ERC Starting Grant Zarathustra

Mario Merino

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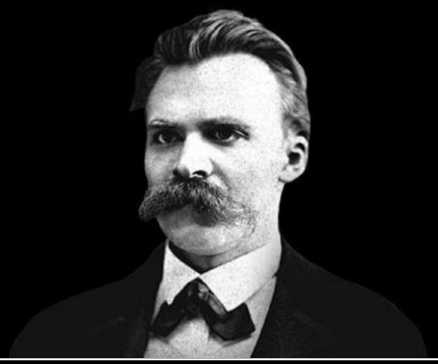
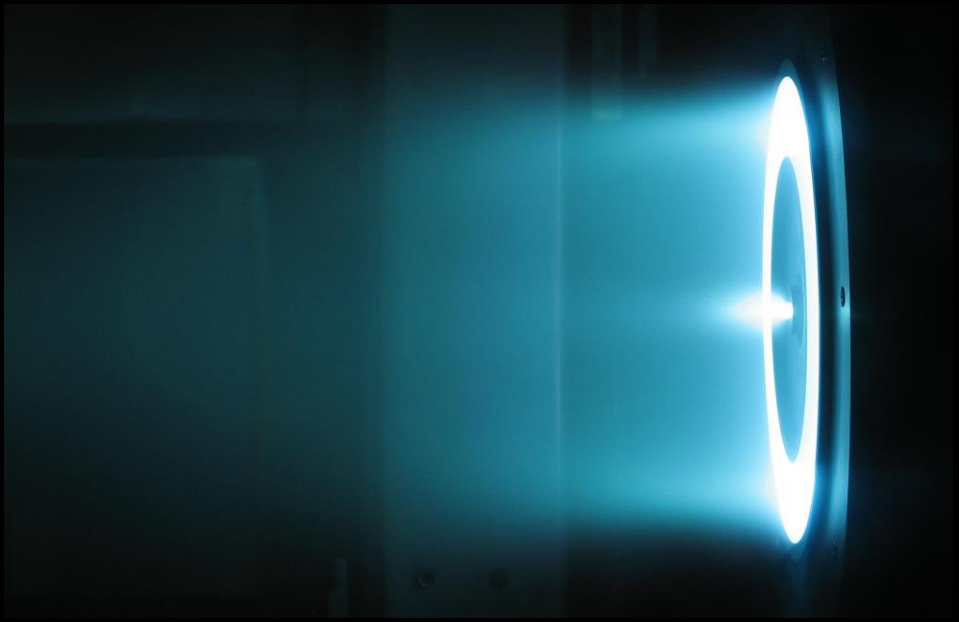
ZARATHUSTRA ?

Revolutionizing Advanced Electrodeless
Plasma Thrusters for Space Transportation

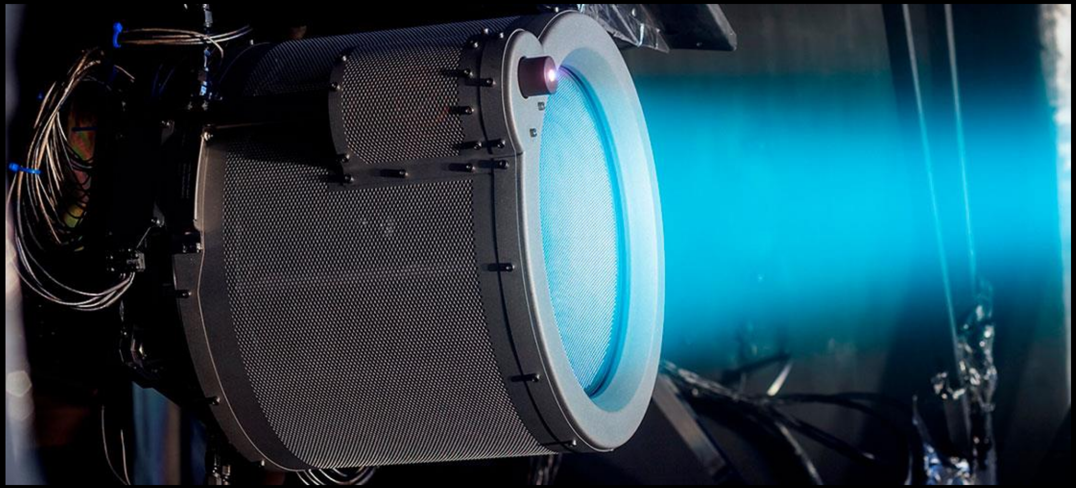


Limitations of current plasma propulsion systems

- Plasma propulsion is interesting because of the huge propellant mass savings it offers with respect to chemical propulsion (x10)
- Hall thrusters (HT) and gridded ion engines (GIT) work really well and keep improving, but:
  - Heavy and complex electronics (especially GIT)
  - Electrodes erode over time and limit lifetime
  - Difficulty to scale to small and high powers needed in many applications



JPL 6 kW Hall thruster



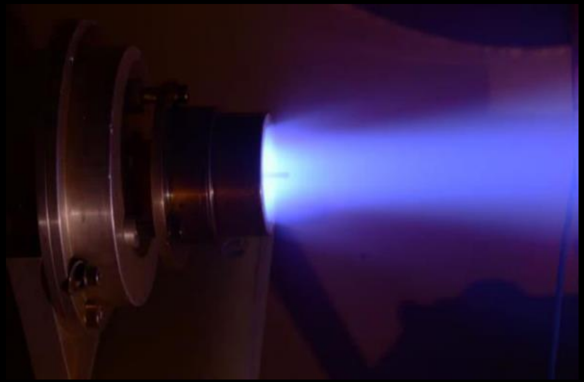
Qinetiq 5 kW gridded ion engine

  - Difficulty to use propellants other than Xe
  - Limited throttleability range
- Meanwhile, the space transportation sector is becoming more demanding and is expected to have a continued growth in the coming decades

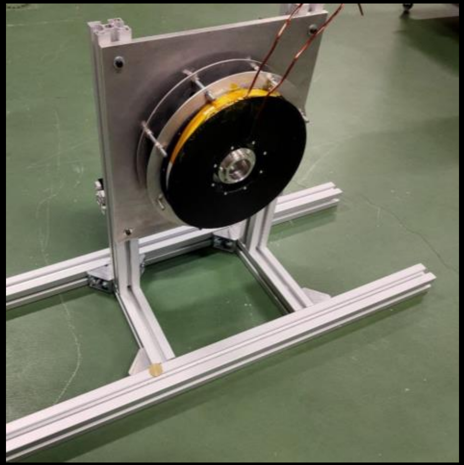
ELECTRODELESS PLASMA THRUSTERS

- Enter Electrodeless Plasma Thrusters:
  - Power is delivered to the plasma via RF/microwave fields
    - Absence of electrodes simplifies design, prevents lifetime issues, and enables operation with virtually any propellant
    - Scalability does not depend on electrodes any more
  - Plasma is accelerated contactlessly by a magnetic nozzle
    - Magnetic field can be adapted in-flight to facilitate throttling and enable thrust vector control without any moving parts
- Two major technologies are being developed worldwide:
  - The Helicon Plasma Thruster (HPT)
  - The Electron-cyclotron Resonance Thruster (ECRT)

HPT (EP2-SENER;
see H2020 HIPATIA project)



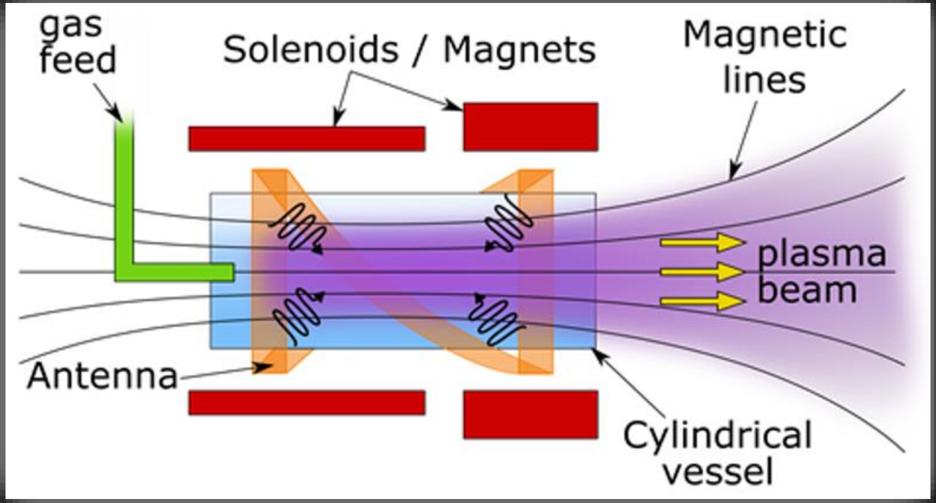
ECRT (ONERA)



ECRT (EP2)

Key challenges and necessary breakthroughs

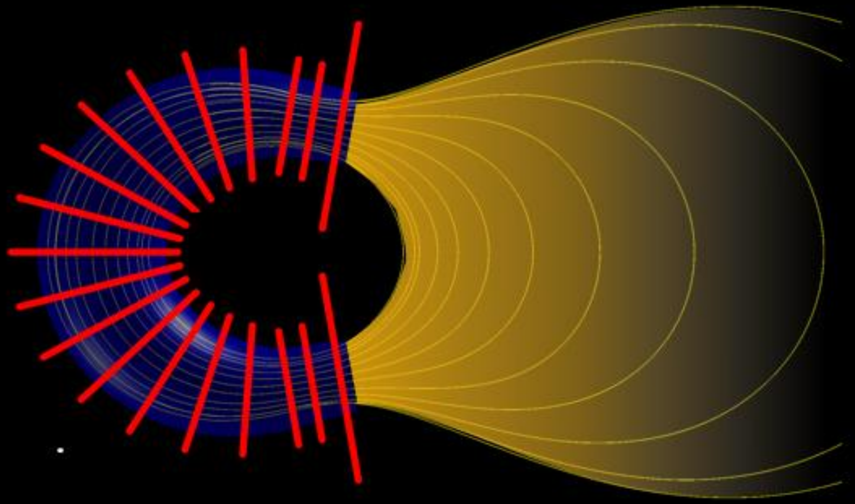
- In spite of their big promise, EPTs are still underperforming:
  - Max 15-20% thrust efficiency (HT and GIT can reach about 50-70%)
  - Large plume divergence angle (big issue for satellite integration)
  - Incomplete understanding: large "distance" between model prediction and experimental measurements
- Three major aspects are deemed responsible for this situation:
  - Missing physical understanding of the plasma-EM fields interaction
    - This is key for effective and efficient plasma heating
  - Large knowledge gaps on particle transport phenomena
    - 'Anomalous' transport (arising from instabilites, turbulence,EM-field interactions, wall-interactions) is a fact in electric propulsion but very little is known
    - Responsible for the large plasma losses to the walls
  - Cylindrical plasma source design has inherent problems that cannot be overcome
    - Substantial amount of generated plasma (50%?) is lost to the unshielded rear wall



Objectives of ZARATHUSTRA

"To unravel the physical underpinnings of electrodeless plasma thrusters and revolutionize their design"

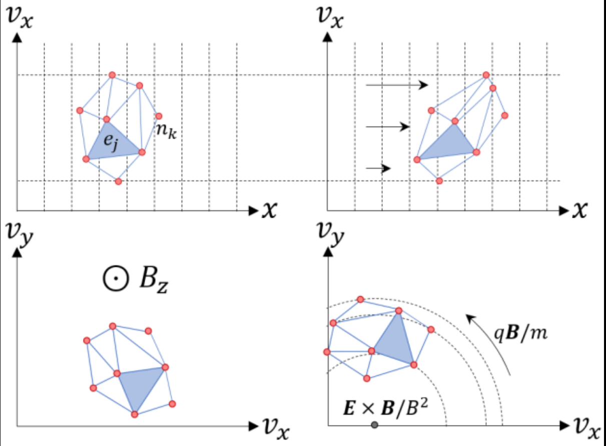
- Two objectives cover major gaps in SoA:
  - Reveal the underlying physics of EM plasma heating in EPTs
  - Elucidate the role of plasma turbulence, wall interactions, and applied EM fields on anomalous transport in EPTs
- The third objective brings innovation:
  - Establish a first proof of concept of a non-cylindrical "Magnetic Arch thruster" and characterize it



Methodology

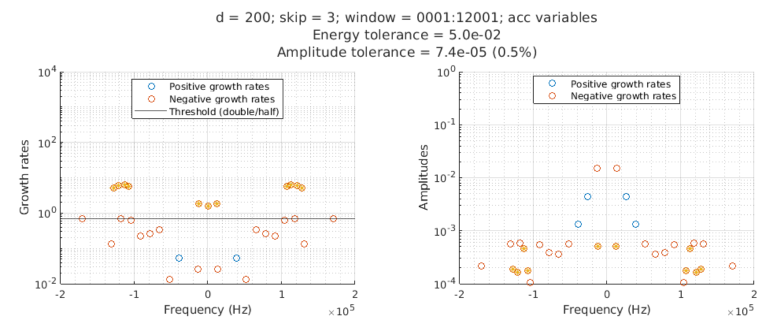
ZARATHUSTRA follows a multidisciplinary approach to achieve its objectives:

1. A two-tier numerical simulation approach
   - 3D discontinous Galerkin fluid models to determine basic equilibrium flows
   - Advanced electromagnetic kinetic algorithms to elucidate phase-space stability and wave heating



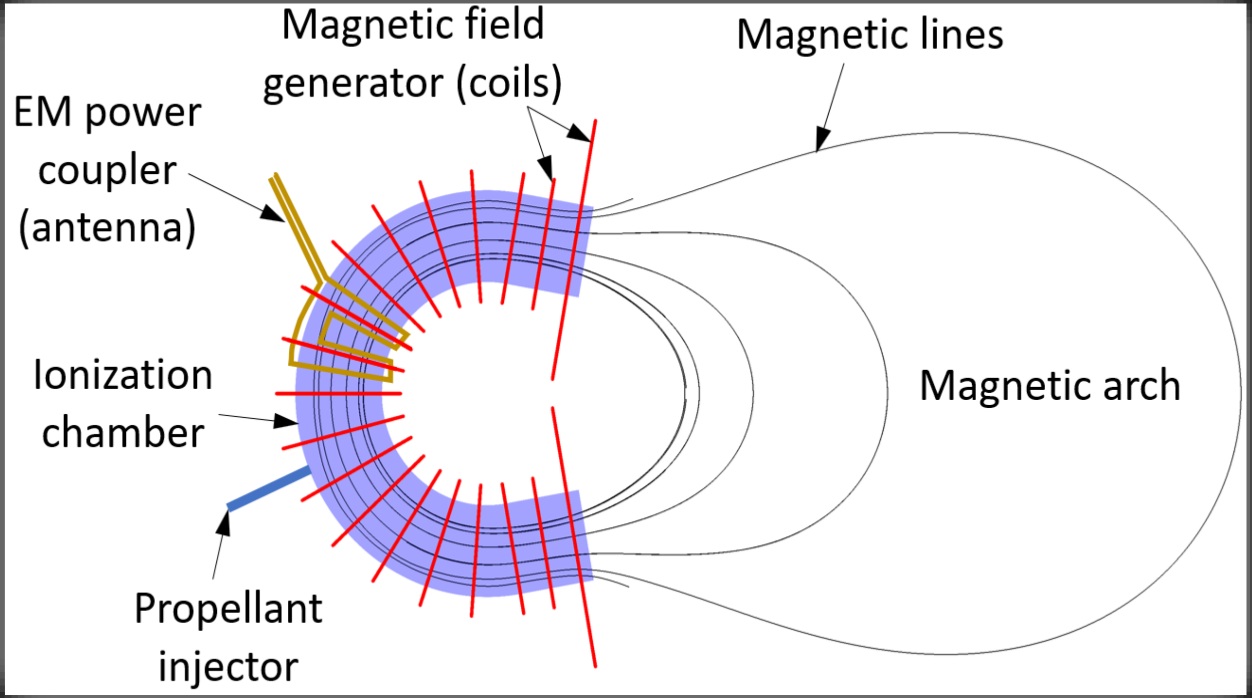
2. State-of-the-art experimental measurements
   - Flexible combination of plasma diagnostics: full-sweep probes to determine plume properties; fast probes to measure oscillations
   - Cylindrical and U-shaped plasma sources for comparison

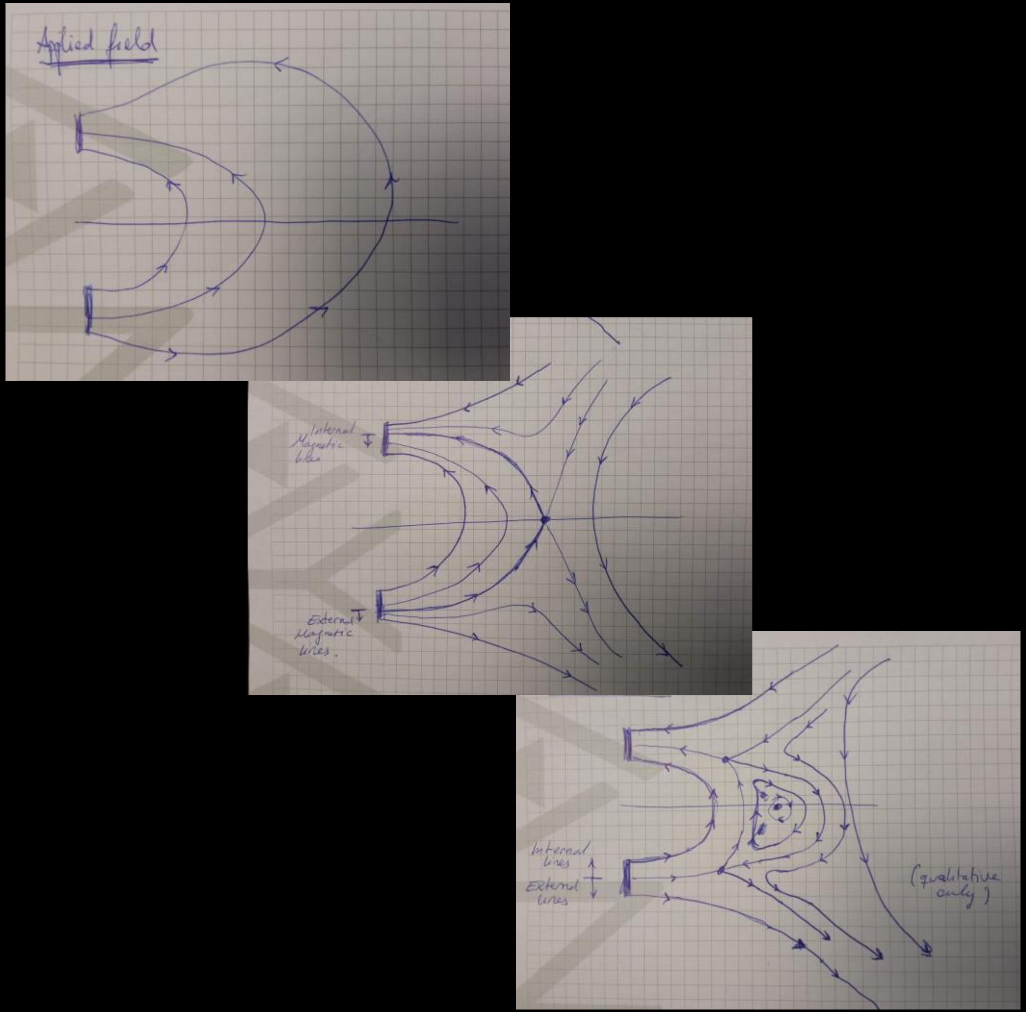
3. Data-driven analytics to process simulation and experiment data
   - Modal analysis (POD, HODMD, EMD)
   - Non-linear time series analysis (e.g. transfer entropy, bicoherence, mutual information)



Methodology

4. Agile Magnetic Arch thruster prototype development
   - Focus on external acceleration region (interesting physics!)
   - All previous points will guide and help iterate thruster design





ZARATHUSTRA Impact

- The success of the project will result in:
  - The first theory of anomalous transport and EM heating in EPTs, two essentially unexplored aspects of the physics of these devices (which may well be coupled)
  - Characterization and demonstration of the feasibility of the novel Magnetic Arch Thruster concept
  - Novel EM-kinetic algorithms, developed as part of the methodology of the project
  - New research line in EP2 research group on data-driven analysis techniques
- Importantly, ZARATHUSTRA will hire and train 6+ young researchers, and consolidate EP2 position at the vanguard of the research in EPTs

Acknowledgments

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Thank you!

https://erc-zarathustra.uc3m.es
erc-zarathustra@uc3m.es
@ERC_Zarathustra