Concepts in Low Power Hall Thruster Design

Igal Kronhaus

Technion – Israel Institute of Technology, Haifa, Technion City 3200003, Israel

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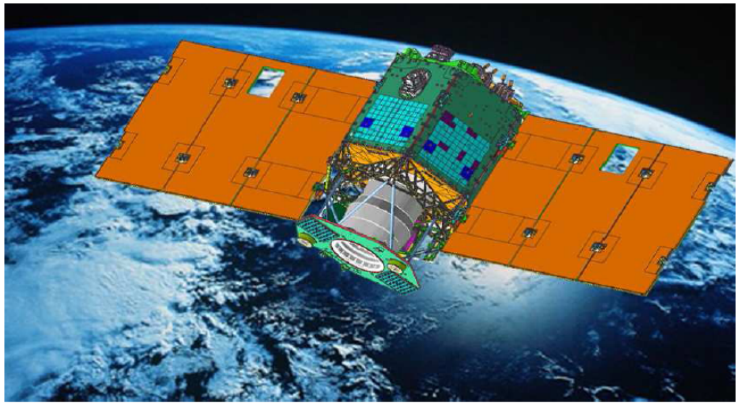
Outline

- Introduction
- The CAMILA Hall Thruster Concept
- Conclusion

Introduction

- In the last years, considerable attention is given toward lowering cost and time in development of Earth observation and communication satellites
- Major mission cost factor is the mass required to be launched to orbit → smaller spacecraft are increasingly being used
- As a mass saving measure electric propulsion (EP) systems are being introduced to small spacecraft → however the available power is limited



VENμS, Israel Space Agency

SMART-1 moon probe, ESA

Introduction cont.

- Historically Hall thrusters (HT) were designed to operate at power levels above 300 W

- Reports in the literature indicate an electrical efficiency drop to 10 - 35 % at power levels below 200 W

- The reduced thruster performance in low power levels is mostly attributed to low propellant utilization, with the following reasoning:

  1) To preserve specific impulse, lower power regimes are accessible only by reducing the discharge current

  2) A lower current, in turn, implies the use of a lower propellant mass flow rate

  3) Finally, decreasing the mass flow rate results in lower gas densities and therefore to an increased ionization mean free path length

Introduction cont.

- In order to improve propellant utilization at low power two options are considered:

  - Channel extension

  However, due to wall losses simple extension of the channel have limited gains

  - Increasing the initial residual plasma density

  How to do this?

Introduction cont.

Effect of residual plasma density

- Ion production inside the thruster channel is preformed by direct electron impact ionization
- It is useful to define a propellant utilization coefficient

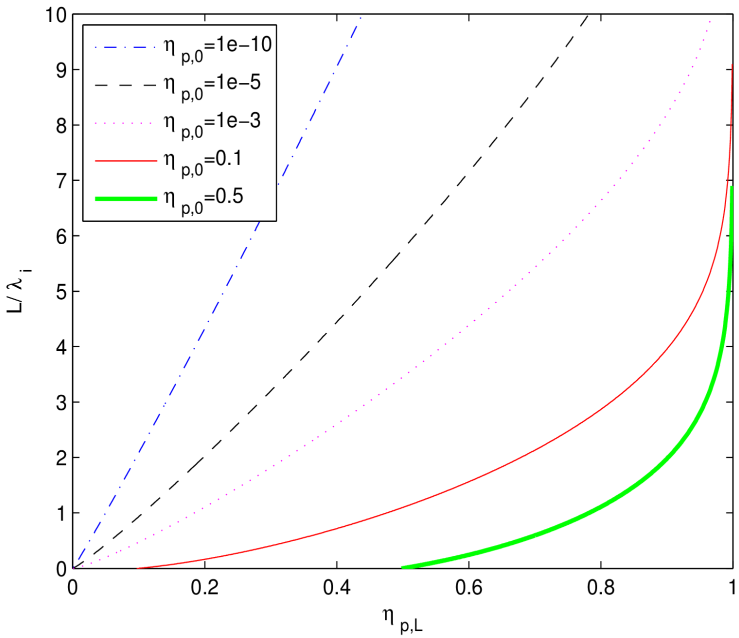
$$\eta_p = \frac{\dot{m}_i}{\dot{m}_g} \approx \frac{I_i M}{\dot{m}_g e}$$

- The one dimensional continuity equations for the propellant atoms and ions are given by

$$\frac{d(n_g v_g)}{dz} = -k_i n n_g, \quad \frac{d(n v_i)}{dz} = k_i n n_g$$

- The effective length L of the discharge chamber with respected to initial utilization coefficient η_{p0} :

$$L = \lambda_i \left(\eta_{pL} \ln \left| \frac{1 - \frac{1}{\eta_{p0}}}{1 - \frac{1}{\eta_{pL}}} \right| \right) ; \quad \lambda_i = \frac{A_c}{\eta_p \dot{m}_g} \frac{M v_g v_i}{k_i}$$



For a fixed L/λ_i increasing initial plasma density induces a large increase in the propellant utilization coefficient

λ_i - mean free path k_i - ionization reaction rate coefficient

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The Co-Axial Magneto-Isolated Longitudinal Anode (CAMILA) Hall Thruster Concept

The CAMILA Hall Thruster Concept

(Kapulkin et al., Patented 2007, ASRI, Technion)

Goal: Improving the ionization efficiency by extending the thruster channel while reducing ion flow to the walls

Method: generate an ion retarding electric field (away from the walls) by incorporating two design changes:

- Co-axial anode surfaces placed parallel to the channel
- Significant longitudinal magnetic field applied in the anode cavity
- Assuming collisional electron transport, the voltage drop across magnetic field is:

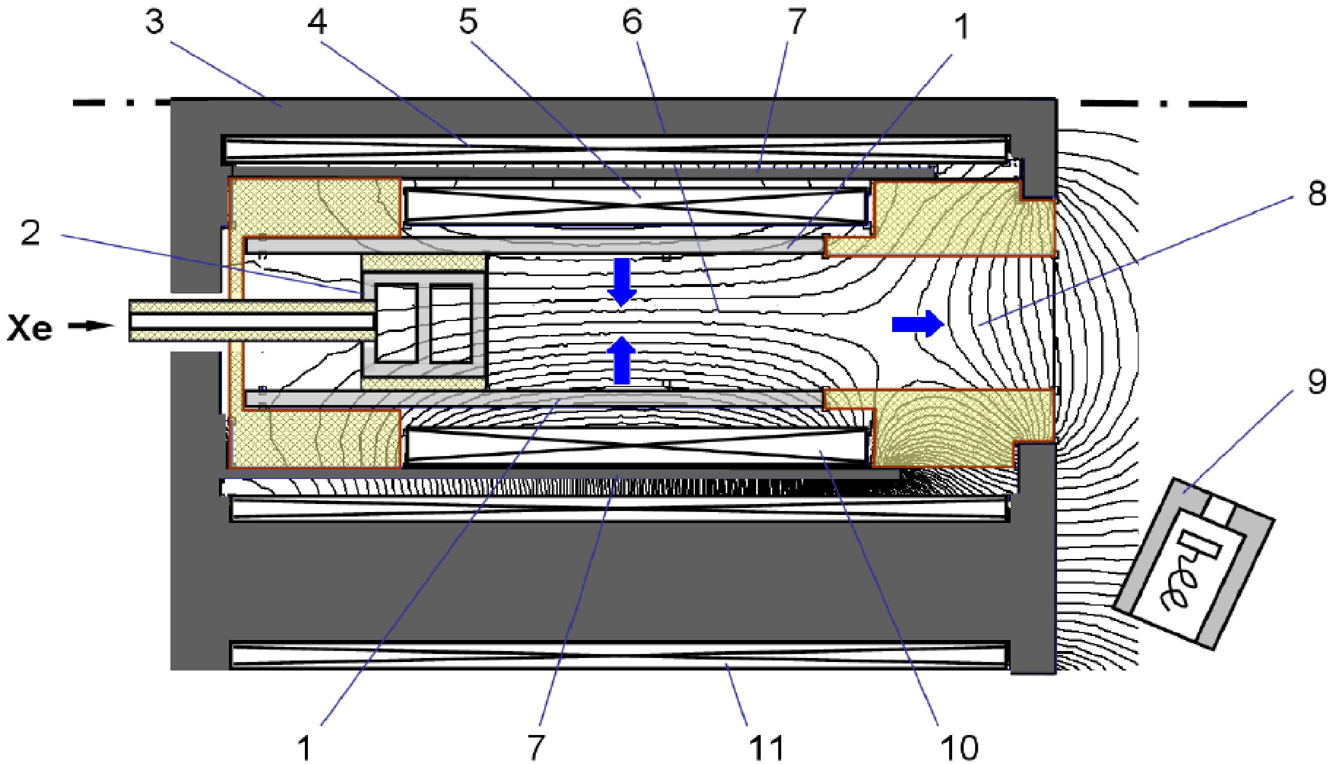
$$U_a \propto h B_z^2$$

For example U_a of 40 V requires $B_z \approx 60$ G

U_a - voltage drop across magnetic field, h - channel width, B_z - axial magnetic field induction

The CAMILA Hall Thruster Concept cont.

Cross-sectional scheme of the CAMILA Hall thruster



1 - anode; 2 - gas distributor; 3 - magnetic circuit; 4 - central magnetic coil; 5 - inner anode coil; 6 - anode cavity; 7 - magnetic screens; 8 - channel; 9 - cathode-neutralizer; 10 - outer anode magnetic coil; 11 - outer magnetic coil

The CAMILA Hall Thruster Concept

Experimental model CAMILA-HT-55 (evolved to CAM200)

Improved performance over classical Hall thrusters was measured even in weak longitudinal magnetic fields
Unexplained by the original model

At power levels of 150 - 250 W anode efficiency is substantially better than 40 %

With a projected lifetime of more than 4000 h (at 200 W), it is probably the best HT thruster in the power range of 150 - 250 W

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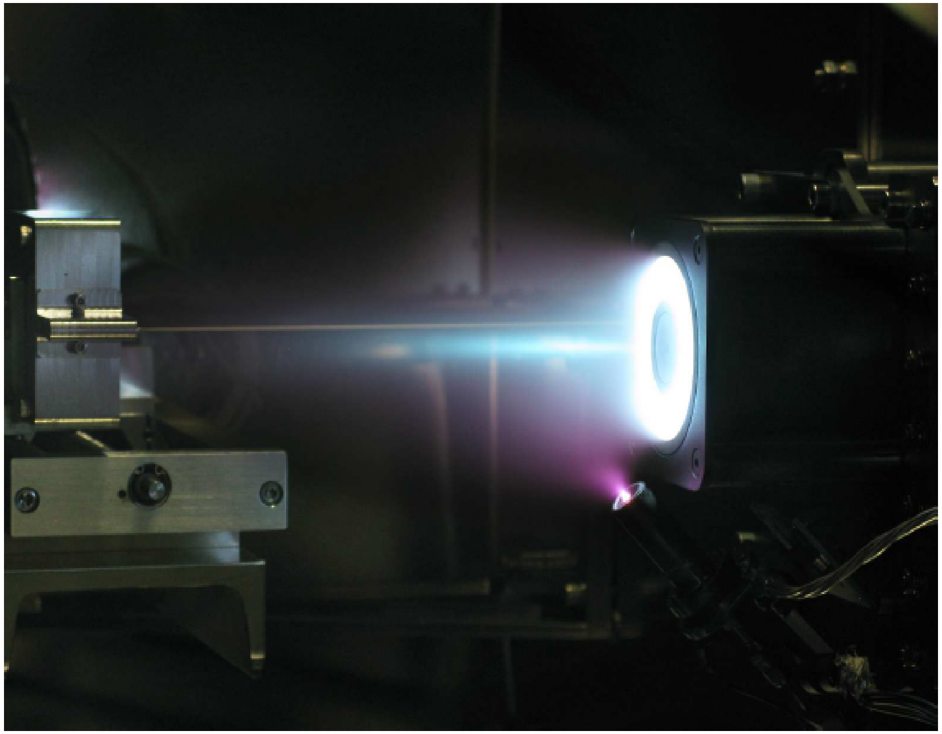
Test facility and thruster

Image of the thruster in operation, the plume outside the thruster is clearly visible



- Experiments were conducted at the Asher Space Research Institute vacuum test facility[1]
- 3.2 m^3 vacuum chamber, residual pressure $< 6 \times 10^{-8}$ mbar; operational pressure $< 2 \times 10^{-5}$ mbar
- Anode and cathode mass flow rates of 0.87 mg/s and 0.25 mg/s respectively
- $P_d \approx 240$ W at 300 V, $B_r \approx 150$ G on the exit

[1]Kronhaus et al., *J. Propulsion and Power*, Vol. 29, pp. 938–49, 2013

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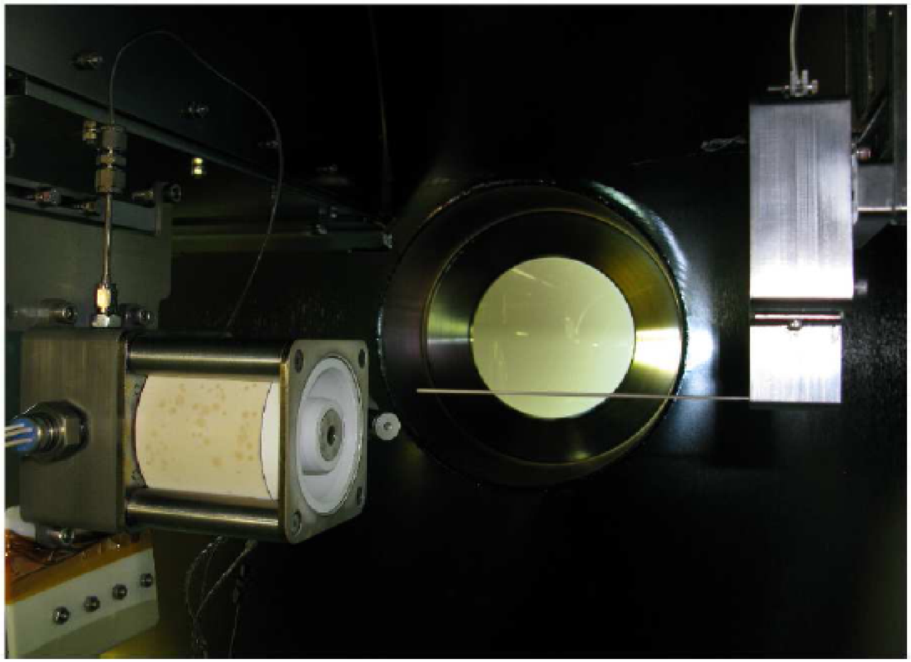
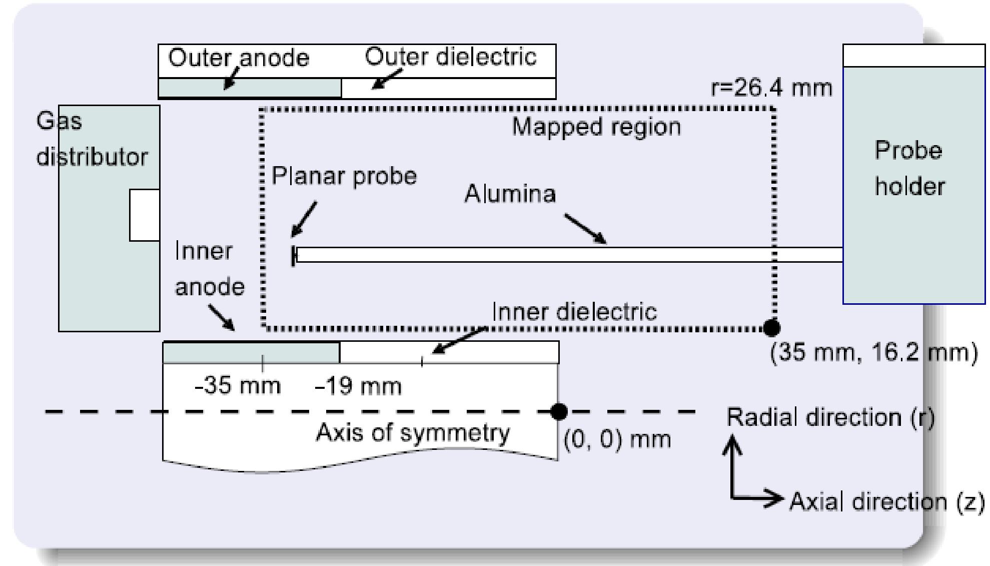
Probe positioner





- Eleven radial locations, spaced 1 mm apart
- Axial sweep from +35 mm to -35 mm, zero on exit
- Precision on both axes better than 0.1 mm
- Residence time < 0.8 s, prevents alumina from melting
- Discharge current perturbation is below 35 % throughout the channel

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Global discharge parameters

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Three magnetic configurations were tested with the following discharge parameters:

Case	$\dot{m}_a$ [mg/s]	U_d [V]	$I_{d,inner}$ [A]	$I_{d,outer}$ [A]	η_a [%]
simplified	0.87	300	0.737	0.053	42.8
optimized	0.87	300	0.531	0.301	46.6
full	0.87	300	0.130	0.696	44.2

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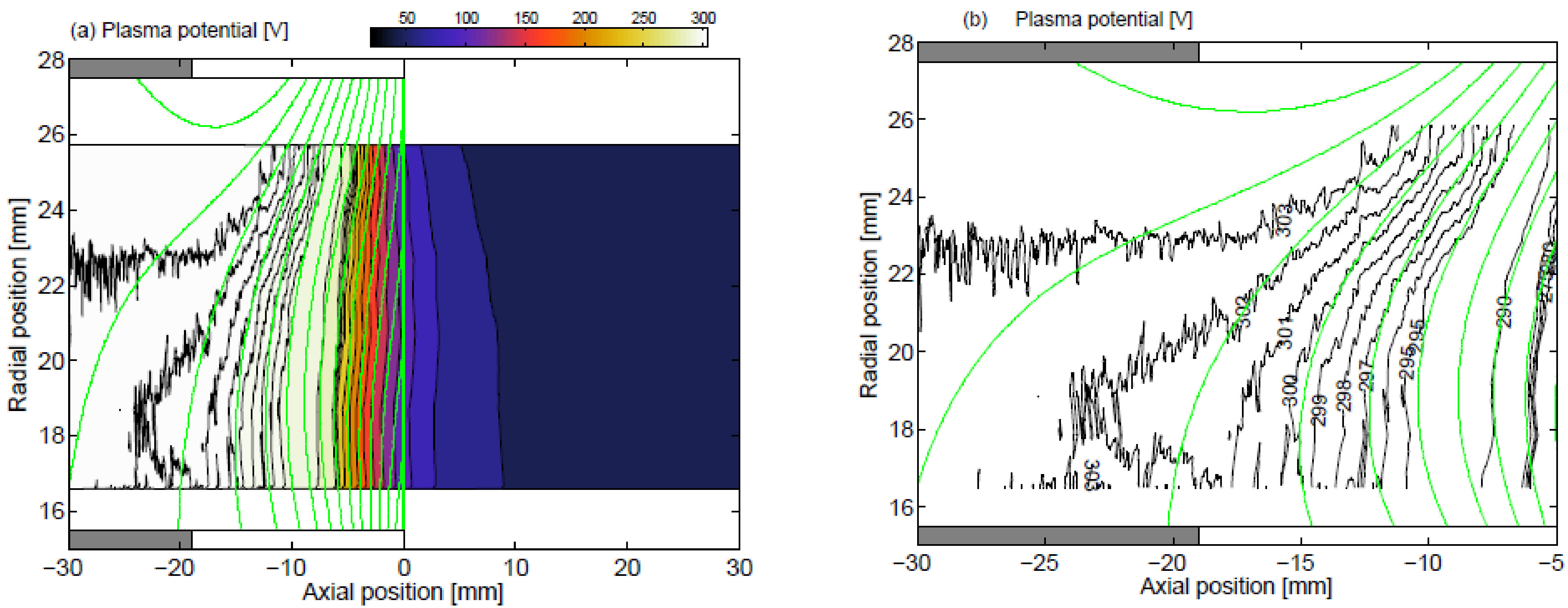
Simplified CAMILA – 2D parameters

Simplified magnetic configuration - without activation of the anode coils



- A single 2D map was processed from ≈ 11 × 1000 data points
- The equipotential contours are indicated on the figure as black lines, green lines are computed magnetic field lines
- The plasma potential is higher than anode potential within the cavity

Ion focusing electric equipotentials are found near the anode-dielectric boundary, moreover, they extend up to the ionization region

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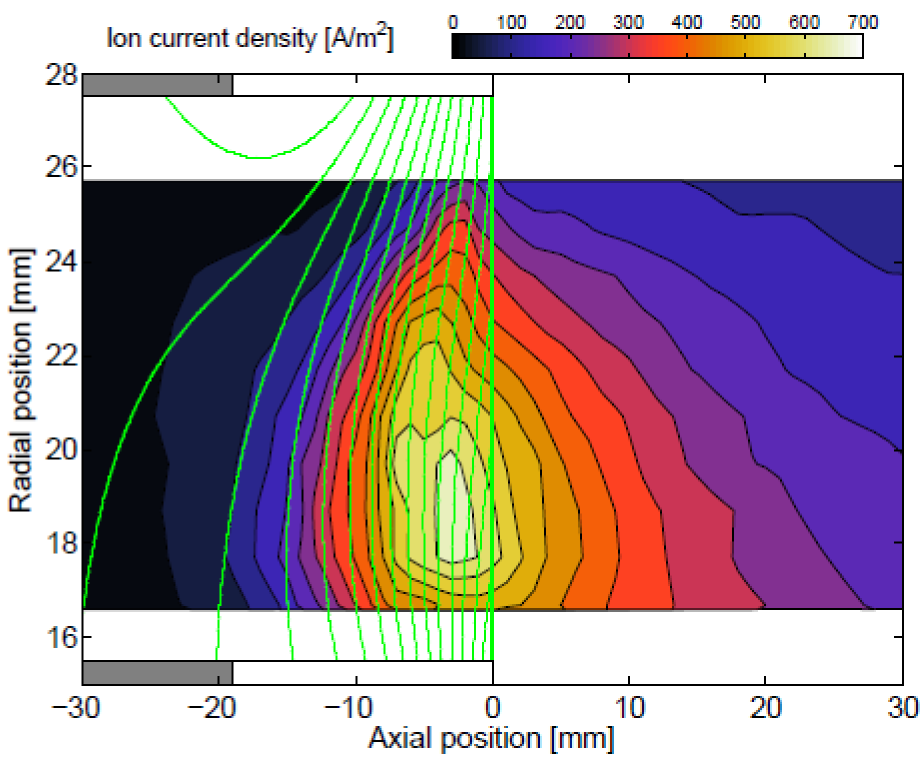
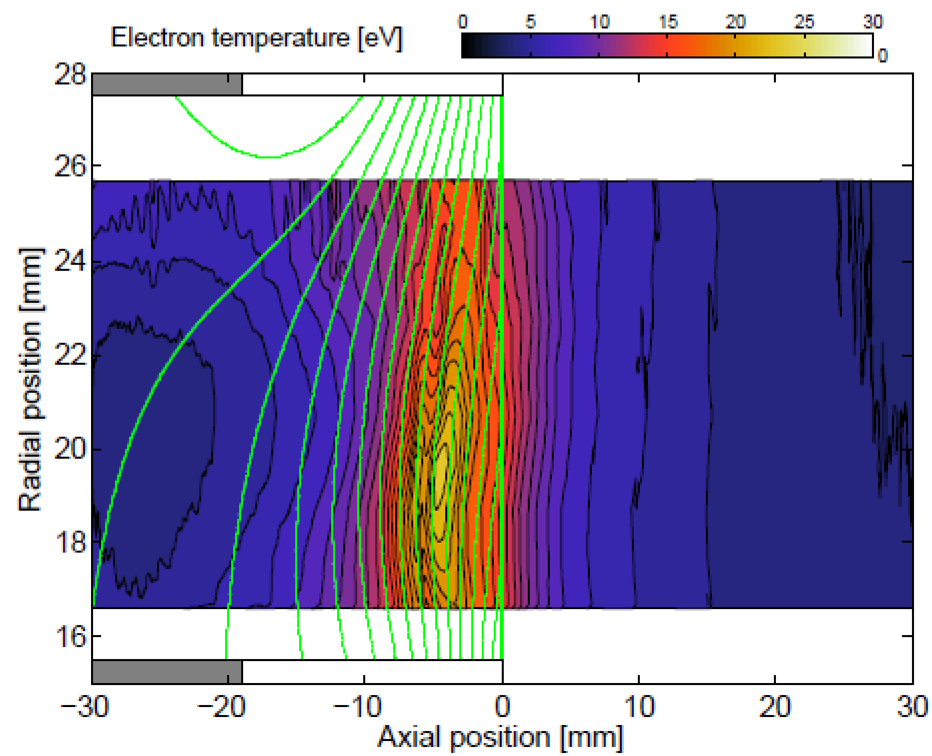
Simplified CAMILA – 2D parameters cont.

The focusing electric equipotentials allow for:

- Reduced ion flow to the dielectric walls with the outer anode effectively isolated
- Reduced ion back-flow from the ionization region to the anode cavity

However, the discharge is not symmetric and the bulk plasma is located closer to the inner wall





Total number of data points in a single ion current density map is 11 × 40

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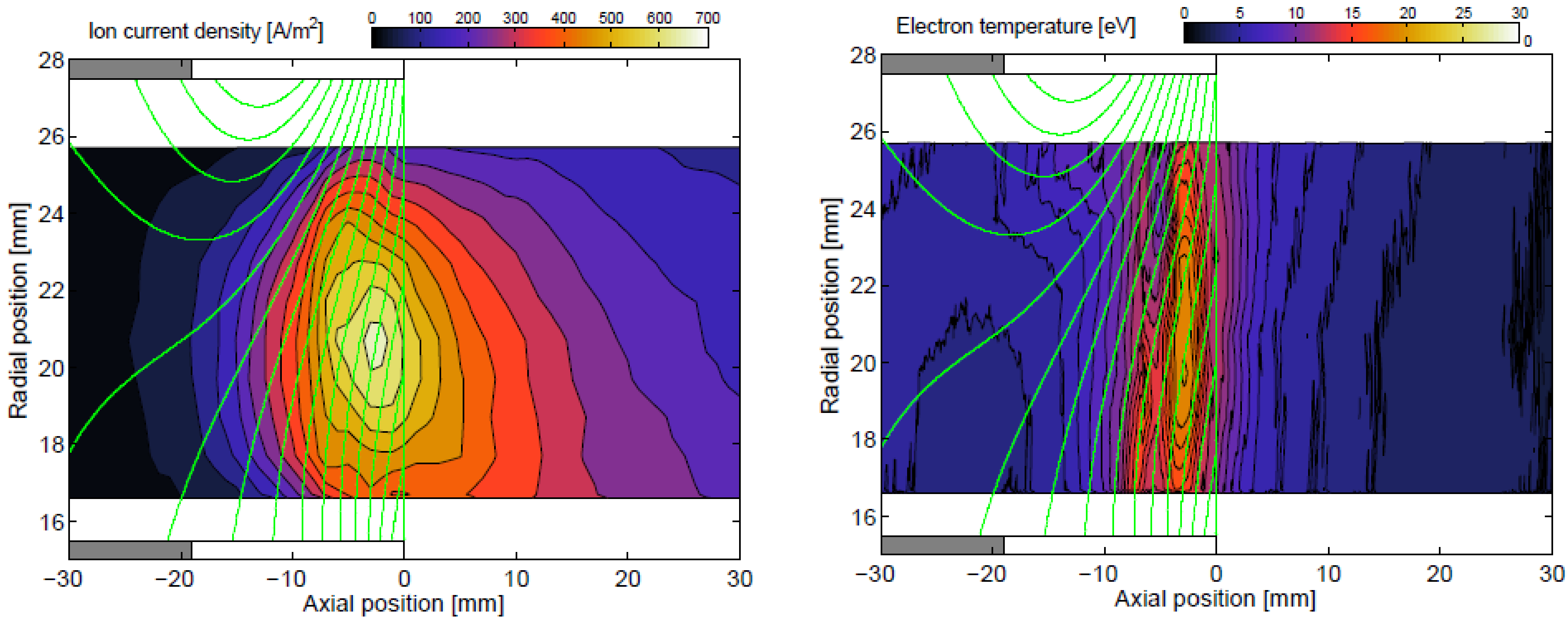
Optimized CAMILA – 2D parameters cont.



- The simplified magnetic field was modified in order to obtain a more even distribution of currents between the outer and inner anodes
- As result, a more symmetric discharge was achieved. Similar ion current density values are measured near the inner and outer walls

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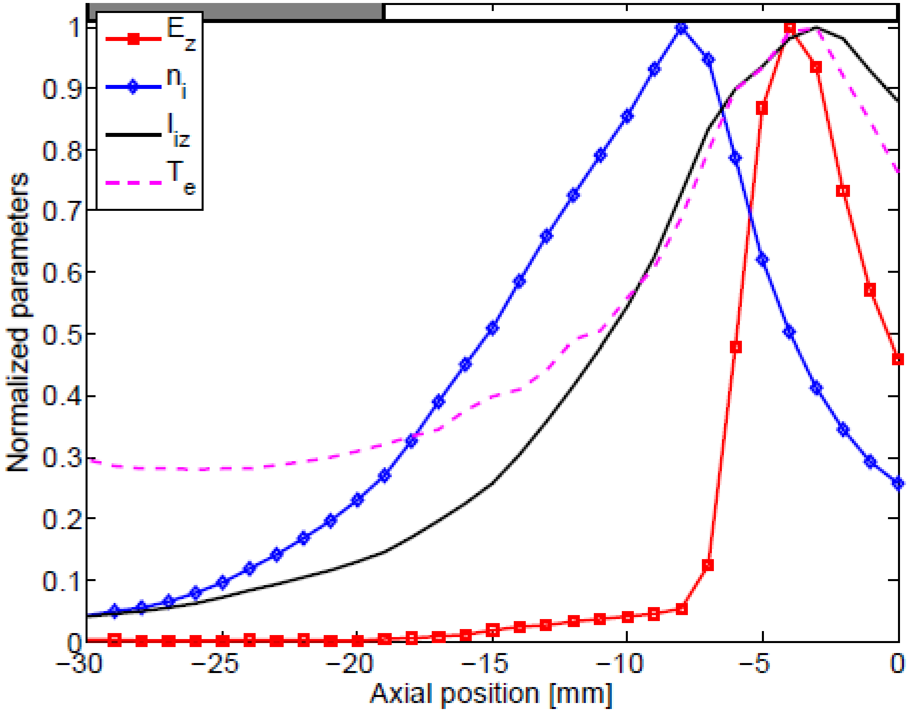
Simplified CAMILA – Averaged Results

- The ionization is carried out mostly within the dielectric channel
- An electric field, directed toward the exit, is present in the ionization region
- The plasma density sharply decreases inside the anode cavity
- ≈ 15 % of the ion current is generated inside the anode cavity



Variations of normalized plasma parameters along the axial direction

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Particle-in-cell model

- The CAMILA channel was modeled by a dedicated fully kinetic 2d3V PIC simulation APL-XOOPIC[1]
- The geometry is axisymmetric and cylindrical coordinates are used. The velocity is tracked in three dimensions
- Electrostatic approximation is used. Only charge distribution and boundary conditions are required for solving the electric potential ϕ
- The magnetic field is precomputed and remains static during the simulation run
- Monte-Carlo electron-neutrals collision module is implemented

[1]Kronhaus et al., *Plasma Sources Sci. Technol.*, vol. 21, no. 3, p. 035005, 2012

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Simplified CAMILA - simulation results

Case	$\dot{m}_a$ [mg/s]	U_d [V]	$I_{d,in}$ [A]	$I_{d,out}$ [A]	P_d [W]	η_a [%]
Experimental	0.55	300	0.370	0.046	124.8	31.7
Steady state	0.55	300	0.215	0.032	74.1	30.7
High power	0.55	300	0.310	0.066	112.8	34

- The simulated anode efficiency is similar to the measured result however it was obtained at lower power level
- The difference between experiment and simulation can be explained by the enhanced electron transport (due to azimuthal oscillations) which is ignored in the simulation
- The simulated anode efficiency improves with increasing power, similarly to the experimental results

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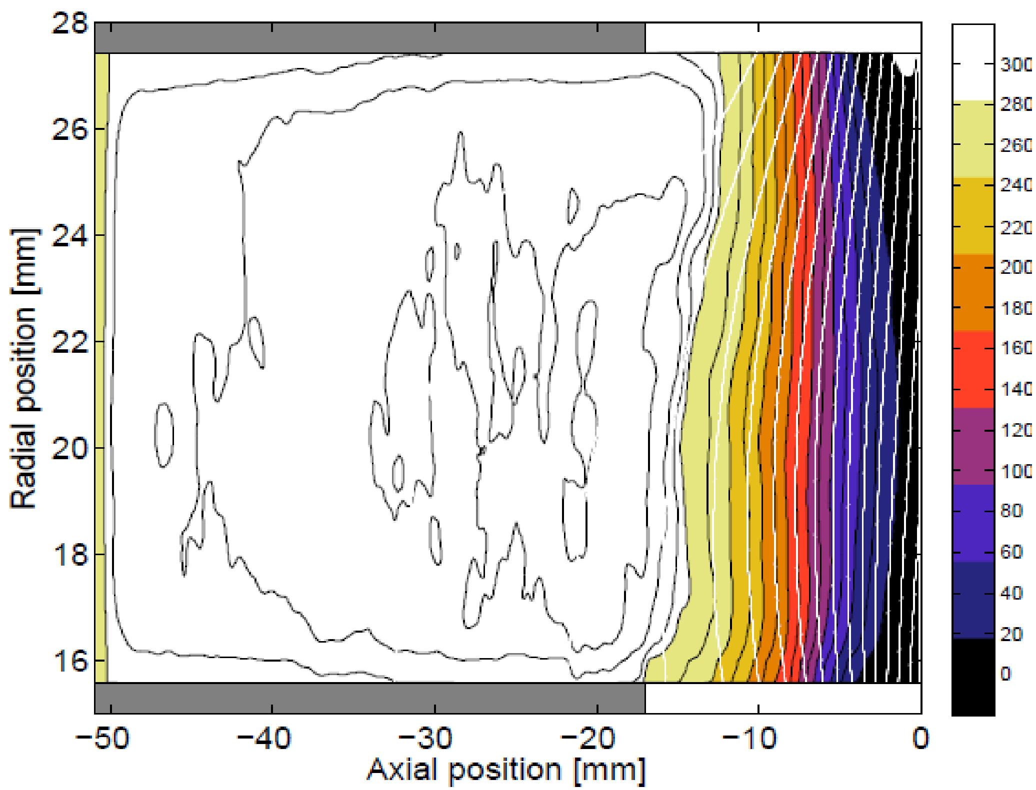
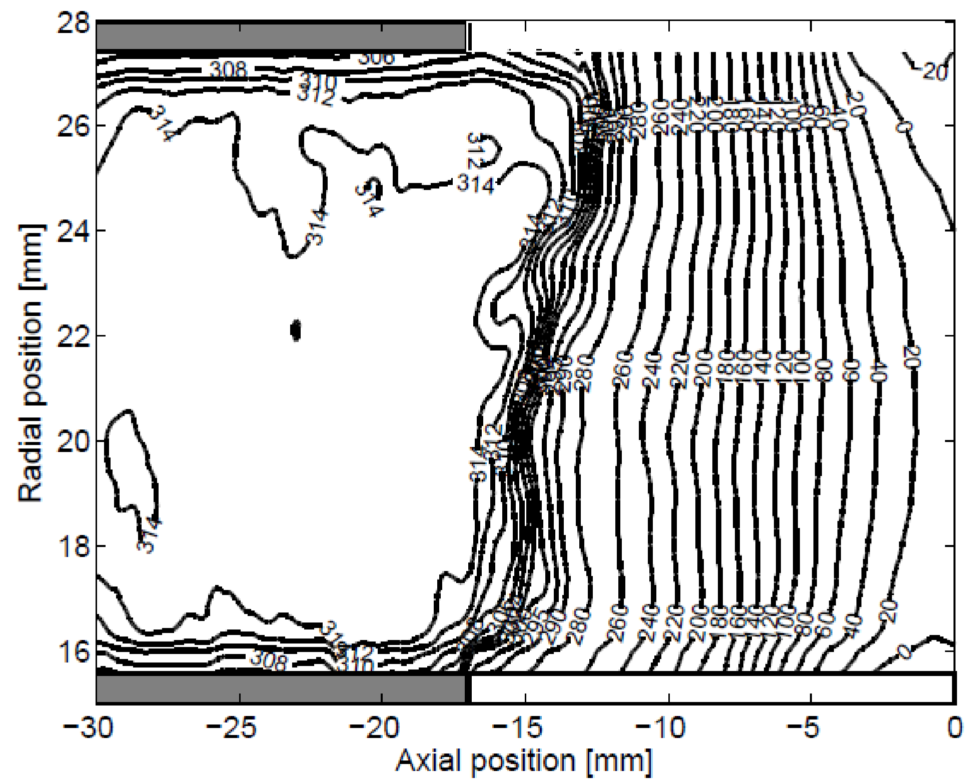
Simplified CAMILA - simulation results cont.

- Ion focusing electric equipotentials appear near the anode cavity and extend to the dielectric channel, similarly to measurements
- The fall in potential is larger in the near anode region compared to measurements





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Origin of focusing equipotentials

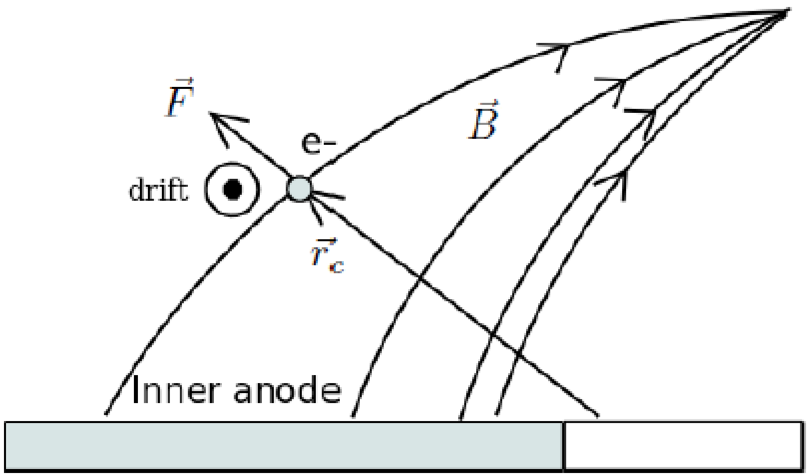
Despite the presence of electron pressure, focusing equipotentials are observed near the anode-dielectric region, in both experimental and numerical results

Their existence can be attributed to:

- Placement of anode parallel to the channel
- Electric equipotentials approximately follow the magnetic field lines and electrons move along them
- Electrons execute azimuthal drift motion due to magnetic field gradients

Two main processes retard electron flow toward the anode:

- Curvature drift (including grad-B drift)
- Magnetic mirror force



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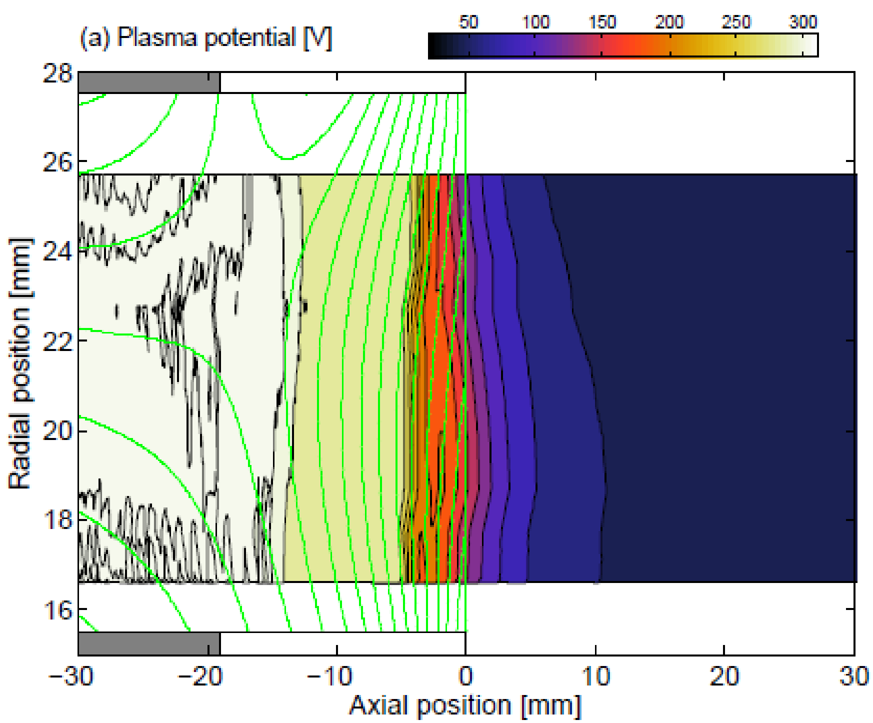
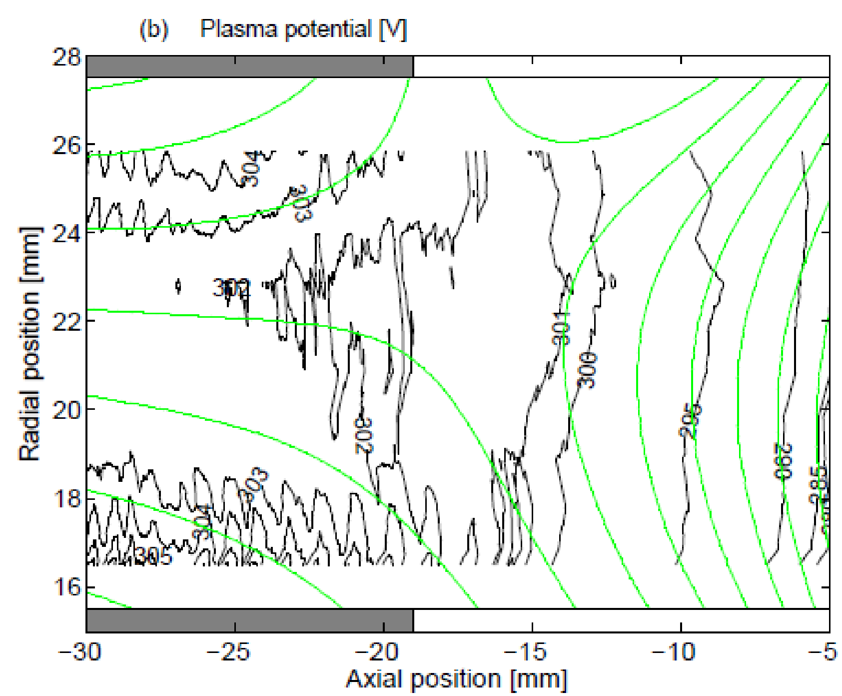
Full CAMILA - experimental results

Application of anode coils with increased longitudinal magnetic field (but still weak < 50 G)

- A radial electric field is generated inside the anode cavity, directed away from the anodes
- The radial electric field is weaker than expected by the simplified model, 4 V difference between near anode regions and centerline
- Near anode regions are at higher potential than the anode potential





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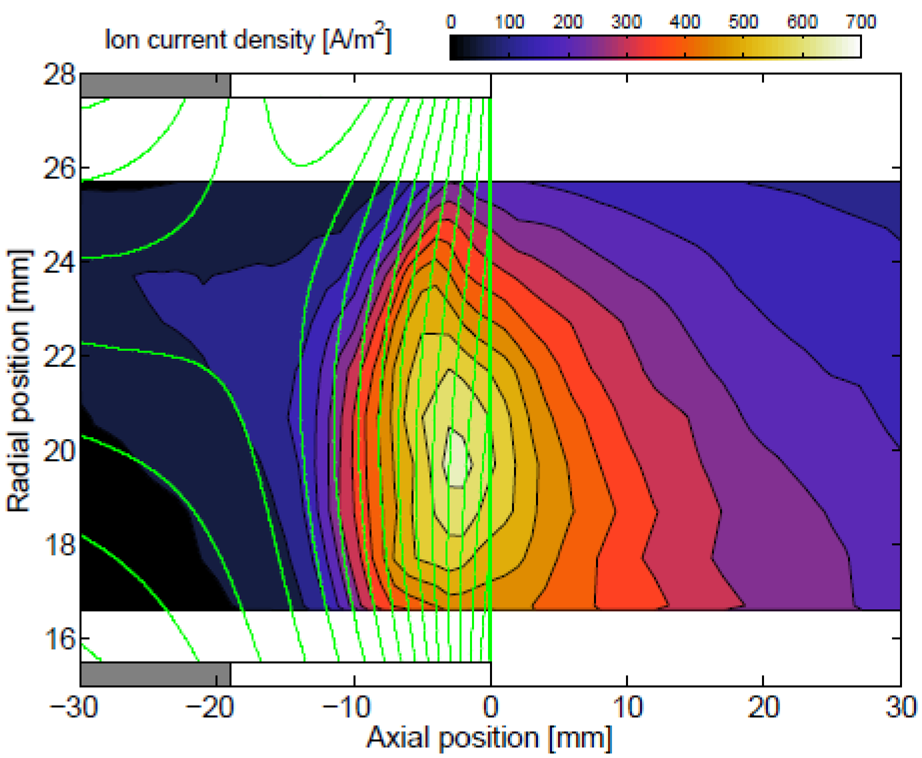
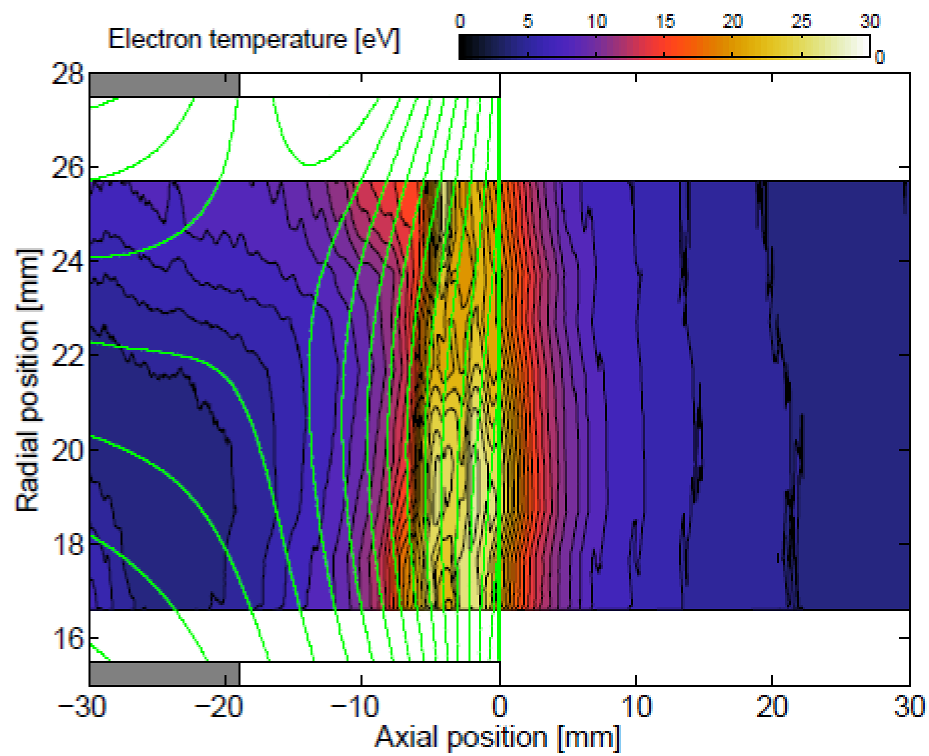
Full CAMILA - experimental results cont.

- The ionization is carried out predominantly within the dielectric channel
- Significant ion current is generated inside the anode cavity ≈ 19 %
- Ionization inside the anode cavity is carried out by energetic electrons arriving from the dielectric channel
- The plasma is at higher density near the anode cavity centerline, correspondingly to the structure of the near anode regions





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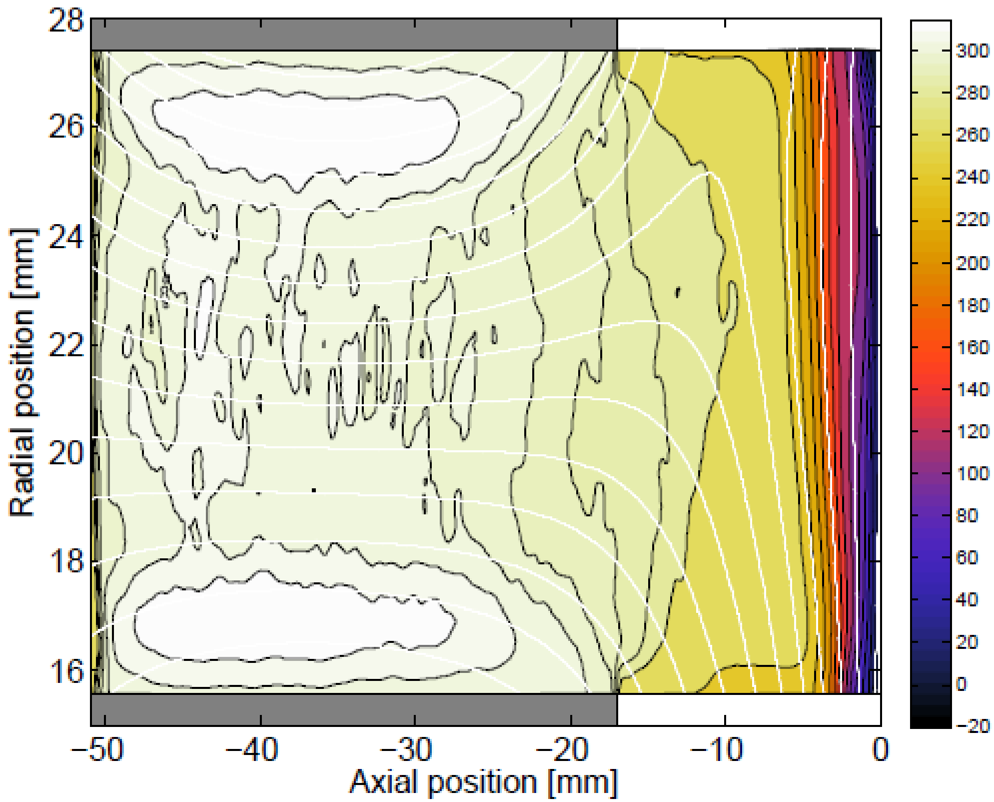
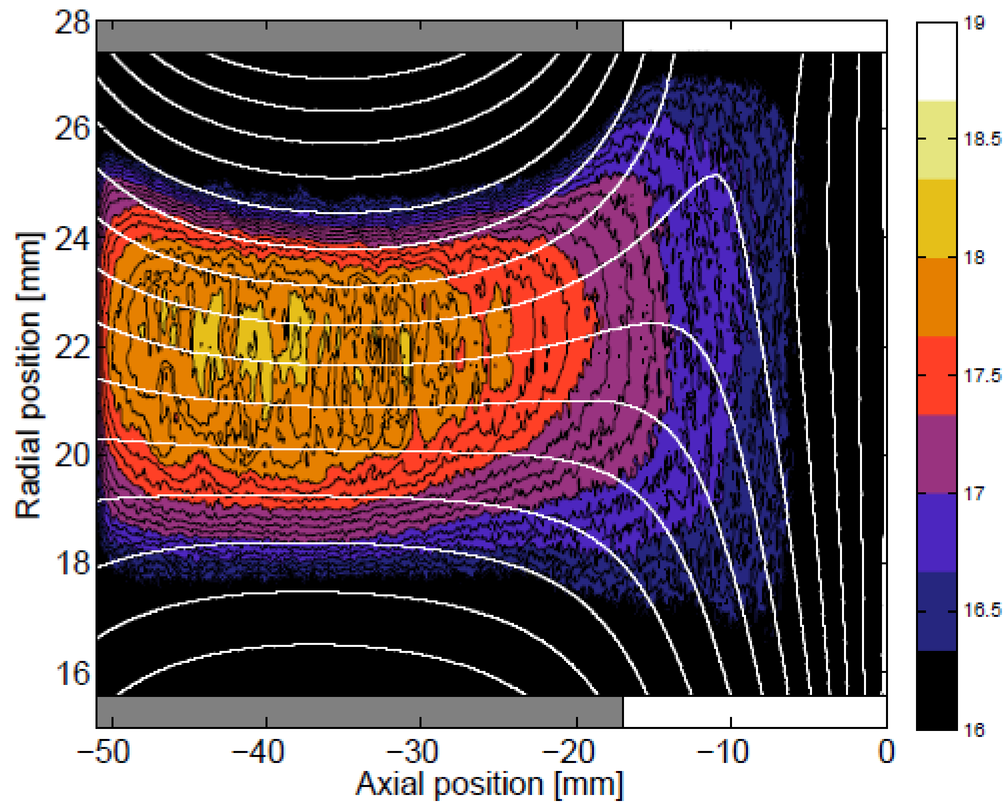
Full CAMILA - simulation results

- Simulation of full CAMILA was demonstrated using a strong axial magnetic field in the anode cavity (~ 350 G)
- The anode centerline has lower potential than the anodes (≈ 10 V), reducing ion flow to the anodes
- Plasma is now generated along the entire anode cavity enhancing ionization efficiency





Conclusions

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Several mechanisms for improving propellant utilization efficiency were presented, as realized in the CAMILA Hall thruster

- Investigation of local plasma parameters in a CAMILA type Hall thruster show that the anode region influence is extended to the dielectric channel, generating ion focusing equipotentials and improving ionization efficiency

- The establishment of focusing equipotentials is attributed to the electron dynamics, electrons following curved magnetic field lines to the wall anodes

- In full CAMILA, it was proven that it is possible to obtain a radial electric field pointing toward the center of the anode cavity. However, the electric field strength was found to be lower than expected

Thank You!