Hardware in the loop for an electrodynamic tether emulator

Angel del Pino Jiménez, Amadeo Velasco,
Gonzalo Sánchez Arriaga

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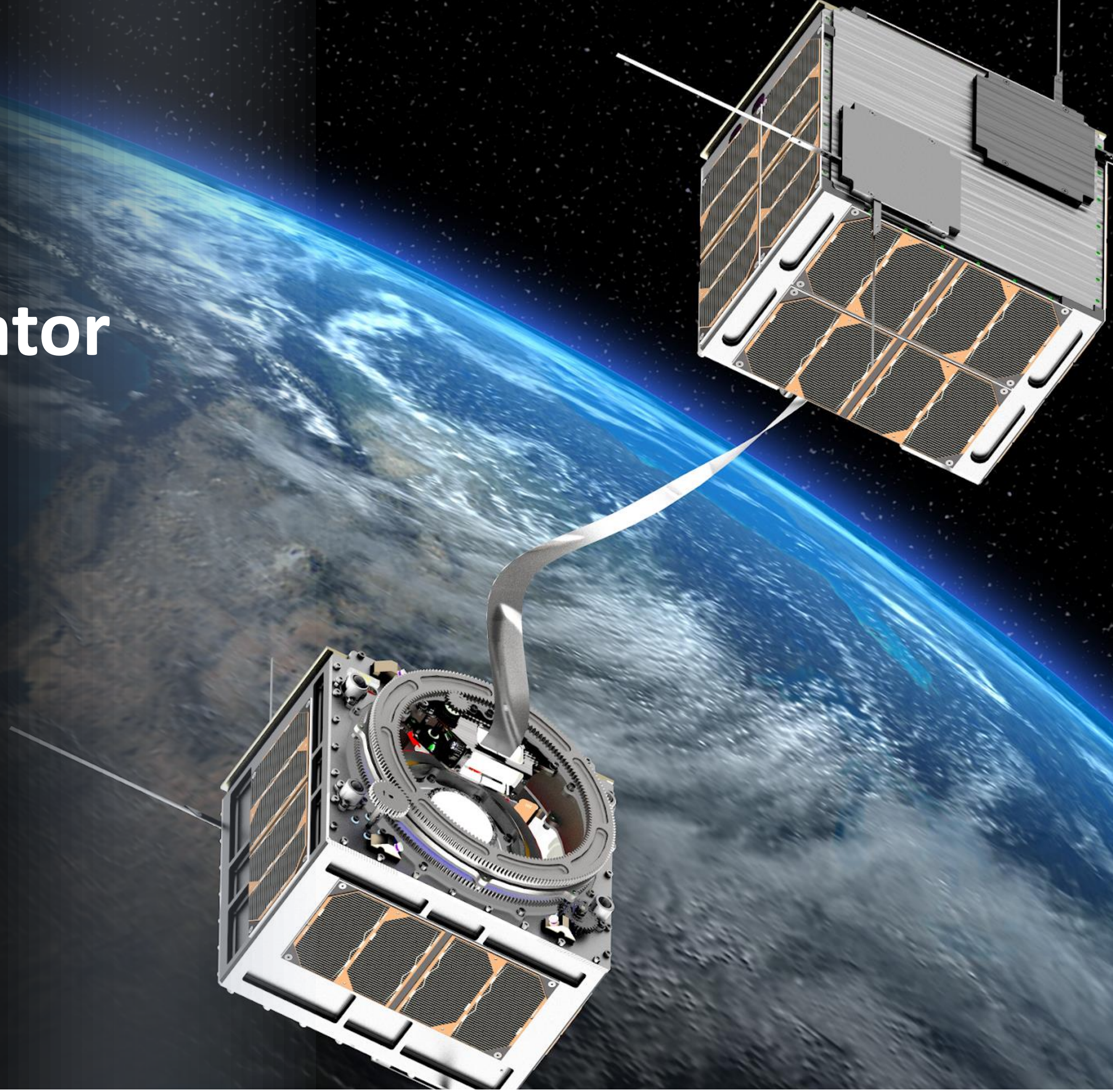

E.T.PACK-F
uc3m | Universidad Carlos III de Madrid
SENER Aeroespacial
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1. Introduction: Context and motivation

Overview

- E.T.PACK-F deorbit device has a Bare Electrodynamic Tether (BET) to capture electrons and a Hollow Cathode (HC) to emit electrons back to the atmosphere.
- BET and HC are connected via the Electric Power Module (EPM), which controls the voltages and the current.

Deorbit Device description

- **Electron Emitter Module (EEM).** It contains the HC and the EPM.
- **Deployment Mechanism Module (DMM).** It hosts the BET and its deployment mechanism.

Objectives of this work:

- Develop a theoretical model for the BET-EPM-HC circuit.
- Develop a hardware-in-the loop (HIL) of the BET-EPM-HC circuit for ground testing.

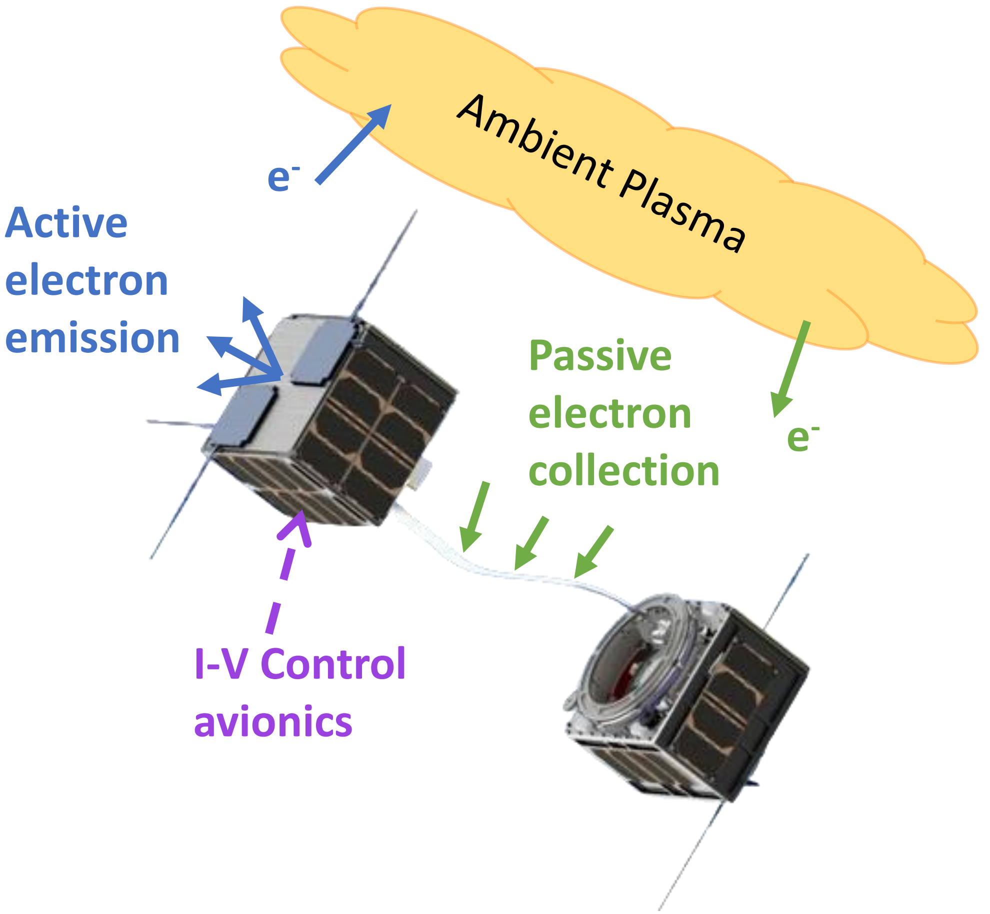

Figure 1: E.T.PACK-F mission satellites (EEM upper module, DMM bottom module) with basic system operation

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2. Theoretical model

The theoretical model couples the three I-V curves of the BET, the EPM, and the HC (see Fig. 2).

I-V curves models:

1. EDT: We use the I-V model of a bare EDT (see Ref. [1]).
2. EPM. It is modelled with a resistor and a power supply to control the voltage.
3. Heaterless HC model. It corresponds to the HC developed at TU Dresden, which has two elements: the keeper and the emitter. The I-V curves of each elements were obtained experimentally. To keep the plasma discharge, the current should be above a threshold.

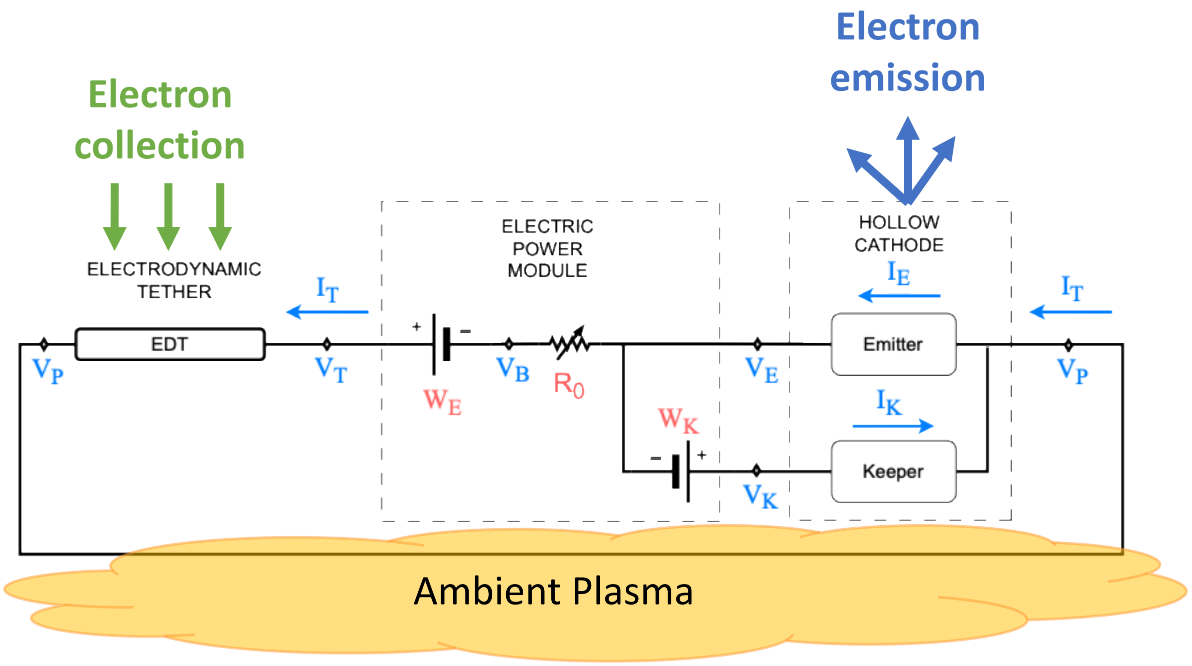

Figure 2: Electric circuit of the EDT-EPM-HC and plasma system

[1] J. R. Sanmartín, M. Martínez-Sánchez, E. Ahedo, Bare wire anodes for electrodynamic tethers, J. of Prop. & Power 9 (3) (1993) 353–360.

2. Theoretical model

Electrodynamic Tether (EDT):
For a fully bare and straight tether the I-V curve reads (see Sanmartin et al, 1993)

$$V_T - V_P = f_t\left(I_{T,min}; \mathbf{p}\right) \qquad (1)$$

Function f_t involves vector $\mathbf{p}$, which includes tether geometry such as its thickness h_t, width w_t, conductivity σ_t, tether length L_t, and two ambient parameters: the projection of the motional electric field along the tether direction (E_m) and the plasma density (N_0).

Parameter	Value	Parameter	Value
L_t	450 m	h_t	$40 \mu m$
w_t	2.5 cm	σ_t	$3.54 \cdot 10^7\ 1/\Omega m$
N_0	$10^{11}\ 1/m^3$		

Table 1: Parameters used in the calculations of Fig. 3

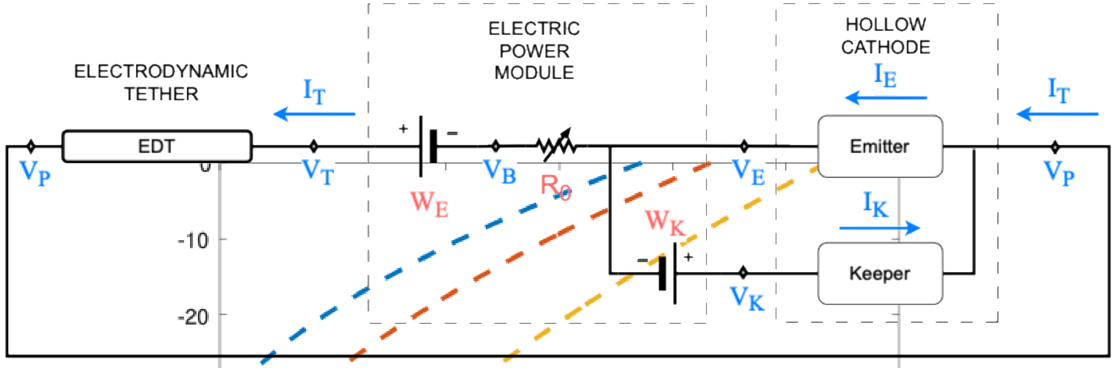

Figure 2: Electric circuit of the EDT-EPM-HC system

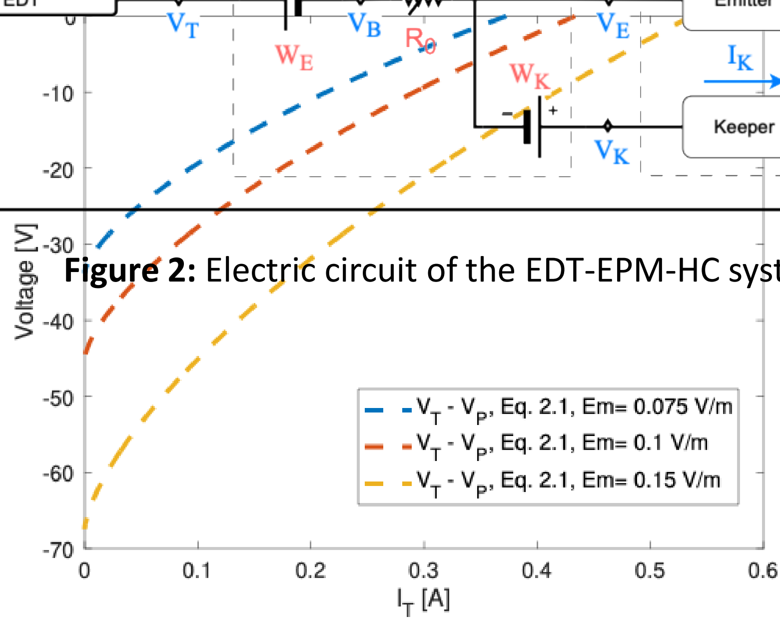

Figure 3a): Different I-V Curves for a BET

2. Theoretical model

Electric Power Module (EPM):

The proposed EPM includes:

- A power source that delivers a power W_K to run the HC.
- A variable resistor of resistance R_0 to limit the tether current and protect electronics components.
- Anther power source that delivers a power W_E to control the tether voltage.

The purpose of power W_E is twofold:

- To enhance tether performance.
- Reach currents above the thresholds $I_{K,min}$ and $I_{E,min}$ to maintain the plasma discharge.

At a given instant and depending on the ambient variables and the mission phase, we set $W_E = 0$ and $R_0 \neq 0$ or $W_E \neq 0$ and $R_0 = 0$.

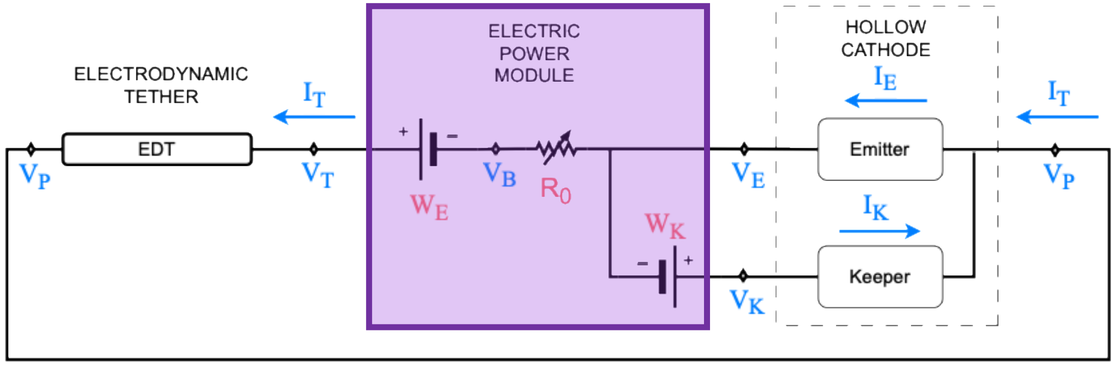

Figure 2: Electric circuit of the EDT-EPM-HC system

The potential differences across the power sources and the resistor read

$$V_T - V_B = \frac{W_E}{I_T} \qquad (2)$$

$$V_E - V_B = I_T R_0 \qquad (3)$$

$$V_K - V_E = \frac{W_K}{I_T} \qquad (4)$$

Finally, the current continuity equation

$$I_T = I_E - I_K \qquad (5)$$

2. Theoretical model

Hollow Cathode (HC):
The HC system includes two components:

- **Emitter** (subscript E, e.g. for emitter current I_E)
- **Keeper** (subscript K, e.g. I_K)

These components have been characterized in laboratory experiments at TU Dresden [2] by measuring the current I_T at the anode and the potential differences between points E-P and K-E in the circuit. Each element has a minimum current value, $I_{K,min}$ and $I_{E,min}$, to maintain the plasma discharge. The I-V curves are here represented by the linear fittings

$$V_P - V_E = a_E I_T + V_{0,E} \qquad (6)$$

$$V_K - V_E = a_K I_T + V_{0,K} \qquad (7)$$

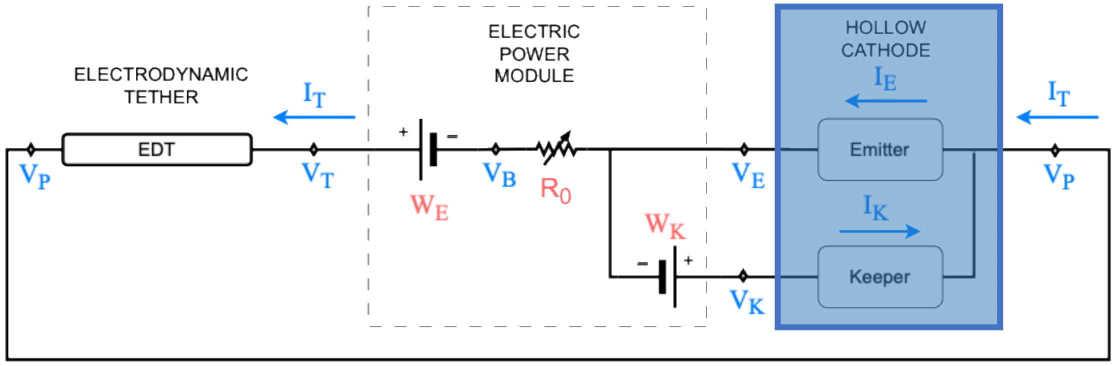

Figure 2: Electric circuit of the EDT-EPM-HC system

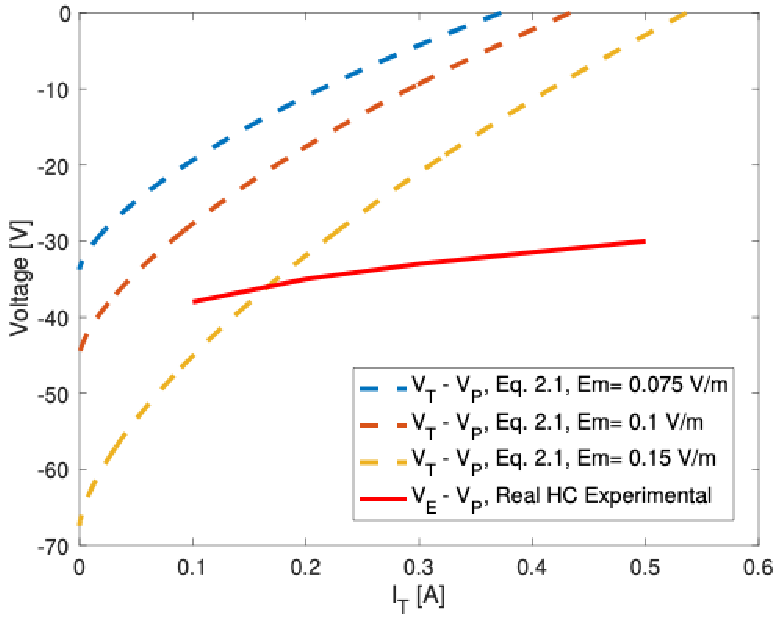

Figure 3b): Different I-V Curves for a BET + HC

[2] C. Drobny, Development of a low-current plasma-based cathode using the emitter material c12a7 electride for space applications. PhD Thesis. 2023

2. Theoretical model: Results

Parametric analysis in the $E_m - N_0$ plane

The power required to maintain the plasma discharge in the cathode can be estimated. For the best-case scenario, with the minimum current constraints ($I_{T,min} = 0.2A$ and $I_{K,min} = 0.1A$) this power can be calculated. Using equations (1)-(7), the minimum power reads:

$$W_{E,min} = I_{T,min}[f_t(I_{T,min}; \mathbf{p}) + a_E I_{T,min} + V_{0,E}] \quad (8)$$

$$W_{K,min} = I_{K,min} \cdot (a_K I_{T,min} + V_{0,K}) \quad (9)$$

$$W_{T,min} = W_{E,min} + W_{K,min} \quad (10)$$

A parametric analysis over the motional electric field and plasma density is displayed in Fig.5.

Outcomes for 500-600km range, E.T.PACK-F like mission:

- With 3W power: Very restricted operational region.
- Increasing power to 4W: Enlarges operational region.

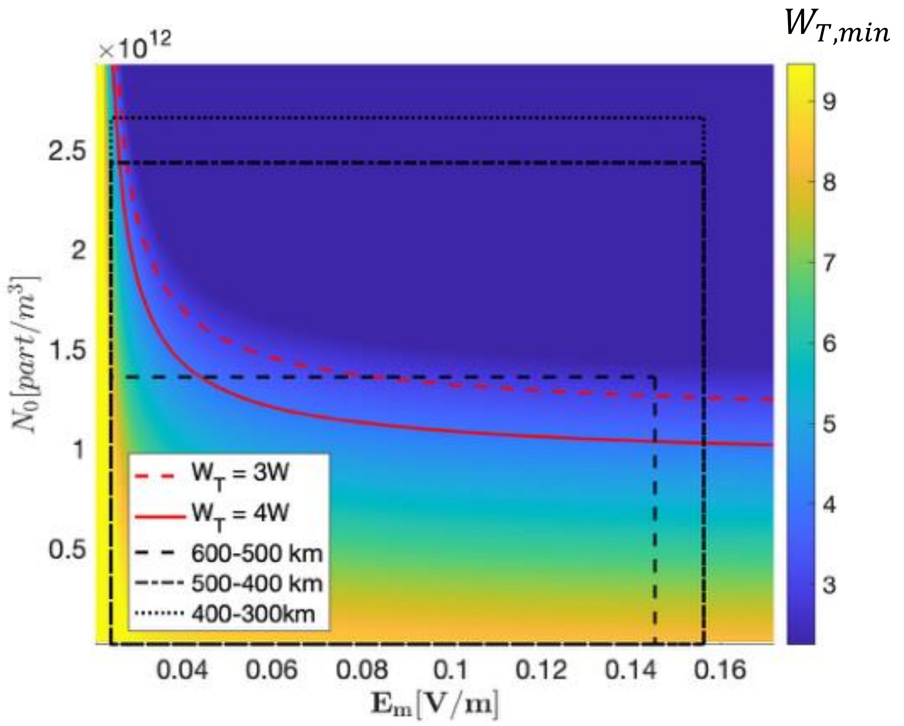

Figure 5: Minimum required power ($W_{T,min}$) in the $E_m - N_0$ plane.

***Note:** $E_m - N_0$ range limits have been obtained using BETsMA v2.0 for different deorbiting cases, where the maximum and minimum values per altitude range (300-400km, 400-500km and 500-600km).*

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3. Hardware emulator: HIL setup

Hardware in the Loop (HIL) emulator description

The HIL emulator consists of three main elements: EDT, EPM and HC. They are emulated as follows

- **EDT** is emulated as:
  - Programmable Power Supply W_T .
  - Fixed resistor R_T.

-**EPM** is emulated with:
  - External power supply of power W_E.
  - Variable resistor R_0 to dissipate power.

- **HC** combination of Zener diodes with a reverse voltage of $\Delta V_{HC} \equiv$ 30V.

Additionally, a microcontroller (MCU) with a voltmeter one computer (PC) that compute tether profiles and commands the programmable power supply are included.

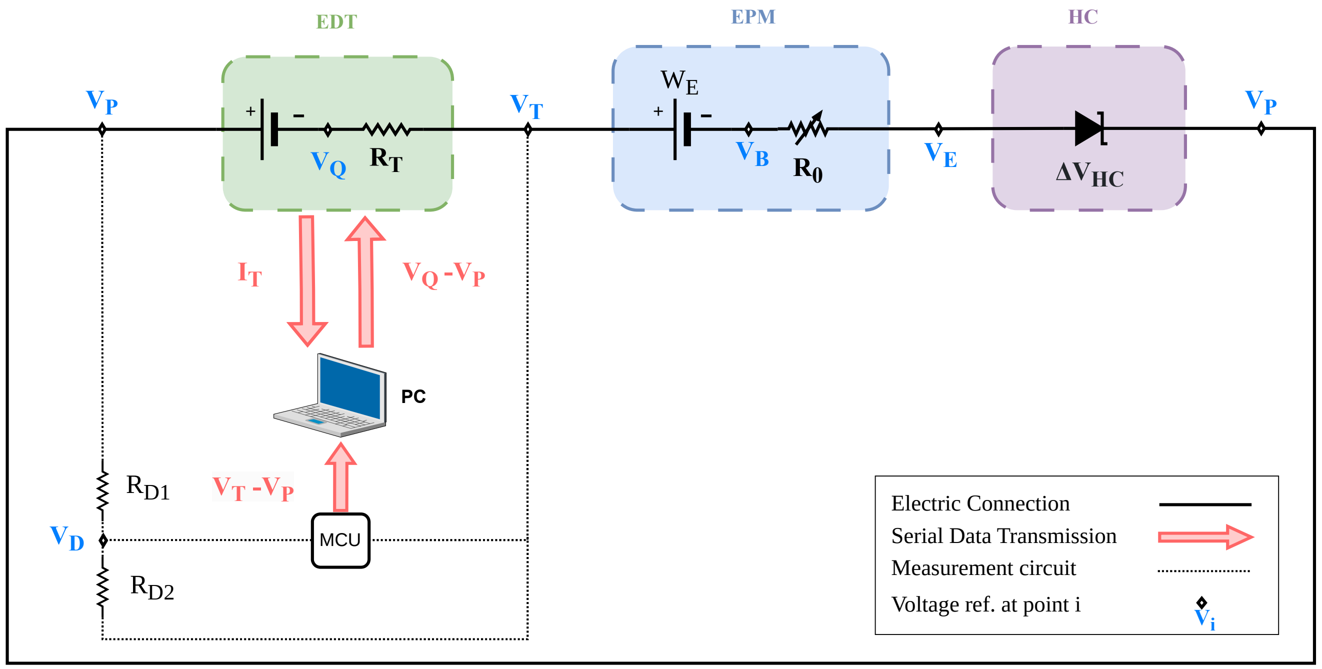


Figure 6: Hardware in the loop diagram

3. Hardware emulator: HIL methodology

Solution to emulate the I-V curve of the bare EDT

1. MCU measures and sends $(V_T - V_P)$ to the PC.
2. PC calculates $I_T|_{th}$ and $(V_Q - V_P)$ as follows:
   - $I_T|_{th}$ as a function of $(V_T - V_P)|_{\mathrm{m}}$, with eq. (1)
   - $(V_Q - V_P) = (V_T - V_P)|_{\mathrm{m}} - I_T|_{\mathrm{th}} R_T$.
3. PC commands the programmable power supply by sending $(V_Q - V_P)$ and limiting the current to $I_T|_{th}$.
4. PC queries $I_T|_{\mathrm{m}}$ from the programmable power supply and compares with $I_T|_{th}$.

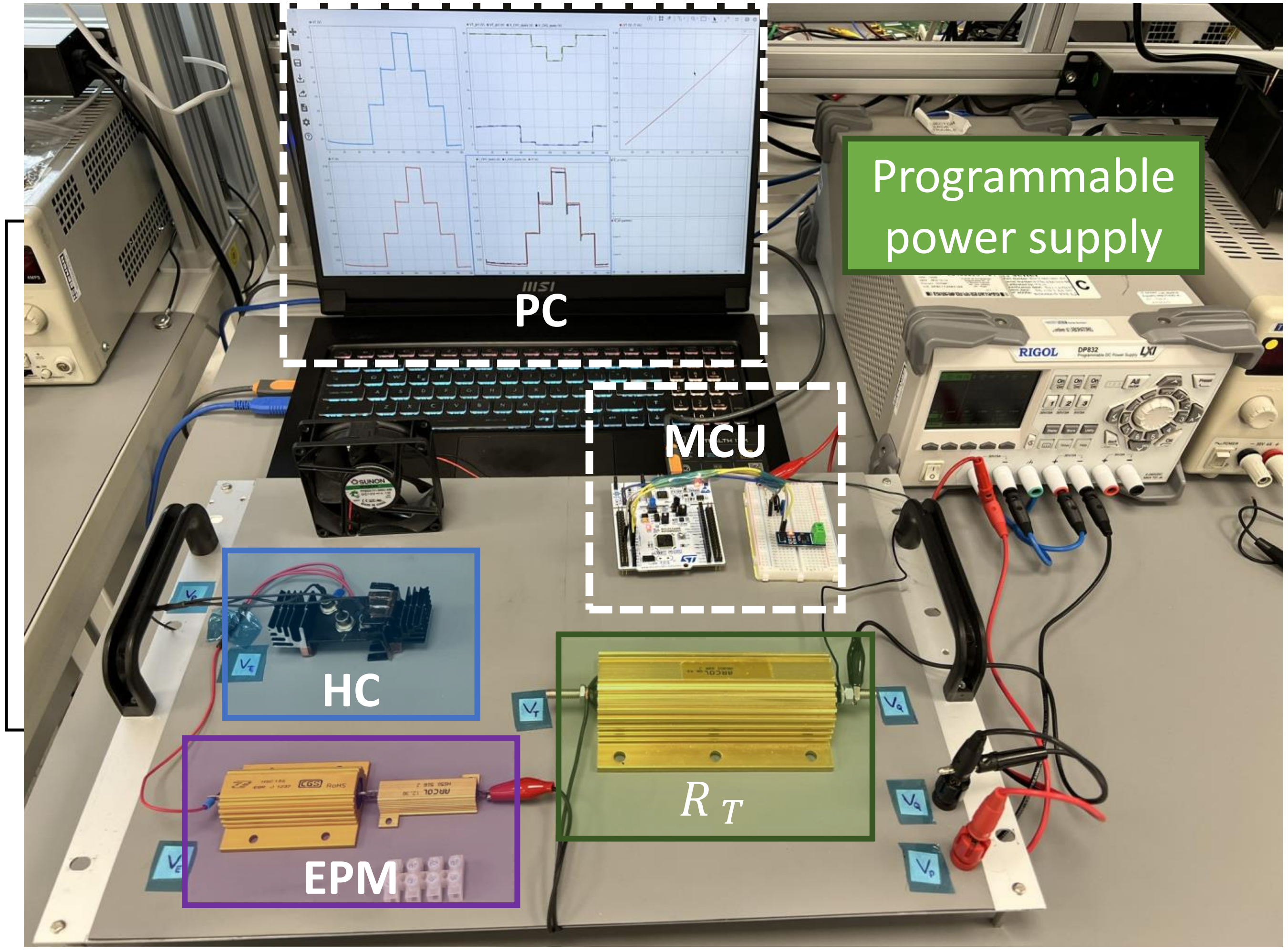
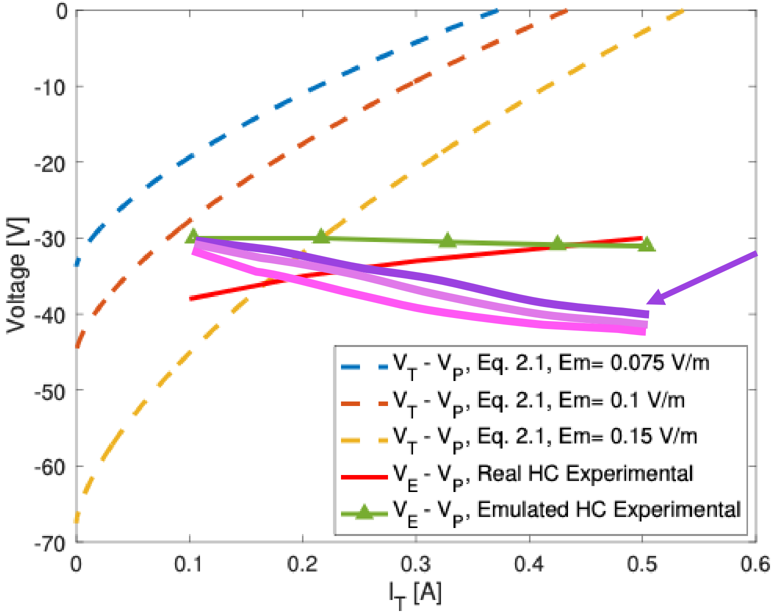


Figure 7: Hardware in the loop laboratory setup

3. Hardware emulator: results

Temperature effect on Zener diodes:

HC drop is emulated with a combination of three Zener diodes in parallel. The selected model is PN1N2989B, that can withstand a maxim power of 10W (0.32A). However…



Unconsistent non-matching curves

Figure 3b): Different I-V Curves for a BET + HC + zeners

Performance improves if we include cooling elements in the setup

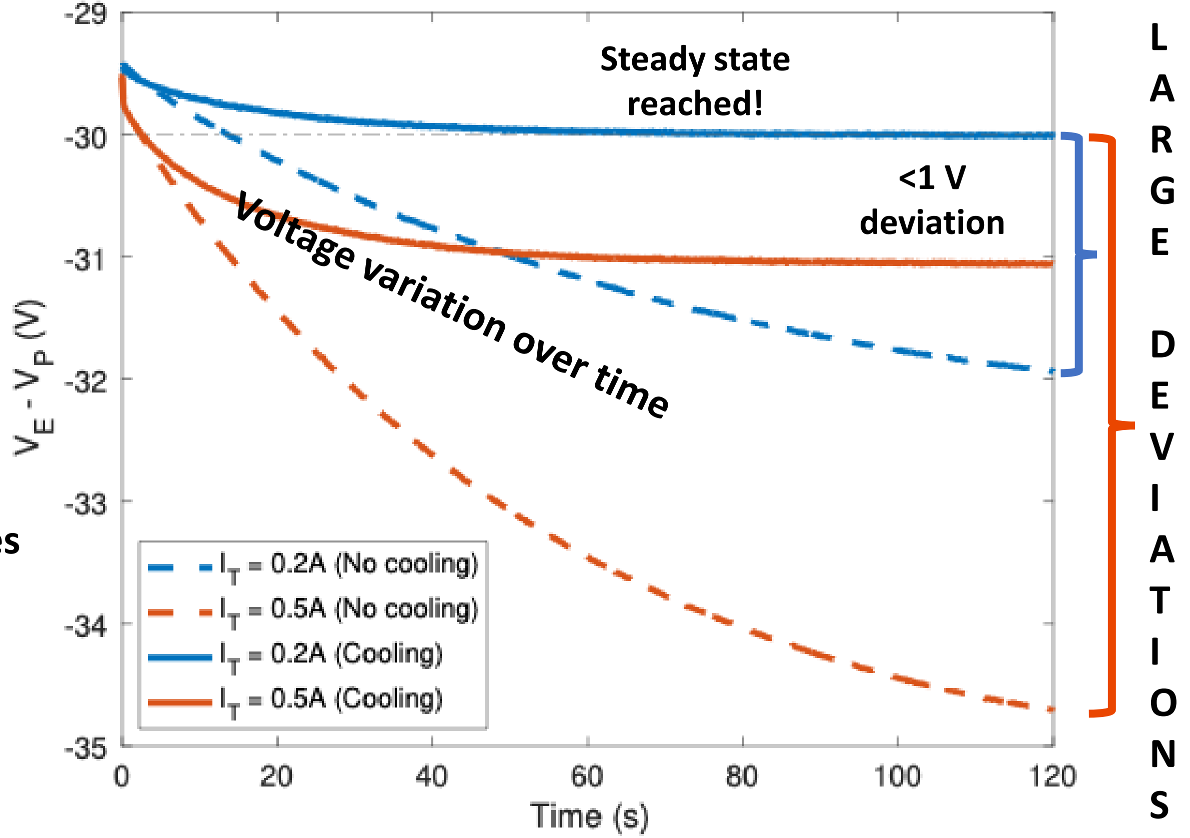


Figure 4b): Temperature effect on Zener diodes

3. Hardware emulator: results

Temperature effect on Zener diodes:

HC drop is emulated with a combination of three Zener diodes in parallel. The selected model is PN1N2989B, that can withstand a maxim power of 10W (0.32A).

Passive elements (aluminum heatsinks) and active ones (a 8mm fan) have been included in the laboratory setup.

Cooling elements are required in order to keep the voltage drop in the desired range.

A steady state is reached in approximately 1 minute.

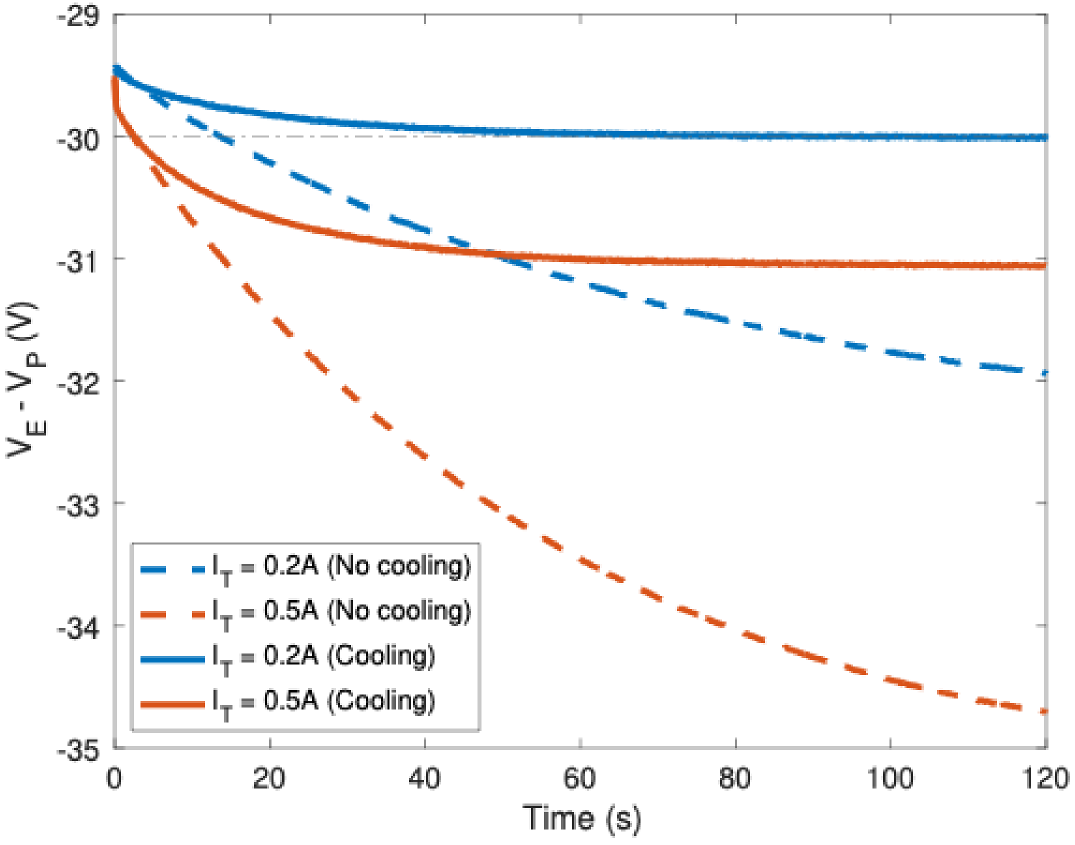


Figure 4b): Temperature effect on Zener diodes

3. Hardware emulator: HIL results

Validation of the EDT-EPM-HC emulator

Tests were conducted to validate the EDT block using the EPM by either injecting or dissipating power.

- **Power Injection:** An external power supply was used to positively polarize the tether in 5V increments.
- **Power Dissipation:** A set of resistors ranging from 0 to 300Ω was placed in the EPM. These resistors were manually changed during a single test.

Experimental curves are compared against theoretical ones, theoretical current with measured voltage and viceversa, obtained with eqs.

$$(V_T - V_P)\,|_m = f_t(I_T\,|_{th}; \mathbf{p}) \qquad (11)$$

$$(V_T - V_P)_{th} = (V_T - V_B) + R_0 I_T\,|_m + V_{HC}(I_T\,|_m) \qquad (12)$$

Outcomes:

- Cooling was required for the system to reach a steady state at the HC equivalent.
- The emulator was successfully verified.
- Slight deviations in the current measurements, attributed to the low precision of the query system

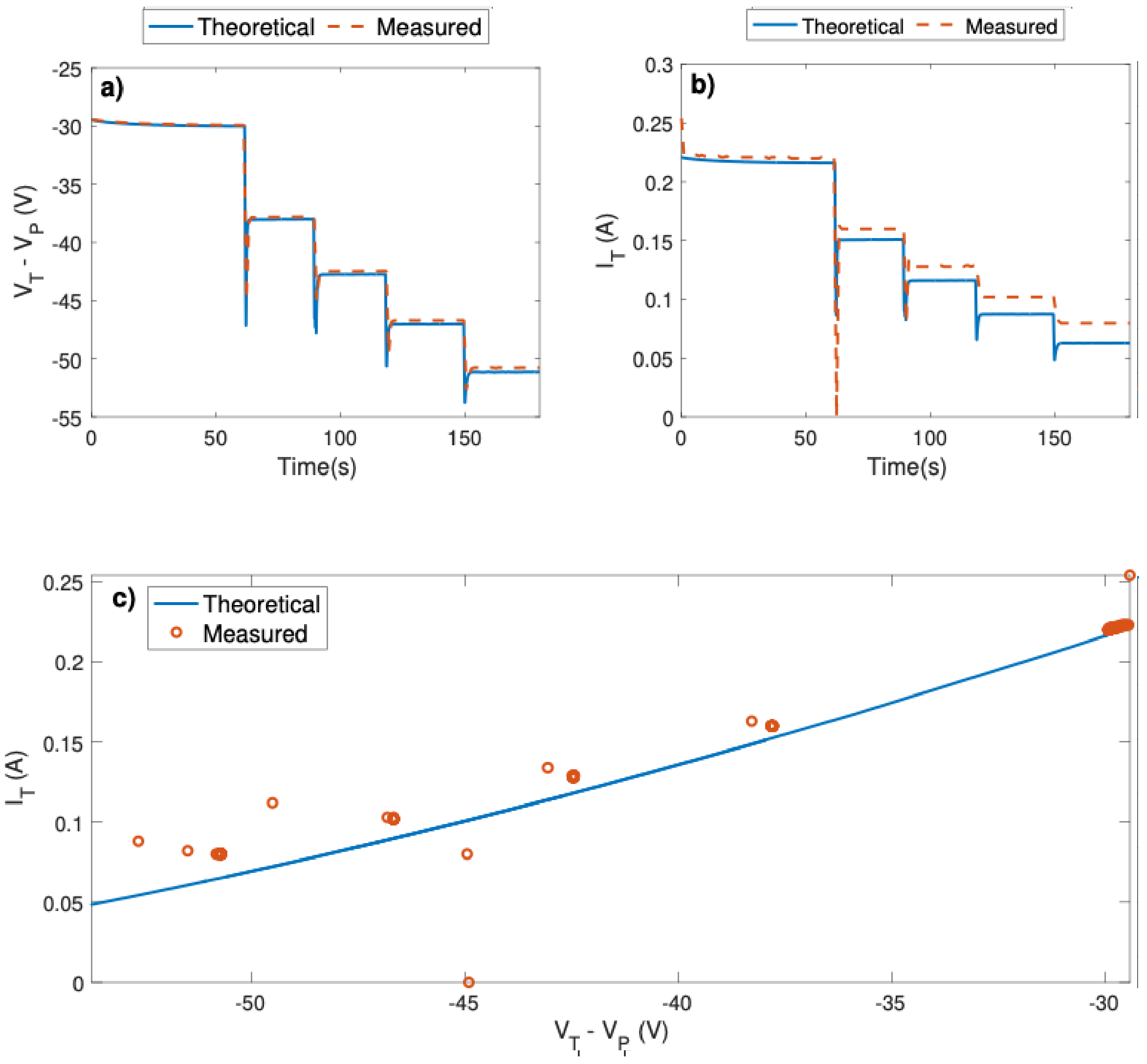


Figure 8: Power injection tests
Figure 9: Power dissipation tests

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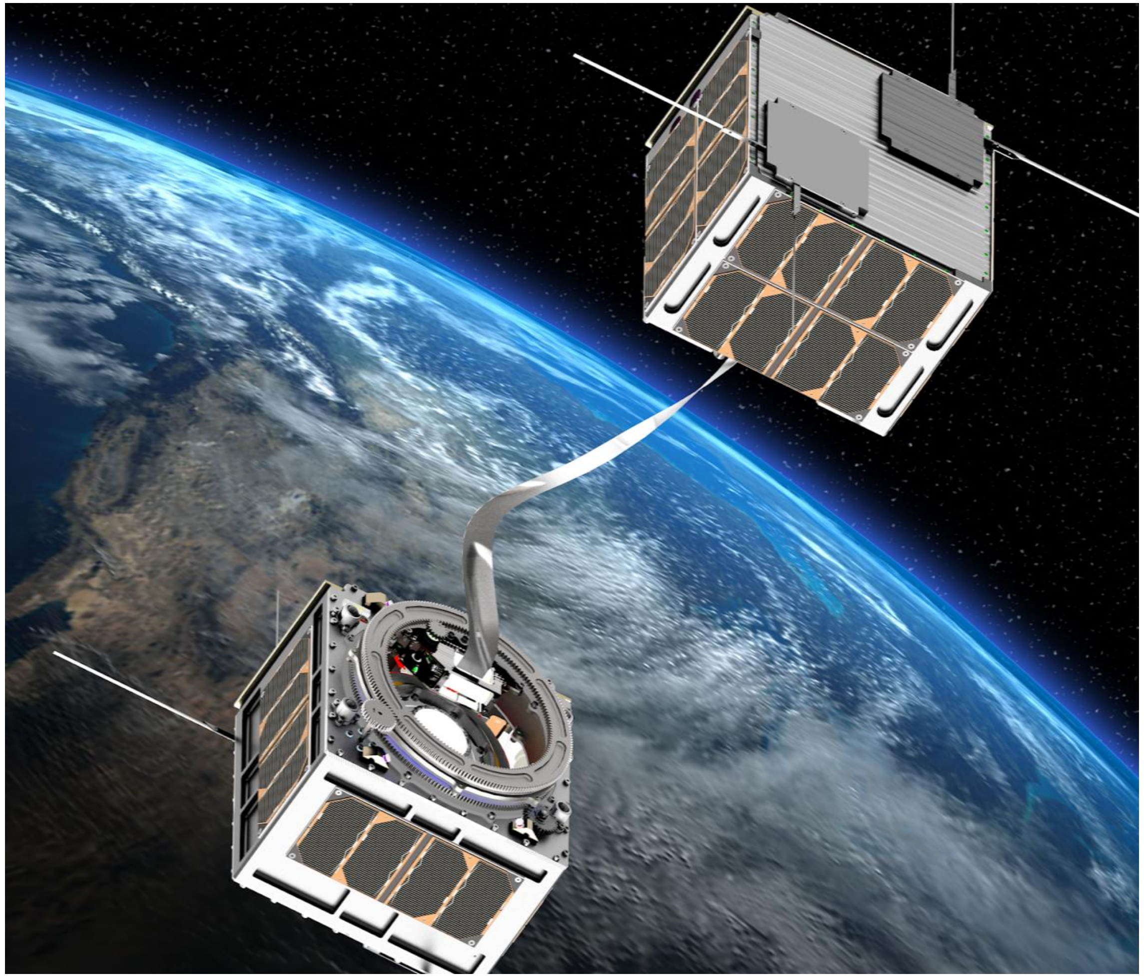
4. Conclusions & Future Activities

Conclusions:

- A theoretical model for the EDT-EPM-HC circuit was constructed.
- The model provides useful information, like the required power to keep the HC on as a function of motional electric field and plasma density.
- For E.T.PACK-F mission, 4 W of power ensures a broad operational range.
- A complete HIL setup was developed for the EDT-EPM-HC circuit.
- Different tests were conducted to verify de HIL.
- The HIL will be used to test the flight electronics of the EPM of the E.T.PACK's deorbit device.



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Thank you for your attention!
Any question?

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