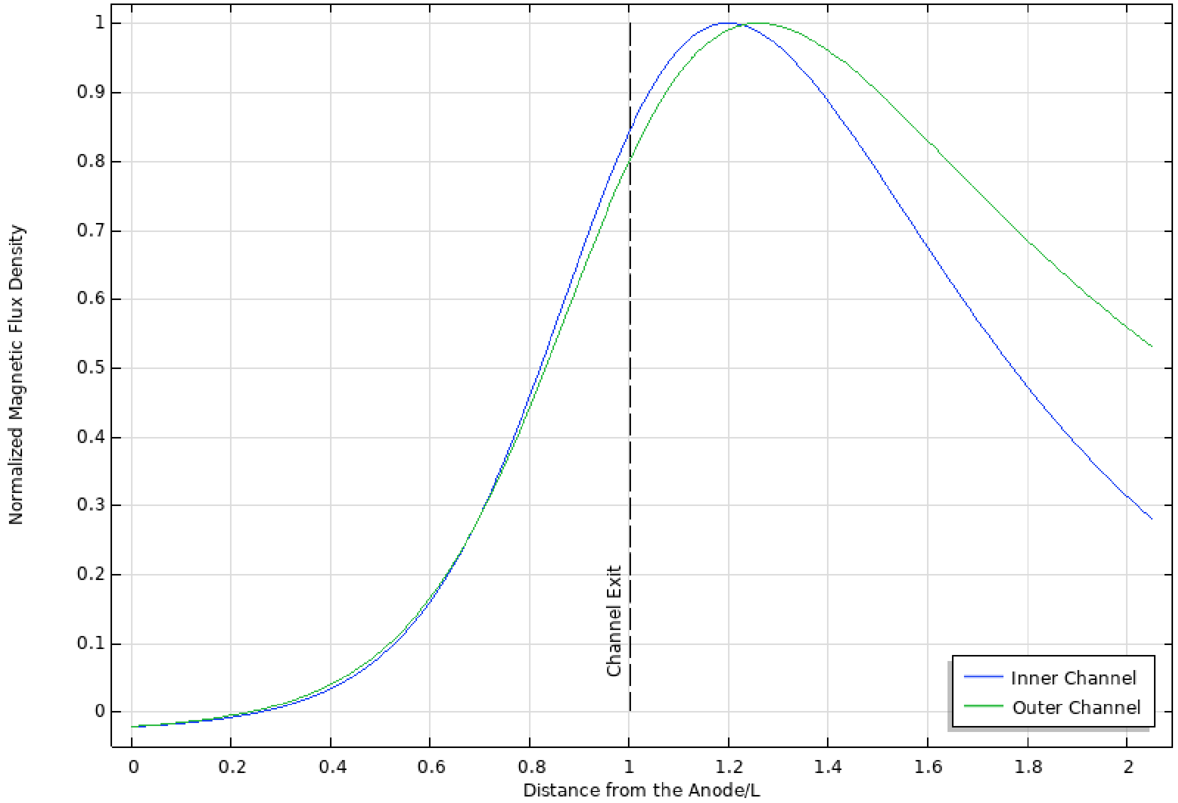
- Magnetic circuit in ARMCO® Iron.
- 4 circumferential (not discrete) main coils.
- 2 circumferential trim coils.

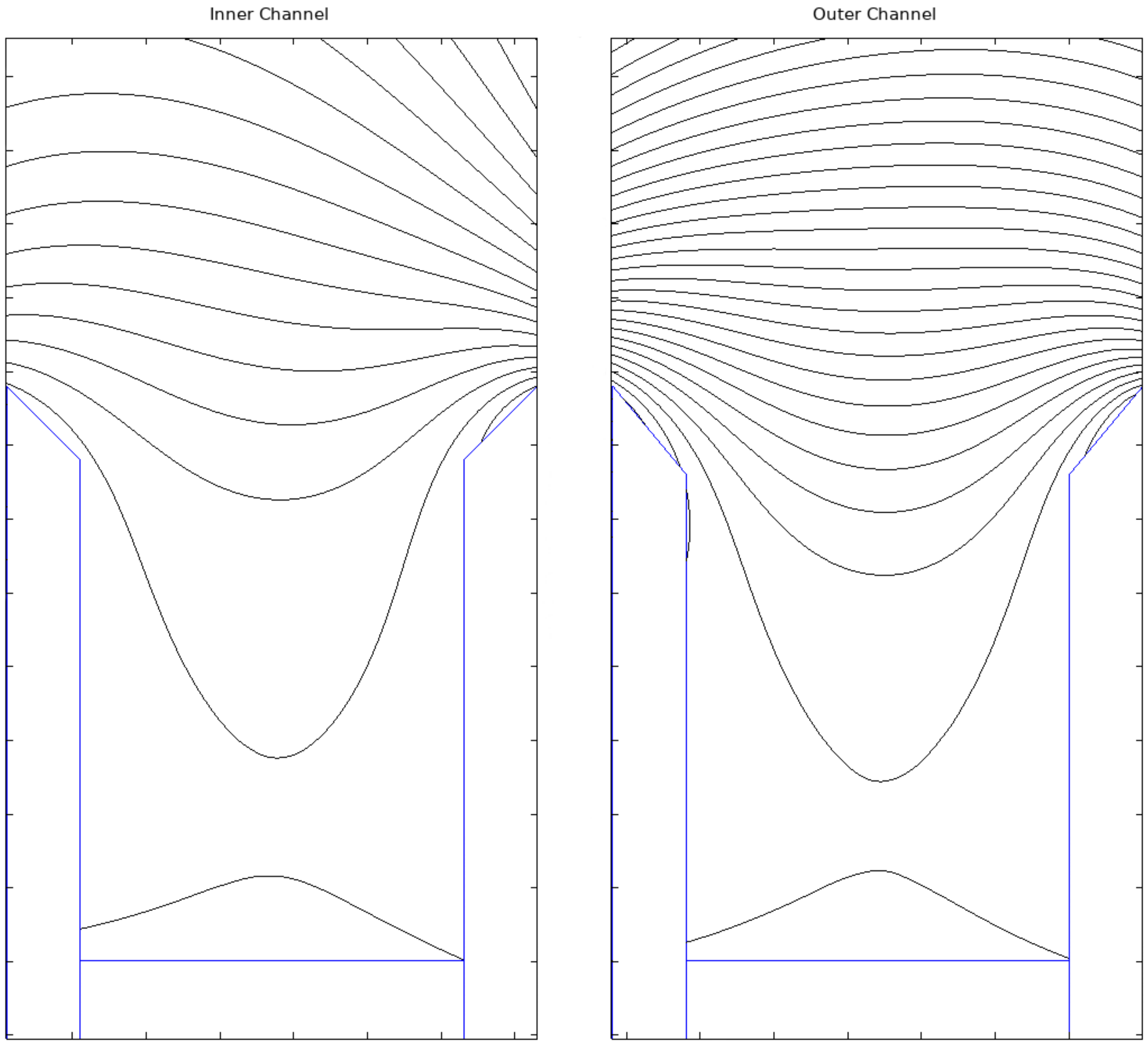


It is possible to switch mode by acting on the currents of the coils.

Magnetic Topology (IO MODE)

- High degree of **magnetic shielding** (great extent of the grazing line, magnetic peak downstream shift).
- High axial gradient of B_r.
- Very similar results for I and O modes.



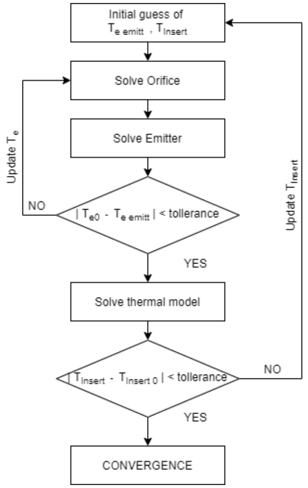


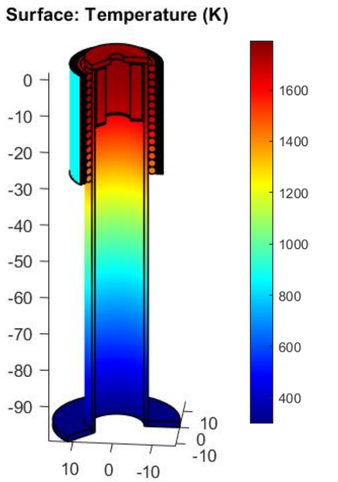
Hollow Cathode Design and Testing

Requirements:

- Operating with both Xe and Kr.
- Discharge current range: 10-100 A (max. required current is 83 A).
- Mass flow rate: < 5 mg/s.
- Minimize discharge voltage.
- Minimize heater power.
- Cathode to be capable to operate with keeper off.
- Overall cathode envelope: Φ40 mm (base excluded).

Cathode design performed with an in-house 0D plasma-thermal model

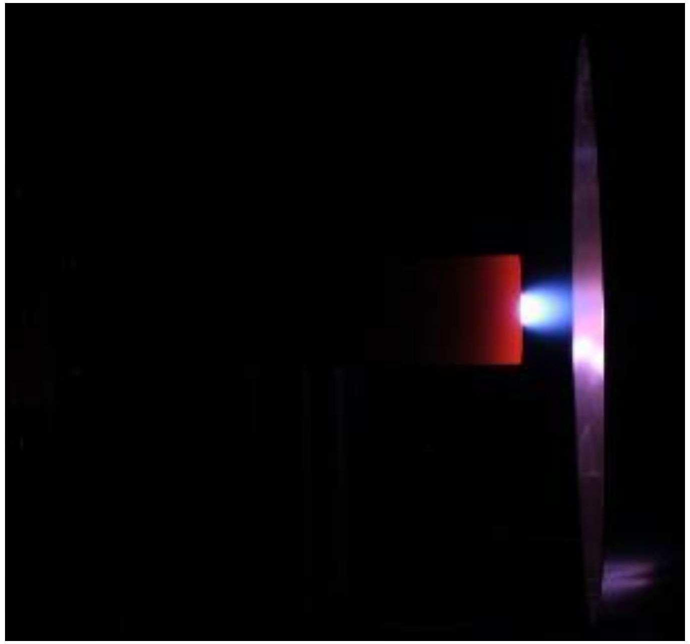




D. Poli, G. Becatti, S, M. Saravia, F. Paganucci, "A Coupled 0-D Plasma Thermal Model for Hollow Cathodes", IEEE TPS, Vol. 51, Issue 3, Pages 816-826, 1 March 2023, ISSN:00933813, doi: 10.1109/TPS.2023.3245151.

Cathode Performance Results

Test	Description
Cathode Thermal Characterization Test	Preliminary cathode thermal characterization of the pre-ignition heating
Cathode Ignition Characterization Test	Investigate cathode ignition performance
Cathode Functional Performance Test	Cathode functional performance test campaign in diode mode
Cathode Parametric Performance Test	Cathode parametric performance test campaign in diode mode to evaluate its performance.



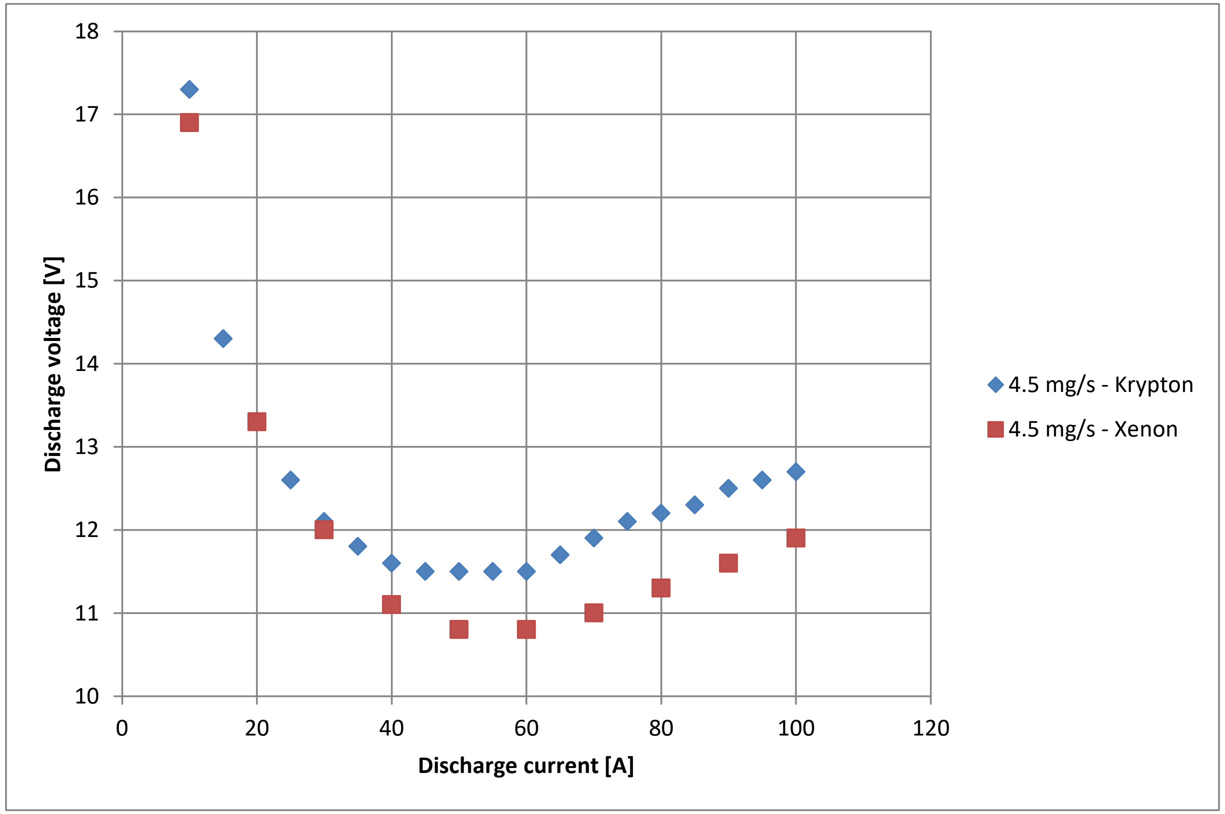
Cathode firing at 100A, 4.5 mg/s (Krypton)

Main outcome:

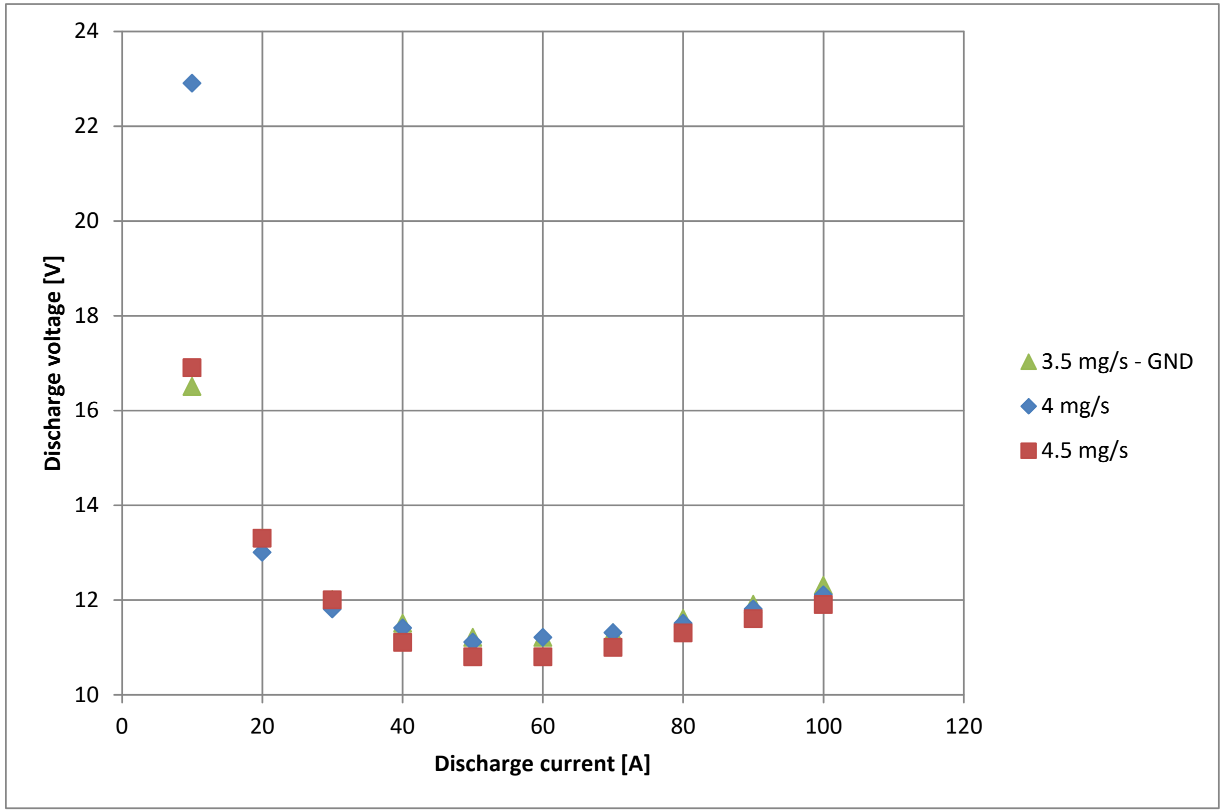
- Repeatable ignitions with Kr and Xe in less than 9 minutes
- Cathode capable of operating between 10-100 A with Kr and Xe
- Discharge voltage maintained below 20 V.

Cathode Performance Results

Discharge voltage vs discharge current comparing krypton and xenon



Discharge voltage vs discharge current with xenon at different mass flow rate



TANDEM Project Status

The thruster and the hollow cathode tested both with Xe and Kr in all the three operating modes.

The test campaign is in progress by Aerospazio Tecnologie S.r.l. in the company premises.

AEROSPAZIO

PROJECT STATUS	
Preliminary Design	*Complete*
Detailed Design	*Complete*
Manufacturing & Procurement	*Complete*
Test Activity	*Ongoing*

PLANNED TESTS (2023)	
Cathode Thermal Characterization Test	√
Cathode Ignition Characterization Test	√
Cathode Functional Performance Test	√
Cathode Parametric Performance Test	√
Thruster Functional Performance Test	
Thruster Parametric Performance Test	
Thruster Endurance Test	
Thruster Characterization Test	

The CHEOPS project

Horizon Europe Project: Technologies and generic building blocks for Electrical Propulsion

CHEOPS Very High-Power Building Blocks (Jan 2023)

Main objectives for UNIPI:

Anode/discharge chamber development

Advanced manufacturing techniques will be adopted with the aim of getting ***lighter, more robust and cheaper*** anode and the discharge chamber blocks for VHP thrusters.

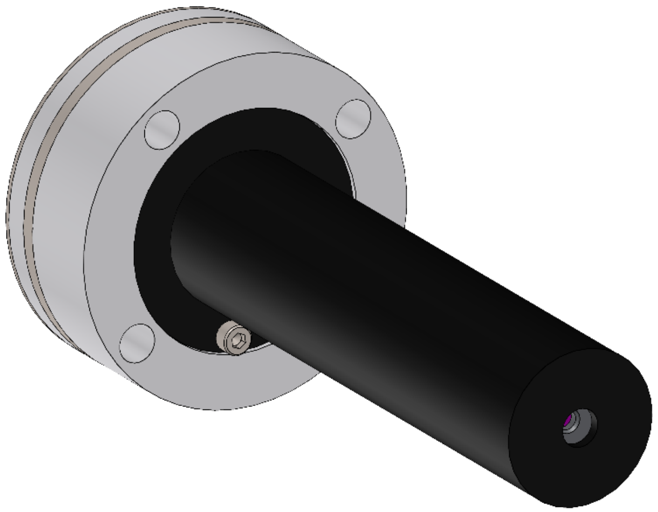
Cathode development

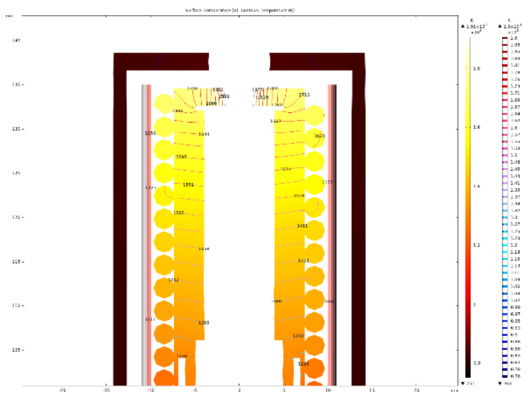
The TRL 5/6 hollow cathode expected as output of this project will be developed starting from previous know-how and literature review.

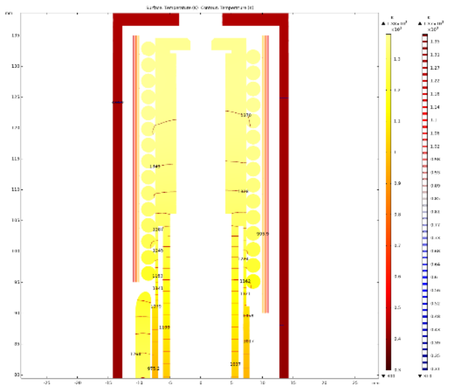
CHEOPS VHP

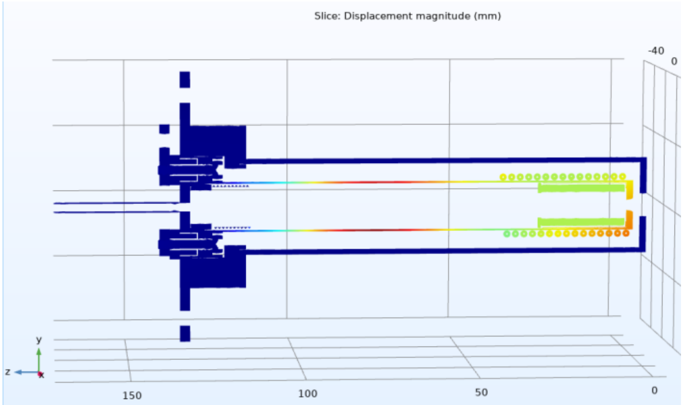
Main goals of CHEOPS Project on Cathode development:

- EM Model (TRL 5-6) of high current cathode for operation with TANDEM thruster and PPS20k
- Cathode capable of operation with different propellant (at least xenon, krypton, argon) with minor performance differences
- Experimental investigation:
  - Performance characterization test
  - Environmental tests (mechanical shock and vibration, thermovacuum)
  - Endurance test of 1000 hours







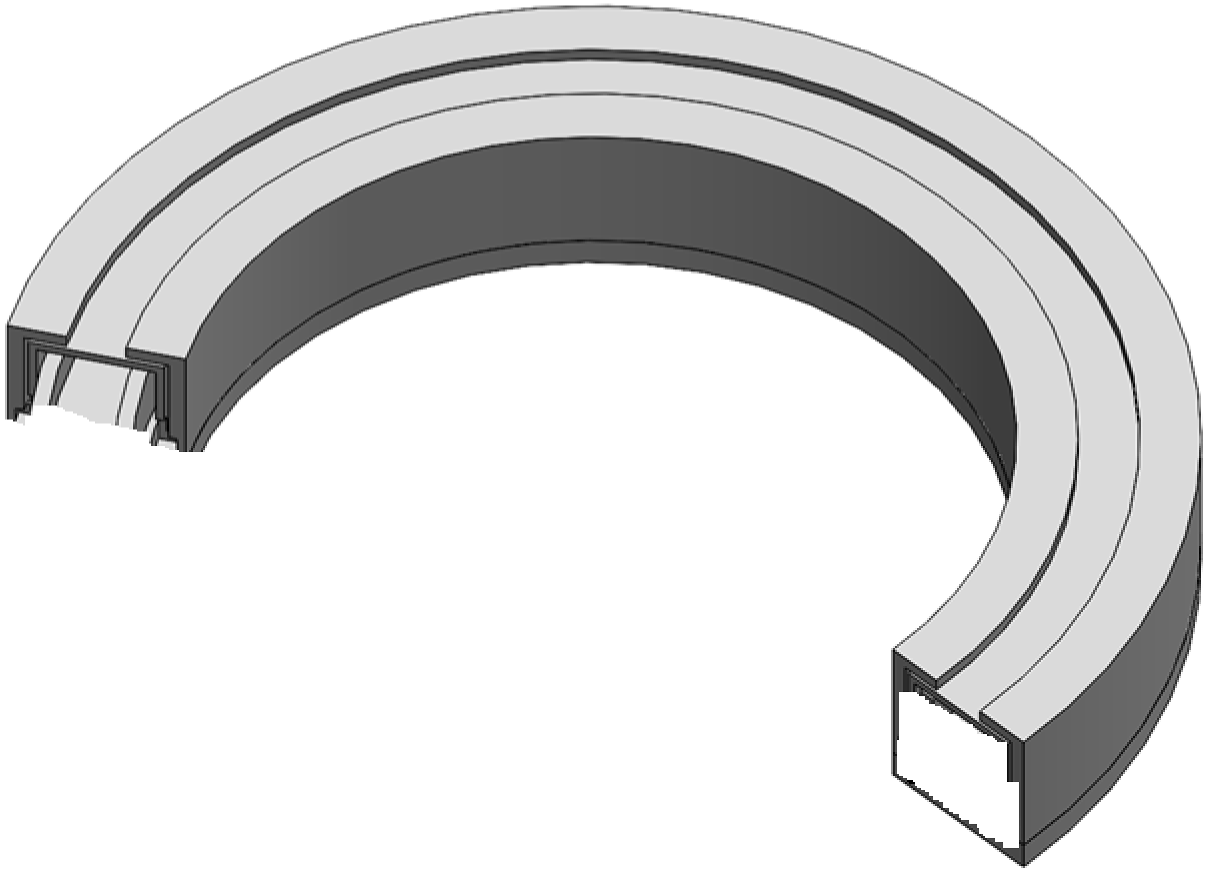


Anode Design and Testing

The inner and the outer anodes-distributors have the same structures.

Main features:

- Each anode composed by 5 components.
- Welded joints.
- Single inlet for each anode.
- Labyrinth architecture.
- High azimuthal uniformity of the flow.



Alternative architectures obtained through **additive manufacturing** are currently object of investigation.

Additive Manufactured Activities

Studies on additive manufacturing of metallic and ceramic components for HTs:

- Printing of ceramic components (electric breaks, discharge channel, gas distributor).
- Printing of metal components (anodes, structural components, magnetic circuits).

RenAM 500E at UniPi for LPBF processes.

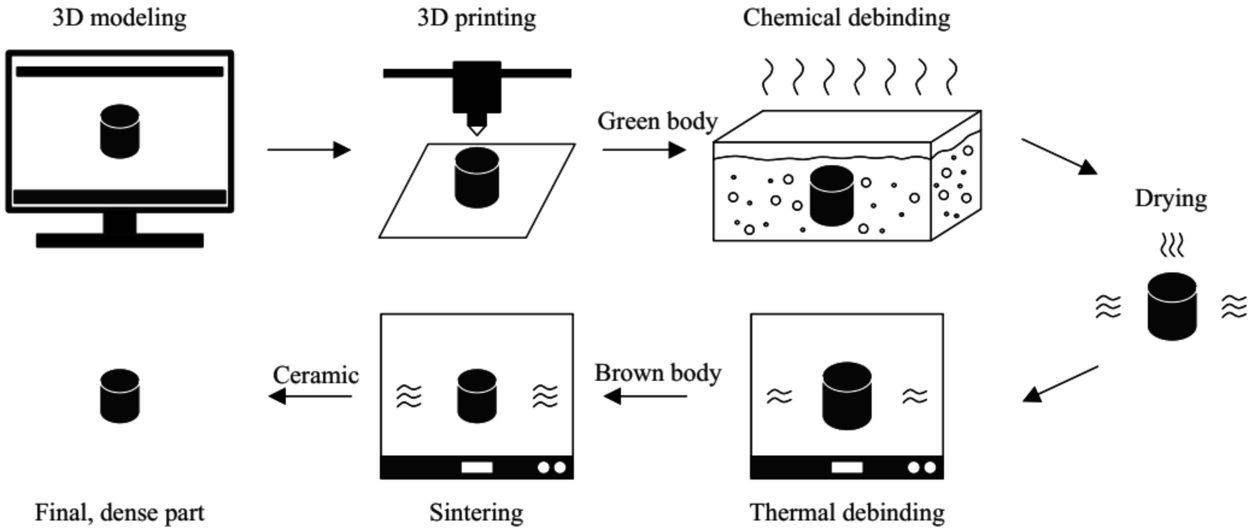
Investigation of metal-ceramic welding techniques for the development of innovative HT configurations:

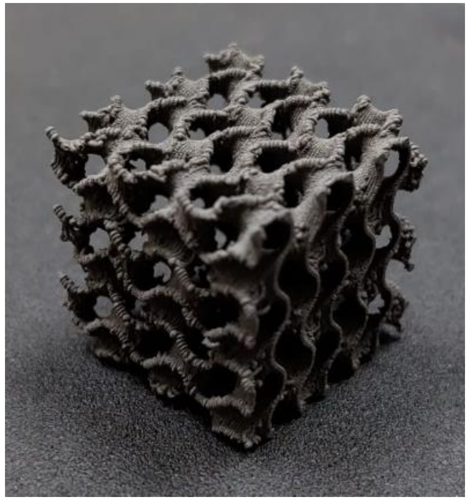
- Adhesives.
- Co-sintering.

Tumaker NX PRO Dual for FDM of pellets.

MEAM of Metals and Ceramics

A 3D printed alumina discharge channel for an Hall thruster.





A 3d printed lattice structure in Inconel 718.

Investigation of material extrusion additive manufacturing (MEAM) with highly-filled polymers with a particular emphasis on its application for the fabrication of metallic and ceramic components of Hall thrusters:

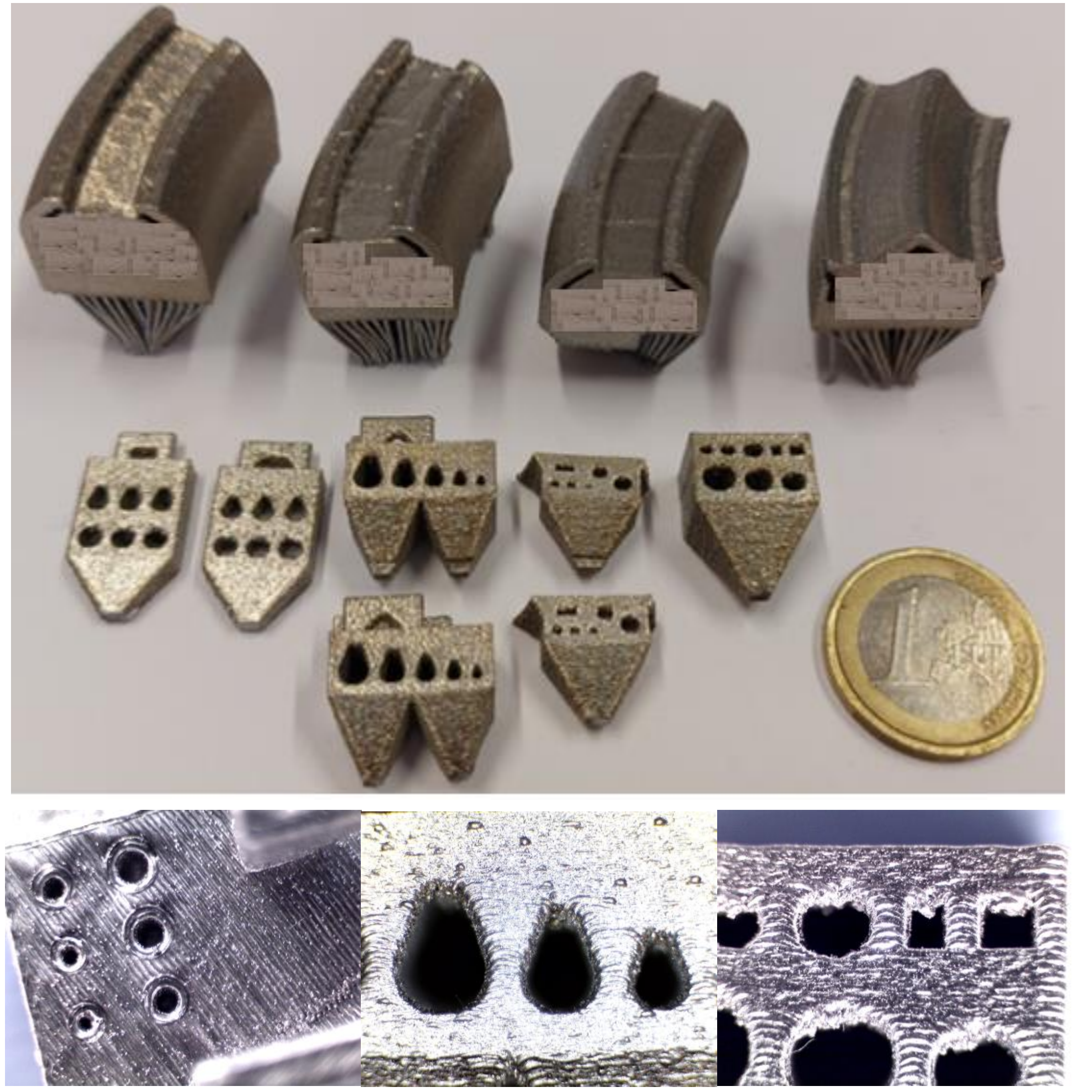
Investigated Materials (pellets and filaments):

- Alumina.
- Inconel 718.
- Stainless steel
- Pure iron.

Development of an Anode through LPBF

Alternative architectures for the anodes obtained through **additive manufacturing** are currently investigated.

Anode slices with various geometries and features and feature-testing specimen were printed in Inconel 718 using Laser Power Bed Fusion (LPBF).



Analysis:

- Mass and volume measurements provide results that are consistent with the design values.
- A digital microscope and a computed tomography have been used to analyze the specimen.
- An excessive roughness has been found only overhanging surfaces.

A complete anode for the TANDEM inner channel is under development and will be tested in the following months.

Thanks for your attention!