Numerical investigation of the Microwave Electrothermal Thruster cavity and plasma at Politecnico di Milano

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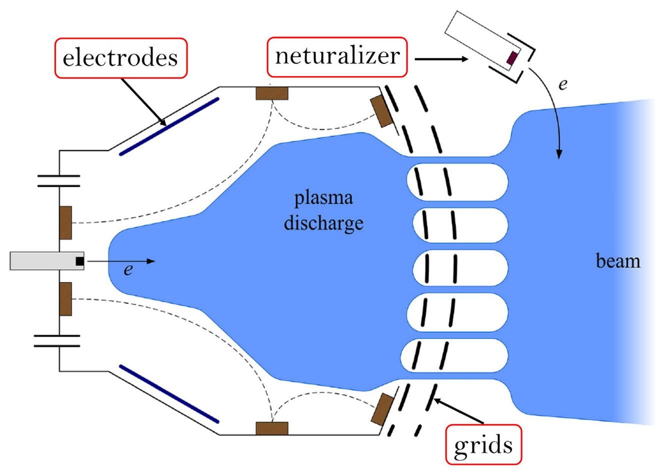
Introduction: Electric Propulsion & the MET

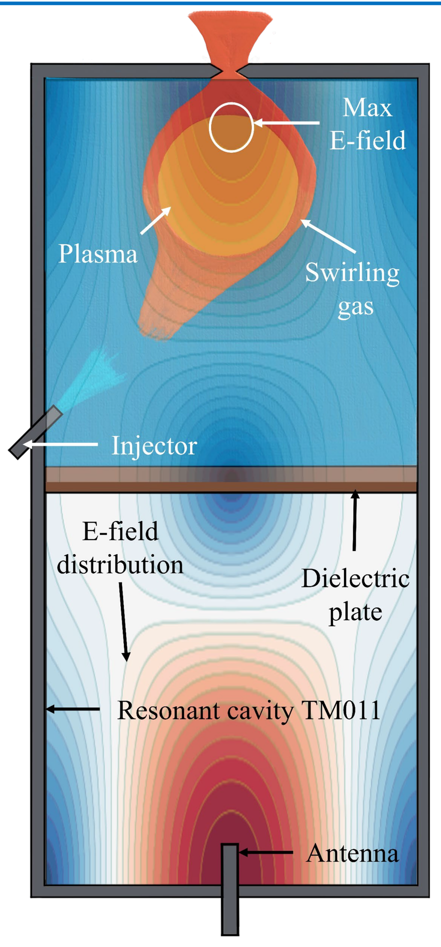
EP → High specific impulse (I_{sp}) [1]:

- Lower propellant mass → $\ln(M_p) \propto I_{SP}^{-1}$
- Higher Δv missions → $\Delta v \propto I_{SP}$

State-of-the-art thrusters suffer from **plasma - induced erosion** [1]



Performance and lifetime ⬇



Microwave Electrothermal Thruster [2-4]

- **Simple and cheap** technology → resonant chamber;
- **Electrodeless** discharge → plasma isolated from walls:
  - Limited erosion;
- Versatile
  - Argon, (Helium), Xenon (common in EP)
  - H_2O, N_2O, hydrazine (innovative)

	Thrust [mN]	Spec. Impulse [s]	Thruster Eff. [%]	Power [W]
Ar	170-280	100	40	200
He	100-400	350	30-80	900-1500
N_2O	400-700	<250	60	900-500
H_2O	100-300	400-1000	10-35	5000

- Offers performance bw chemical and state-of-the-art electric propulsion [5] → new missions feasible

Objectives

Design and **Study** METs

Numerical models

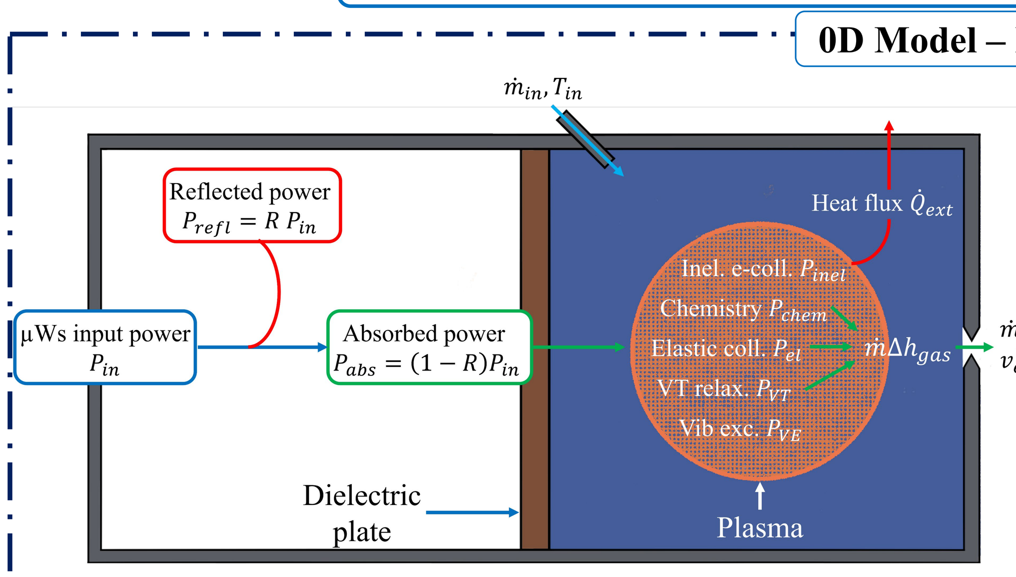
Investigation of MET plasma discharge and operation with conventional (atomic) and innovative EP propellants;

Assessment of the **impact of design choices** (e.g., dimensions) and operating conditions ($P_{in}, \dot{m}$) on thruster performance;

Support the design and construction of the physical MET prototype @ Polimi

Methods: MET global (0D) plasma model

0D Model – Multi-T approach [4]



Set of ODEs: PaBE + PoBE (e, v, g) for n_j, T_e, T_V, T_g

$$\frac{d\,n_j}{dt} = S_j - L_j + \sum_i \chi_{j,i} R_{j,i}$$
$$\frac{d\,E_e}{dt} = P_{abs} - P_{inel} - P_{EV} - P_{el}$$
$$\frac{d\,E_V}{dt} = P_{EV} + P_{flow}^{V} - P_{VT} - \dot{Q}^{V} + P_{ch,V}$$
$$\frac{d\,E_g}{dt} = P_{VT} + P_{flow}^{RT} - \dot{Q}^{RT} + P_{ch}$$

Thrust: $F = \dot{m}_{exh} v_{exh}$

Spec. Impulse: $I_{SP} = \frac{F}{\dot{m} g_0}$

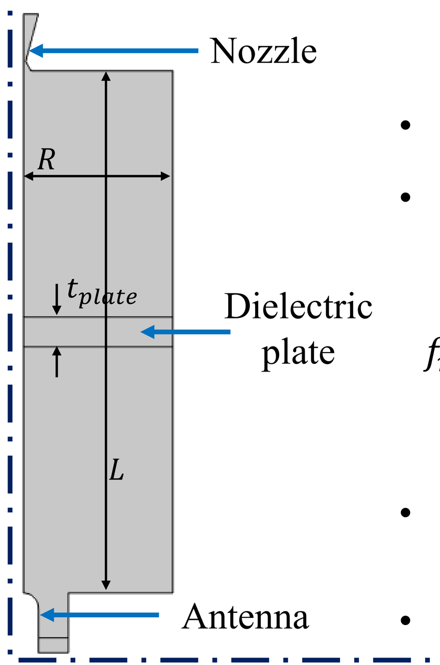
Thruster eff.: $\eta_T \propto F\, I_{SP}$

RT: roto-translational d.o.f; V: vibrational d.o.f

E_x: mean energy → harmonic oscillator (HO) for V

P_{EV}, P_{VT}: relaxation term → Landau-Teller $\propto \Delta E/\tau$

EM 2D-axisymmetric model



Cavity response to μWs excitation

- Maxwell's equations
- Boundary conditions
  - Perfect Conductor vs Lossy Walls
  - Wave excitation at antenna (TM_{011})

$$f_{res}^{Theo} = \frac{c}{2\pi\sqrt{\epsilon_r \mu_r}}\sqrt{\left(\frac{\chi_{01}}{R}\right)^2 + \left(\frac{pi}{L}\right)^2} \qquad \Delta f_{res}^{Theo}[\%] \propto -\frac{(\epsilon_d - 1)t}{L}$$

COMSOL

- Influence of plate **material, thickness, and location** on resonant frequency and field distribution
- Figure of merit: $|E^{max}|$ (near nozzle)

Results

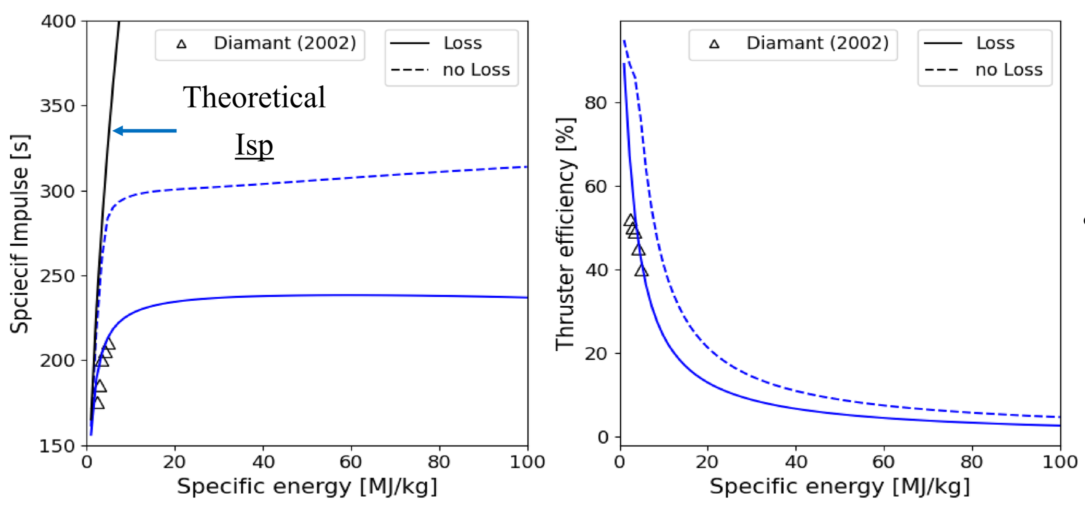
N2 0D MET model study

$R = 50\,mm$, $L = 158\,mm$, $r_{throat} = 0.6\,mm$

$P_{in} = 900\,W$, $\dot{m}_{in} = 1 - 1000\,mg/s$, $T_{wall} = 800\,K$

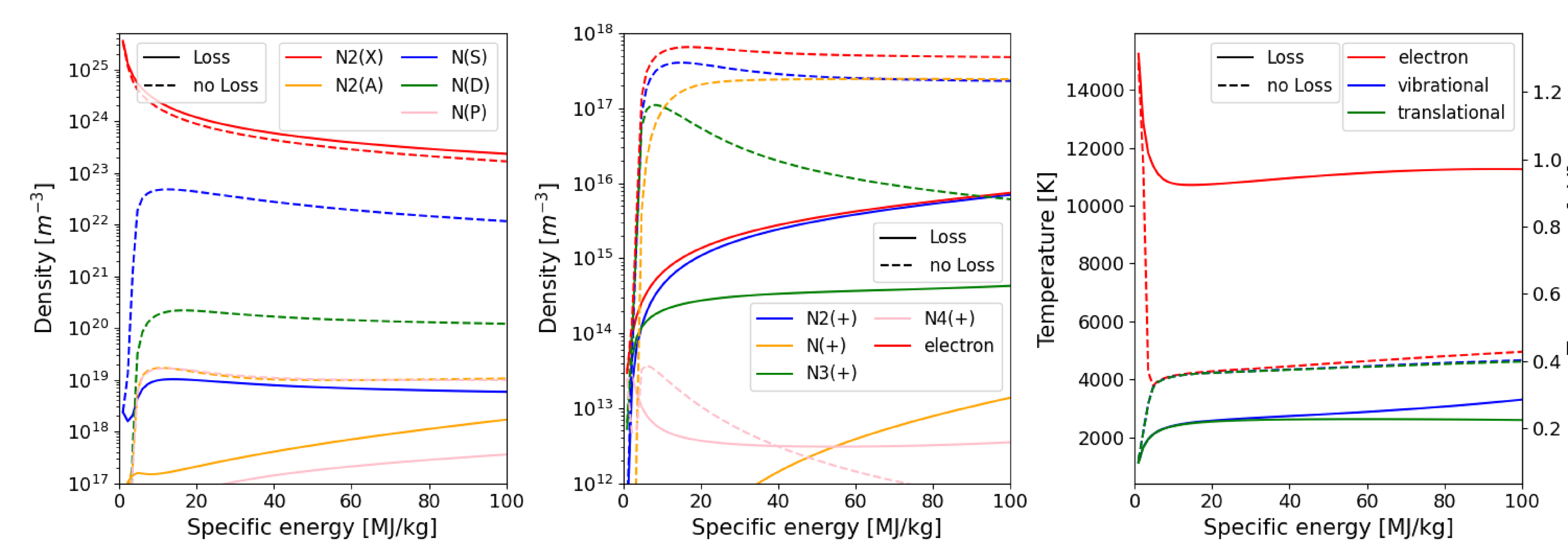
2 simulations: Adiabatic ($\dot{Q} = 0$); Thermal losses on ($\dot{Q} \neq 0$)

Comparison with experimental data [7] – only thruster performance



- **Good agreement** with experimental data (when thermal losses are on)
- **Difference from theoretical curve**
  - plateu-like region I_{sp}
  - Some mechanism limiting the power transfer

Plasma parameters: densities and temperatures – lack of experimental data



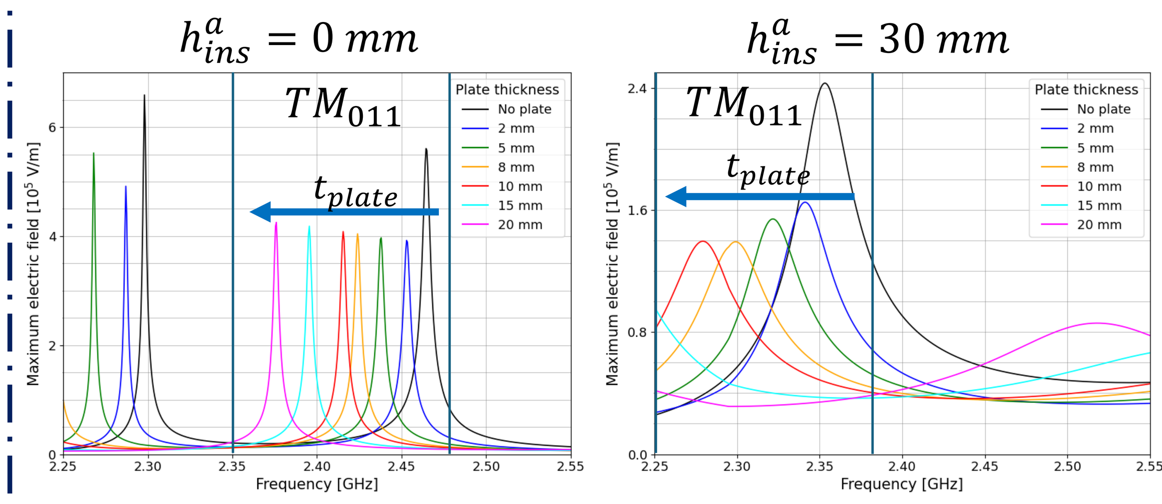
- Densities behav. change a lot when switching the losses on
- **$N_2(X)$ is dominant** → low dissociation / excitation
- **N_2^+ dominant ion**: N^+ depends on the model
- Adiabatic model: full equilibrium
  → Efficient VE and VT
- Non-adiabatic model: $T_e > T_V = T_g$
  → efficient VT
  → $\tau_{VE} \sim t_{residence}^{gas}$ (no eq. bw E and V)

EM MET study

$R = 50\,mm$, $L = 158\,mm$, $r_{throat} = 0.6\,mm$

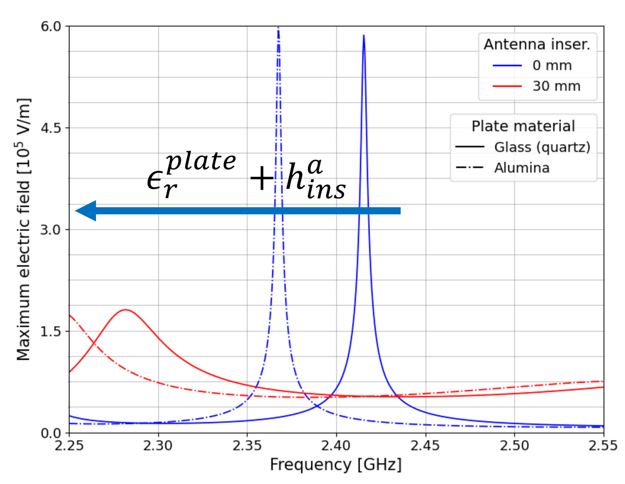
$P_{in} = 1000\,W$, $f_{ex} = 2.25 - 2.55\,GHz$, $f_{ex}^{opt} \sim 2.45\,GHz$

Simulations:
- t_{plate}: Plate thickness (Quartz)
- ϵ_r^{plate}: material Quartz Vs Alumina
- h_{ins}^a: antenna position



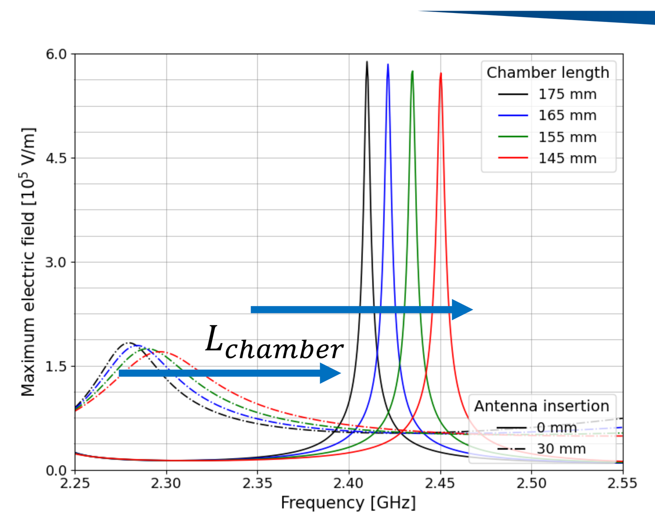
- t_{plate} ⇑ → f_{res} ⇓
- t_{plate} ⇑ → $|E|^{max}$ mild variation
- h_{ins}^a ⇑ → f_{res} ⇓, $|E|^{max}$ ⇓ & larger bandwidth

- Plate materials ($t = 10\,mm$):
  - Glass (quartz): $\epsilon_r^{plate} = 4.2$
  - Alumina (Al2O3): $\epsilon_r^{plate} = 9.9$
- ϵ_r ⇑ → f_{res} ⇓



$\Delta f_{res} < 0$ due to change in: $t_{plate}, h_{ins}^a, \epsilon_r^{plate}$

Thus, $L_{chamber}$ ⇓ → $f_{res} \sim 2.45\,GHz$ (Magnetron operating frequency)



- $f_{res} \simeq 2.45\,GHz$ for $L_{chamber} \simeq 145\,mm$ (design choice)
- 30 mm antenna case:
  → still **inefficient** at 2.45 GHz
  → optimum at 2.27 GHz w/
  → **broader band**: better parameters tuning for discharge control (e.g. pressure)

Conclusion & future perspective

- MET is a promising EP tech with **limited erosion**
- MET numerical modeling **supports thruster design** and provide tool to **investigate** its **operation**
- **0D** model results agrees with experiments, **giving insights** into plasma params
- MET EM model **suggest design parameters** for optimal E^{max} and f_{res}
- Future work will focus on extending the 0D model to other propellants (O_2, N_2O, H_2O)
- Need of a multi-D model improving the physical understanding (e.g., swirling flow impact on discharge)

References

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