Helicon Plasma Thruster
Persepective
and
Development status and future development
At University of Padua

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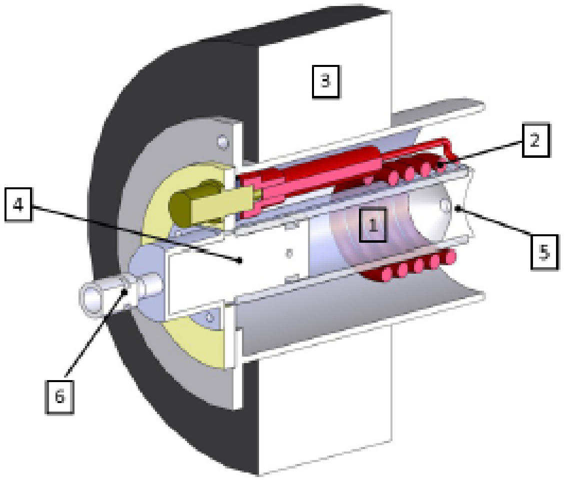
CISAS G. COLOMBO

Outline

- Helicon Thruster overview
- Mission scenario
- Design Tools
- Experimental activities
- Low power helicon
- High Power helicon
- Operations
- Power Processing Unit

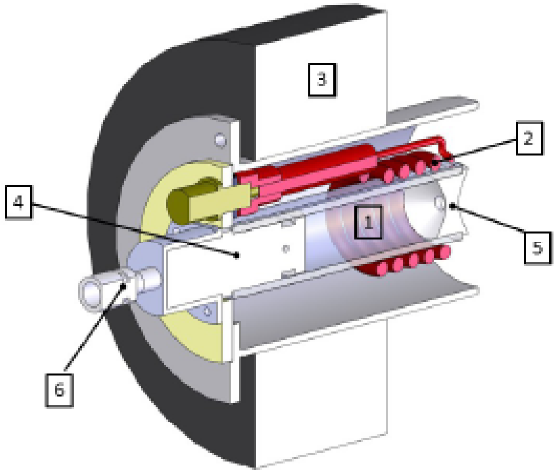
Helicon thruster



1) Plasma source
2) RF Antenna
3) Magnets
4) Injector
5) Outlet diaphragm
6) Gas injection line

- The electrodeless RF plasma thruster basically consists of a RF plasma source, where the plasma is generated and heated, and thanks to a magnetic nozzle / potential drop is accelerated into vacuum
- The **plasma marginally interacts** with the structure therefore the erosion is reduced.
- Internal **electrodes are absent**.
- The **exhaust beam is neutral** thus an external neutralizer is not needed.
- it can potentially **operate with different propellants**.
- One feeding line
- One Power Line

Helicon thruster

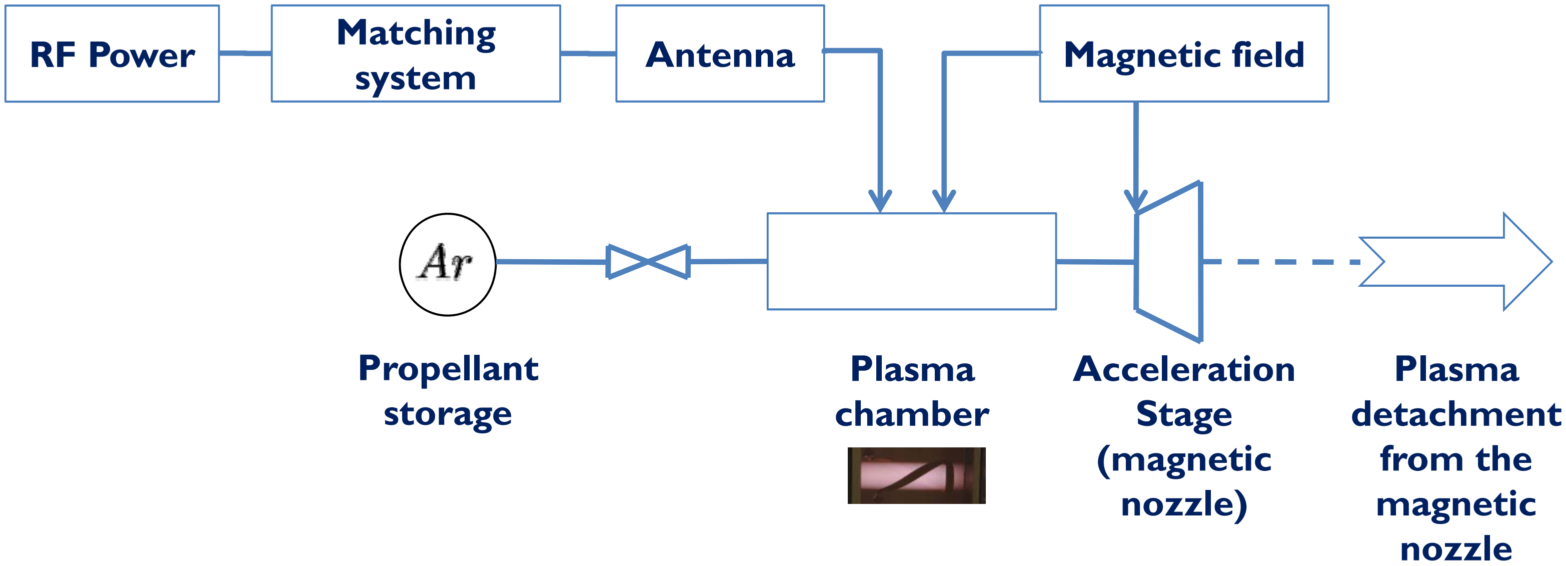


1) Plasma source
2) RF Antenna
3) Magnets
4) Injector
5) Outlet diaphragm
6) Gas injection line

- **Gas versatility**: not having sensitive parts exposed to plasmas they can operate with many different type of gases

- **Geometric versatility**: thanks to their simple shape they allow innovative thruster configuration .

Helicon thruster



Stage #1 Plasma-Wave interaction	Stage #2 Plasma internal dynamics	Stage #3 Plasma acceleration in the magnetic nozzle	Stage #4 Plasma detachment

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Main exploitable feature of HPT

- Focus to exploit the main capabilities of the helicon thruster:
  - Capability to work with a variety of gases
  - High lifetime
  - Throttleability
  - Scalability
  - Low cost

- 21 mission scenarios identified (under ESA contract)
  - Preliminary mission analysis
  - Identification of propulsion requirements for each scenarios

Enabled operations

- High Delta V missions for multiple U satellites
  - Orbit maintenance
  - Orbit configuration / re-configuration
  - End of life disposal
  - Exploration and complex scientific missions
- Utilization of chemical propellant vapours or pressurization gas for HPT usage
- International Space Station wastes enabled missions
  - Satellite Deorbiting
  - Satellite Servicing and Refuelling
  - ISS Orbit rising
  - Deep Space and Moon missions from ISS
- Human missions
  - Cis-lunar, Moon and NEOs exploration roadmap
  - Human mission to Mars

Enabled operations

- Atmospheric Breathing enabled mission
  - Planets and moons explorations
    - Permanent exploration missions on planets and moons with atmosphere: Venus, Mars, Titan, Uranus, Neptune, Saturn, Jupiter
    - Permanent orbiter/drone on Mars
  - Refuelling and sample return from rocky planets and moons with atmosphere
    - Refuelling and sample return from rocky planets and moons with atmosphere: Mars, Venus, Titan
  - Earth missions
    - Observation missions with drag compensation on Earth
    - Earth active debris removal with refuelling during deorbiting phase
- Celestial body mining byproducts enabled missions
    - Asteroid soil volatiles exploiting
    - Lunar soil volatiles exploiting

Propellant availabiltiy

	Operative gases												
	Xe	Ar	N_2H_4	MON	MMH	He	CO_2	CH_4	H_2	N_2	O_2	H_2O	NH_3
Station Keeping Application			X	X	X	X							
Exploration Application			X	X	X	X							
Satellite Deorbiting							X	X	X				
Deep Space and Moon missions from ISS							X	X	X				
Permanent exploration missions on planets and moons with atmosphere: Venus							X			X			
Permanent exploration missions on planets and moons with atmosphere: Mars		X					X			X			
Permanent exploration missions on planets and moons with atmosphere: Uranus						X			X				
Permanent exploration missions on planets and moons with atmosphere: Jupiter						X			X				
Permanent orbiter/drone on Mars		X					X			X			
Refuelling and sample return from rocky planets and moons with atmosphere: Mars		X					X			X			
Earth active debris removal with refuelling during deorbiting phase		X								X	X		
Asteroid soil volatiles exploiting							X		X		X	X	X
Lunar soil volatiles exploiting									X		X		

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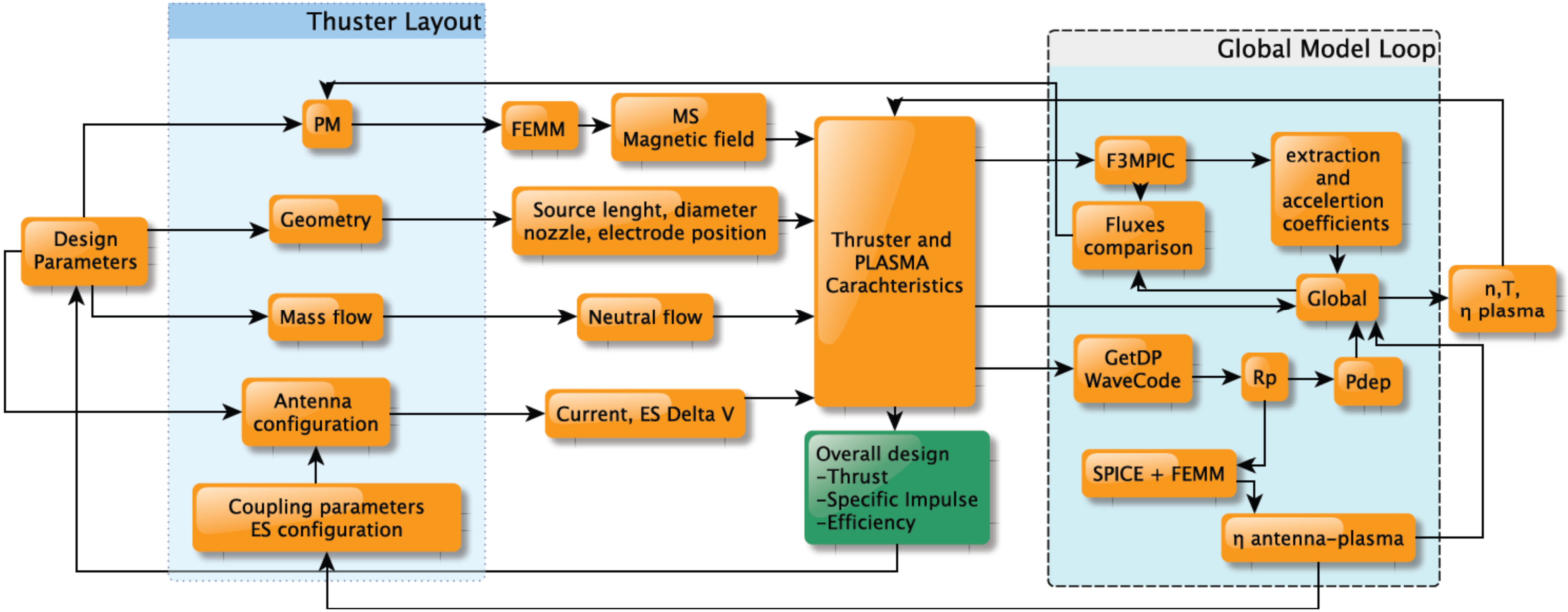
Code combination



F3MPIC, GETDP,FEMM/SPICE

- **F3MPIC** – Particle-in Cell 3D solver with EM fields
  - B, geometry, antenna characteristic → flux parameters (α,β)
- **GetDP Wavecode ADAMANT,** EM solver with plasma tensor
  - Antenna, B, Plasma → antenna to plasma power deposition plasma resistivity
- **FEMM** - MS solver
  - magnet → MS fields
- **SPICE** – circuit solver
  - Plasma Impedance →overall antenna coupling parameter (Z, ω, η)

GLOBAL MODEL

- GLOBAL MODELS are Zero-Dimensional models describing the chemistry of the plasma: different atomic/molecular species and excited states
- Kinetic scheme : continuity equation with plasma chemistry and reactions, plus surface processes.
- Wall diffusion is accounted by empirical-analytical formulations
- Magnetic nozzle exhaust and Potential drop momentum delivery is evaluated by means of exhaust and acceleration parameters computed with F3MPIC
- Electron energy equation

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Thrust balance

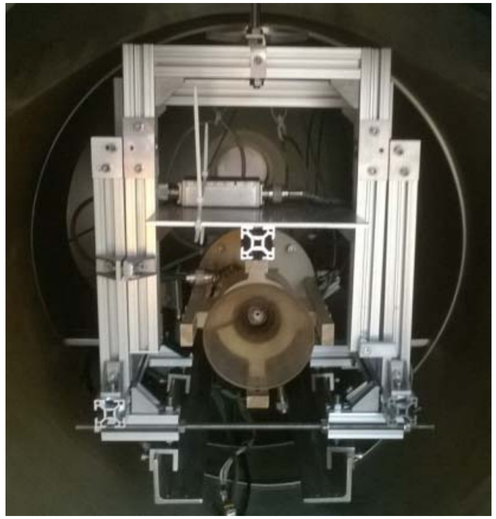
We developed a **Thrust balance** specifically for RF thruster testing.

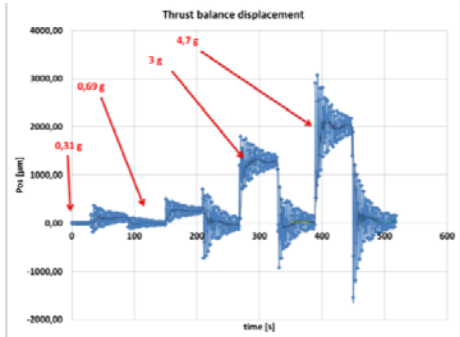
We can tune sensitivity according to expected thrust levels and thruster masses.

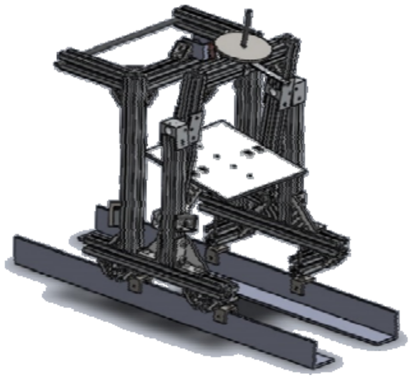
We use a High accuracy **laser interferometer** for displacement measurements.

We reduce mechanical noise by means of **Eddy current brake** for oscillation damping.

We perform in-vacuum calibration of the balance with an **Electromagnetic coil** for immediate compensation of noise/disturbances.

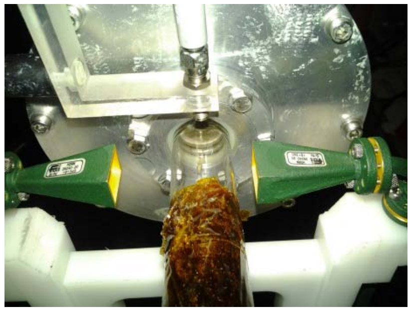
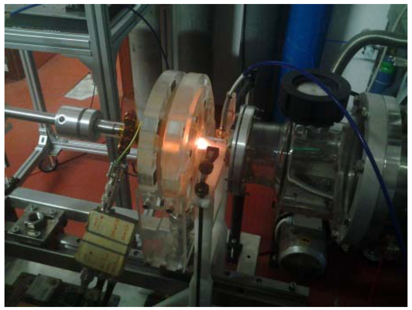
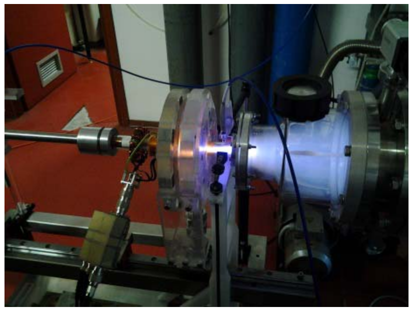
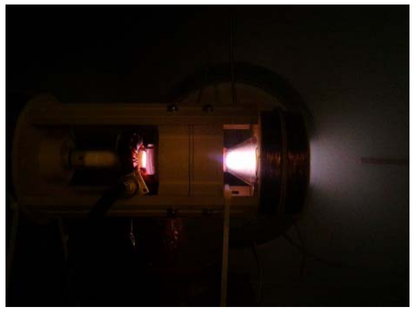






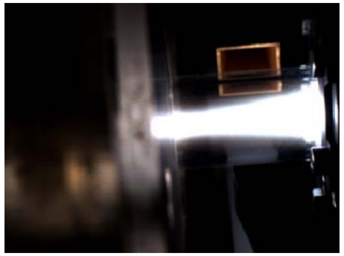
Experimental set-up

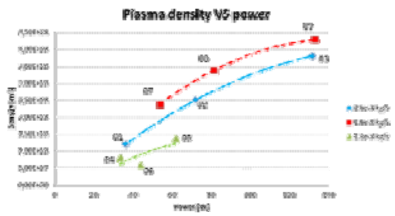
- **Several experiments** were carried out during this activity
- **Purposes:**
  - Codes validation
  - Comparison of R-Helicon and S-Helicon antennas
  - Estimation of plasma parameters at various power levels (from 50 to 375 W)
  - Multipropellant operation testing
- **Setup → CISAS electric propulsion facility**:
  - Vacuum chamber with high capacity pumping system (12600 l/s)
  - Rich plasma diagnostics array → RPA, Faraday probes, microwave interferometer, optical spectrometers thrust balance
  - V/I probes for RF network monitoring
  - In-air, completely reconfigurable experiment → fast and flexible thruster characterization
  - In-vacuum experiment → full thruster characterization in vacuum

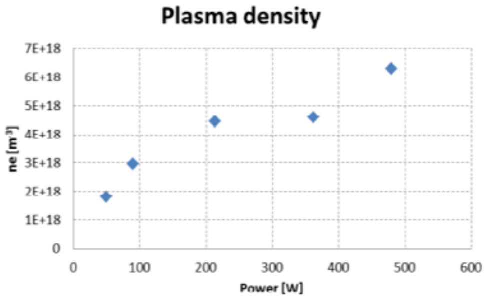
Type of tests

- **Thruster design optimization→** low power optimization tests
  - Thruster geometry experimental optimization
  - Result: identification of optimal HPT geometry for the desired propellant type and input power

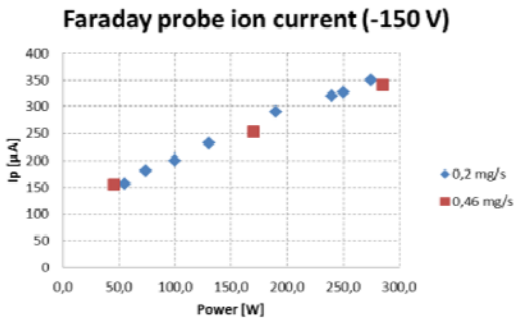




- **Multi-propellant investigation→** Low power testing with CO2
  - Result: the HPT can achieve target performance either with CO2 or Argon, requiring only a geometric re-arrangement → simple adaption to different propellants



- **High power investigation →**Testing at 50 W - 480 W with Argon
  - Result: the technology of the HPT can be scaled at higher power levels with no critical issues



Experimental activities

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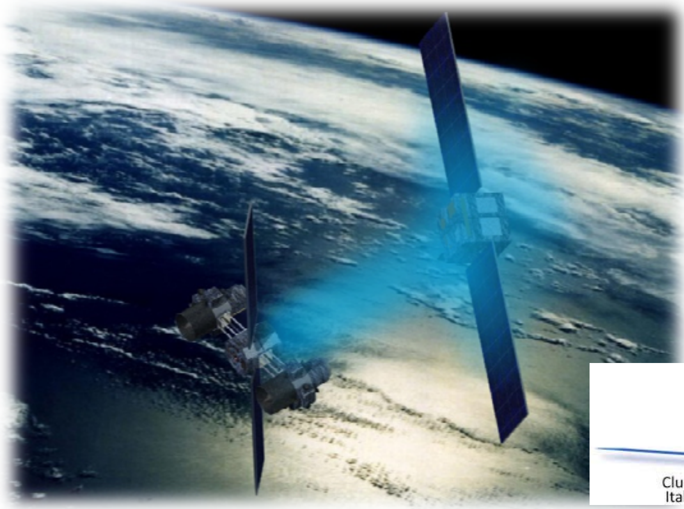
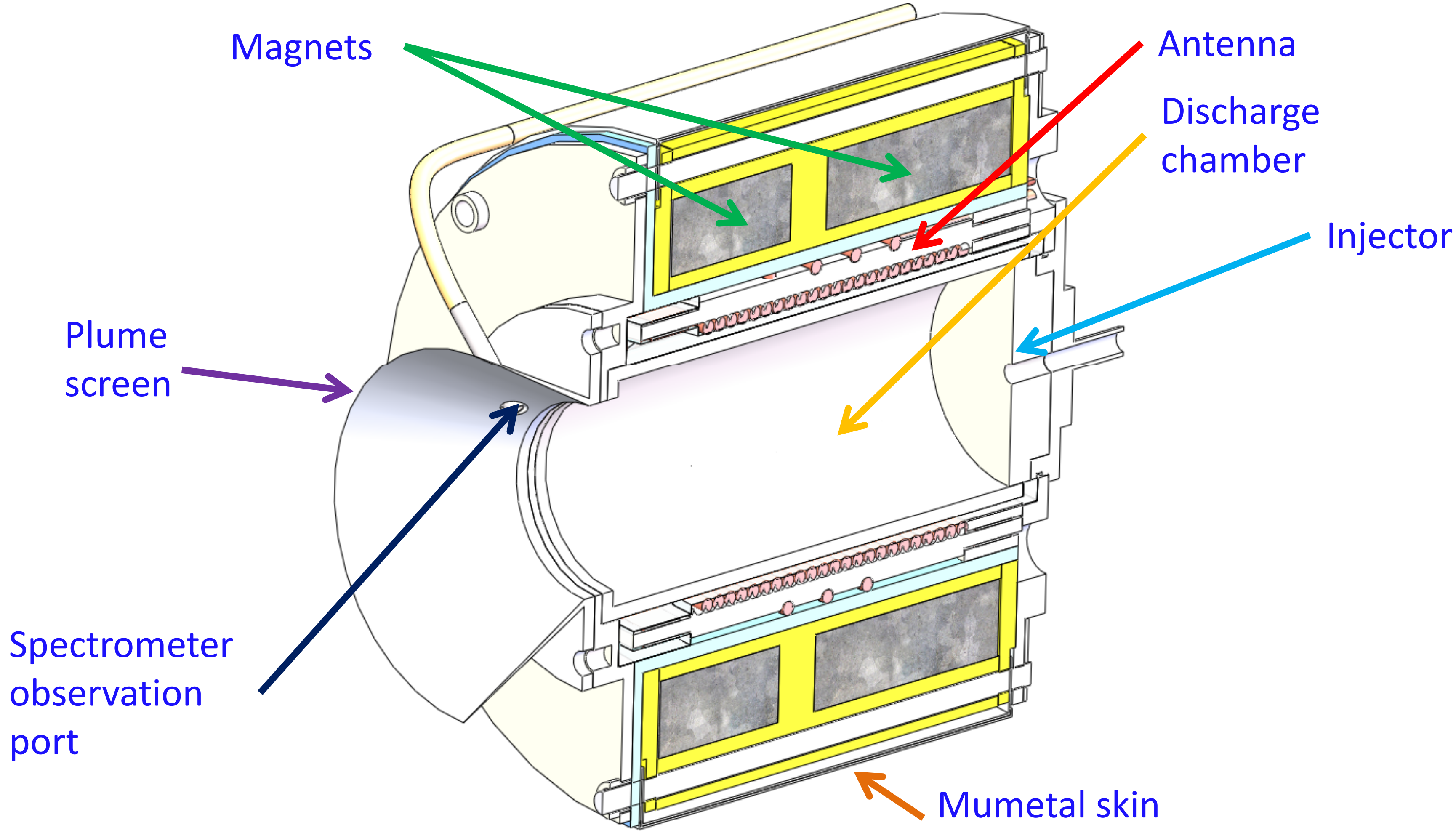
High Power Helicon Design Requirements

- Selected mission → Satellite Deorbiting Mission Scenario from ISS
- ISS regenerative systems → recycling of a wide range of human by-products
- Some gases cannot be recycled → reliable source of propellant for an EP subsystem able to utilize them
- The human crew produces relevant quantities of CO_2 (≈ 6 kg/day)
- Mission requirements:
  - Thrust level: 70-100 mN
  - Specific impulse: 2100-2500 s

Thruster design requirements:
- propellant: CO_2
- thrust: 100 mN
- specific impulse: >= 2100 s



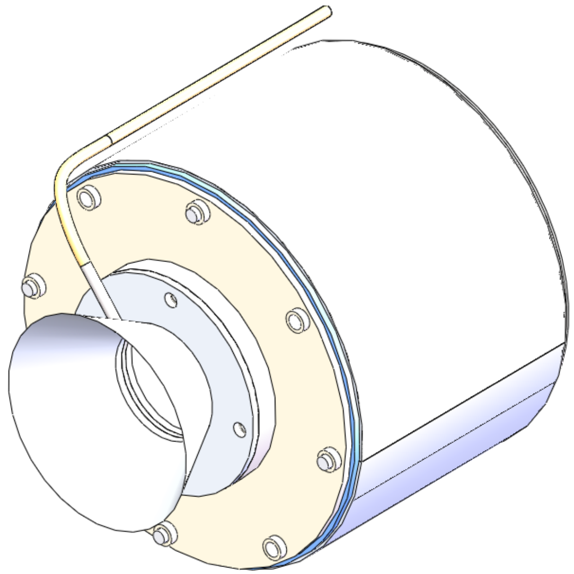
Helicon thruster Overview



Thruster main parameters

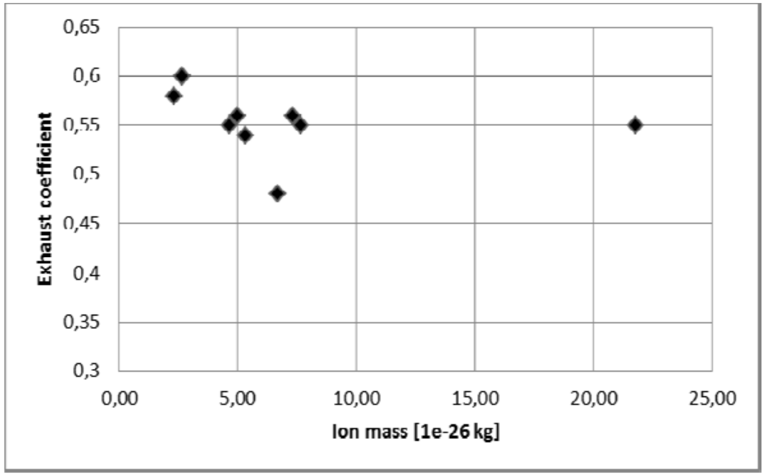
Overall results of thruster design for HPT 100 mN @1.7 kW

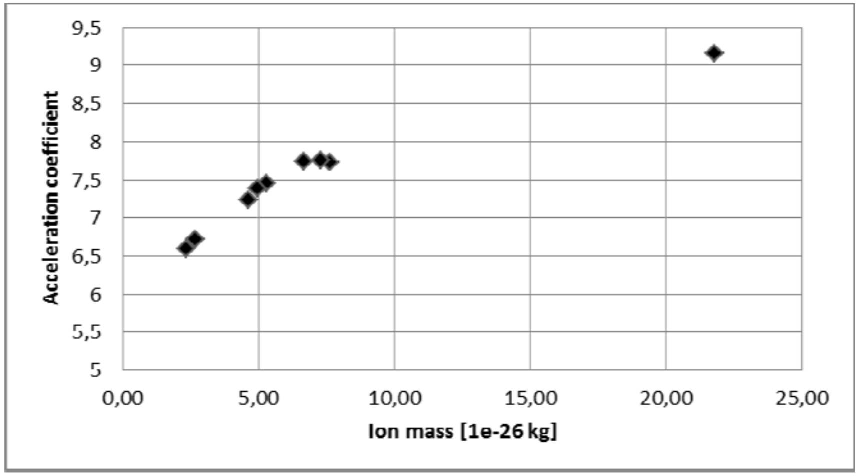
- Thruster configuration
  - 2 MHz S-Helicon antenna
  - SmCo permanent magnets
  - Completely passive TCS
  - overall mass = 6.45 kg
  - size: ϕ = 145 mm, l = 162 mm
- PPU
  - input power = 1771 W
  - mass = 7 kg
- Performance with CO_2 propellant
  - net power coupled to plasma = 1496 W
  - thrust = 94 mN
  - specific impulse = 2139 s



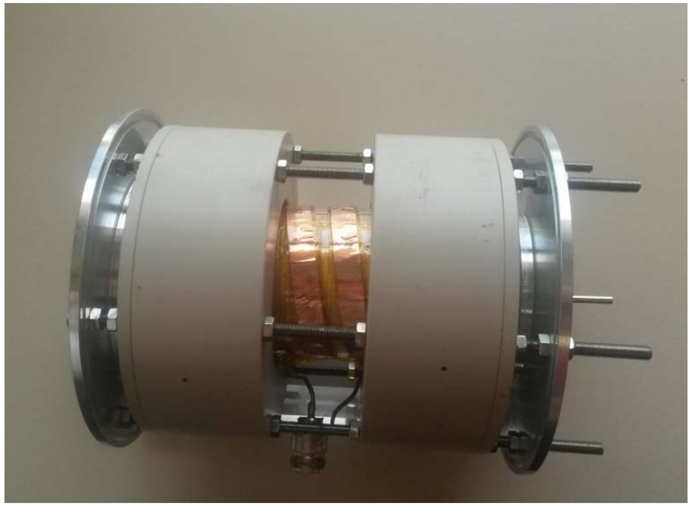
Operations with different propellants

- Use of different propellants → potential advantage both for helicon and S-H technology.
- Investigation by means of the 3D particle-in-cell code F3MPIC:
  - determination of ejection and acceleration coefficients for different propellants
  - multiple ions species analysis
- Analyzed propellants: CO_2, N_2, O_2, Ne, Ar
- The same thruster can potentially operate with different propellants:
  - solution 1 →thruster optimization with different propellants and thruster design as a compromise between the optimized solutions (simpler, lower performance level)
  - solution 2 → reconfigurable thruster: variable magnetic field configuration, variable length and outlet diameter (more complex, higher performance)





Experimental test bed



- **1 kW** prototype thruster
- **Permanent magnets** for magnetic field generation
- Aluminum frame (structural support + thermal management)
- **Boron nitride discharge chamber** → light weight, high operating temperature, high dielectric strength
- **Partially re-configurable geometry** (outlet section, magnets and antenna position) → optimization with different gases is possible
- **Completely passive TCS**
- S-Helicon antenna (International PCT/IB2016/050199 15.01.2016, Italian patent number VR2015A000007 del 16.01.2015) → high power transfer efficiency, high ionization rate

CTNA Cluster Tecnologico Nazionale Aerospazio Italian Cluster for Aerospace Technology

ThalesAlenia Space

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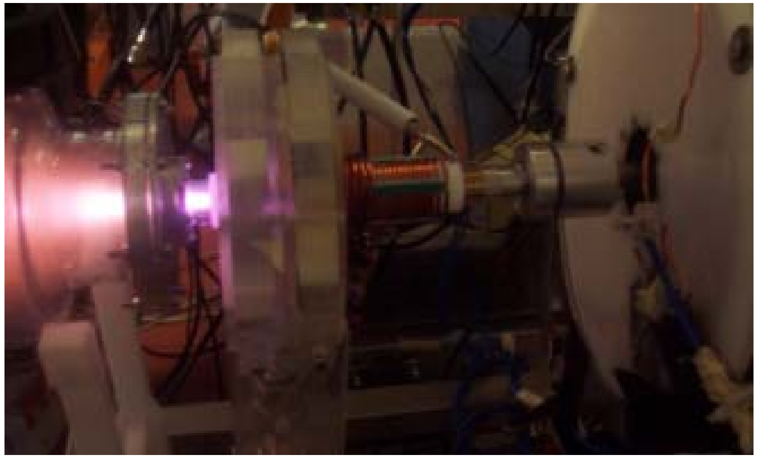
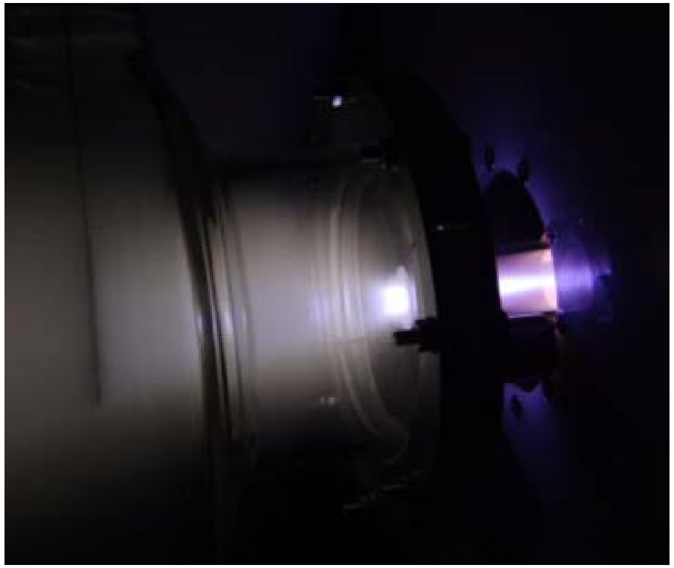
Past activities on low power helicon



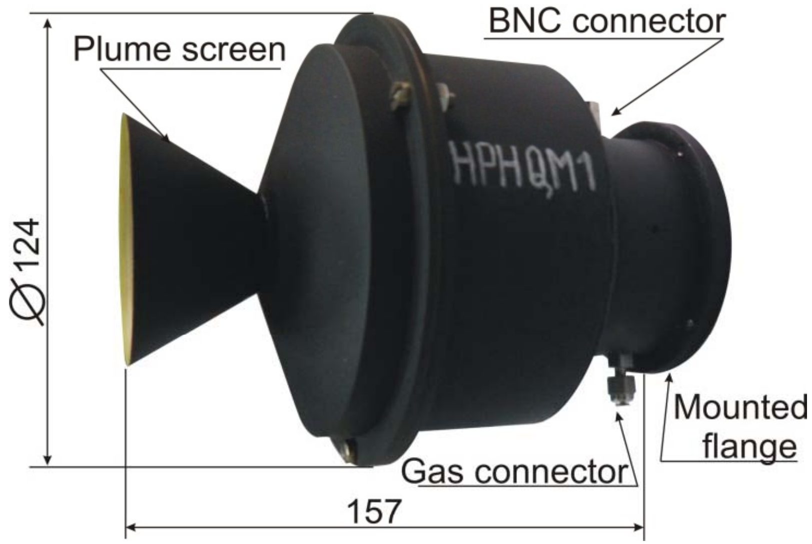
Jan 2009	**Start of the HPT Program**
Jun 2009	**First helicon source operational**
Jan 2010	**1-D plasma simulation code operational, first thruster lab model operational**

Jun 2010	**First high efficiency source operational**
Jan 2011	**First thruster EM**
Jan 2012	**Code completed, advanced thruster design**
Jun 2012	**EM final development and test**



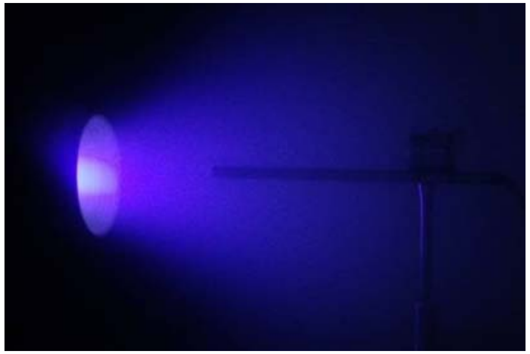
First Engineering Model

The first HPT EM was realized in cooperation with KhAI under an FP7 program which ended in June 2012.



Thruster main characteristics:

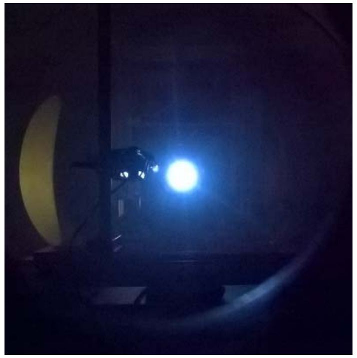
Power, W	**50**
Thrust , mN	**1.5**
Isp, s	**1350**
Efficiency	**0,35**
Mass Flow Rate, mg/s	**0,2**
Working gas	**multiple**
Mass, kg	**1,2**
Lifetime, h	**>>5000**



Low power HPT today

The thruster EM was consequently optimized to get a new EM.

The technology was updated to get:
- Lower mass and size targeting nano to micro satellite markets
- Lower complexity and costs



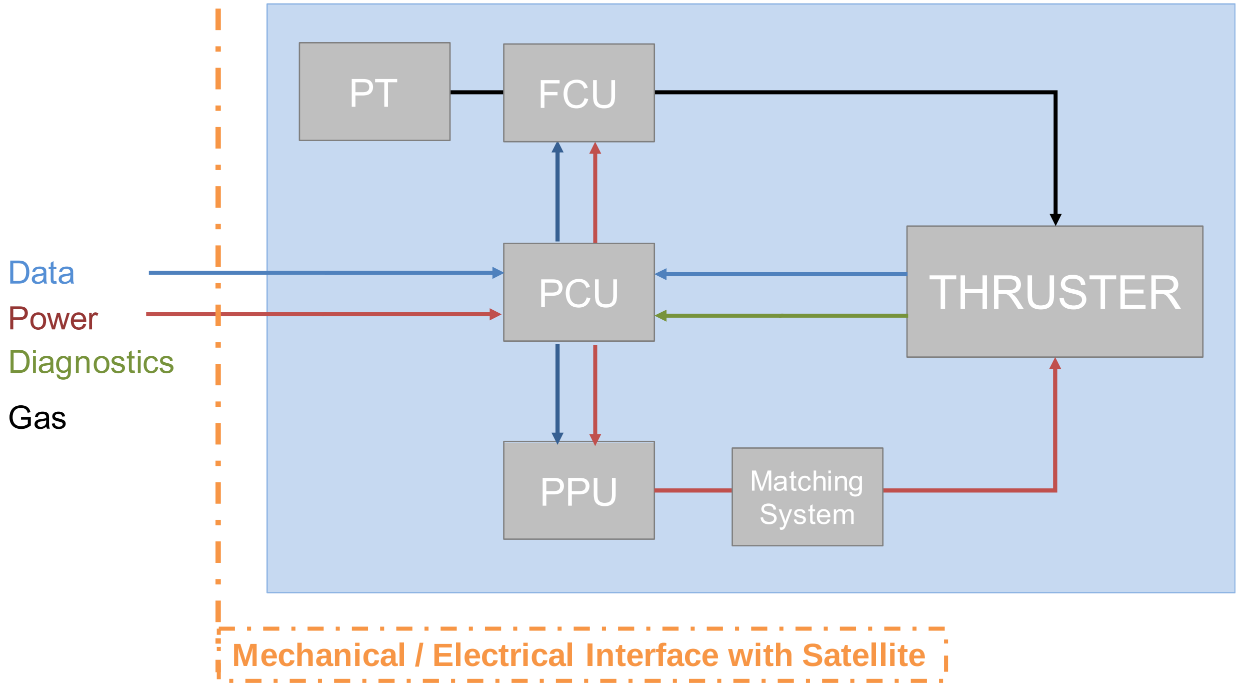
The new technology is flexible and versatile to achieve different thrust level requirements with very limited modifications.

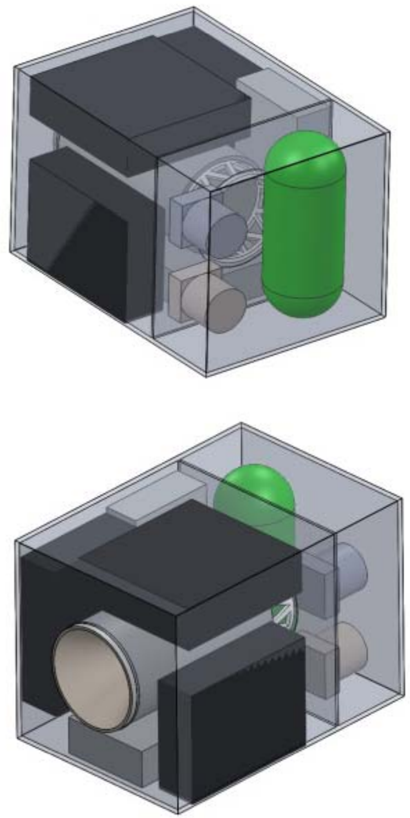
The complete system fits in a 100x100x100 mm envelope, with standard data and power interfaces with the satellite.

In function of the required Total Impulse, the propellant tank has different sizes.

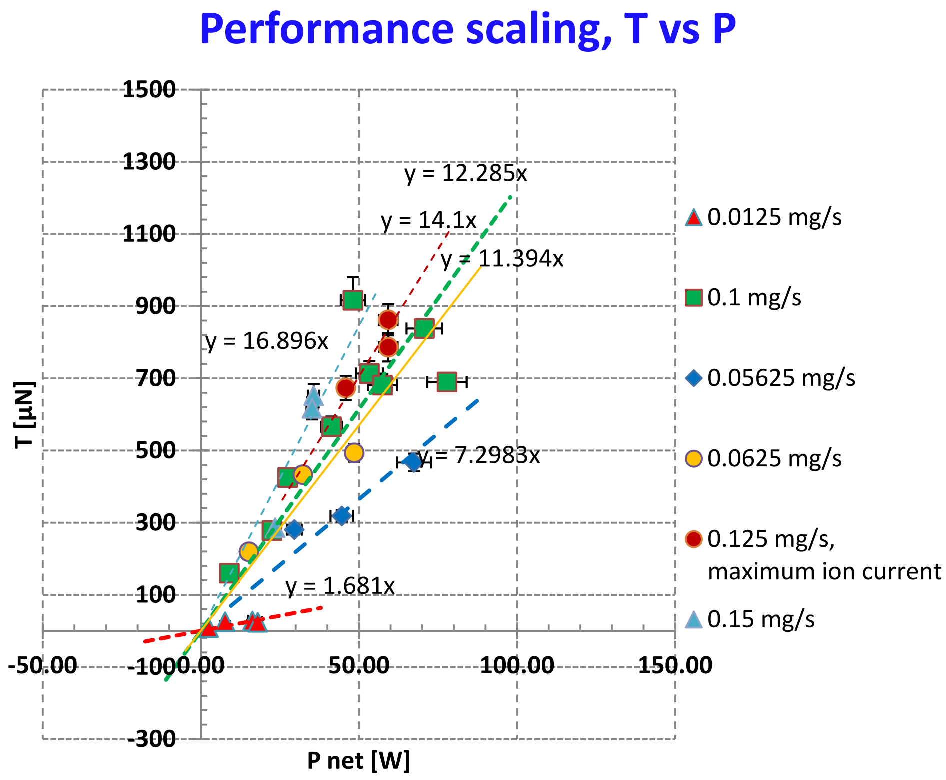
Low power HPT platform

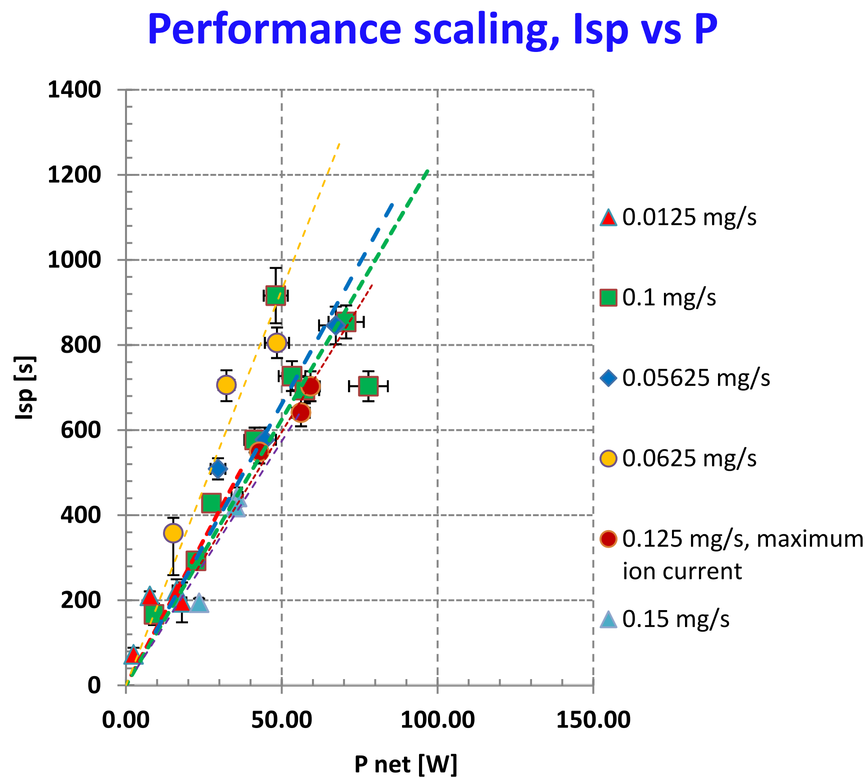
PCU Power Control Unit
PPU Power Processing Unit
FCU Flow Control Unit
PT Propellant Tank





Low power HPT actual perfromances





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Thruster operation: IMPEDANCE MATCHING

- Impedance matching between amplifier and antenna is critical for power efficiency

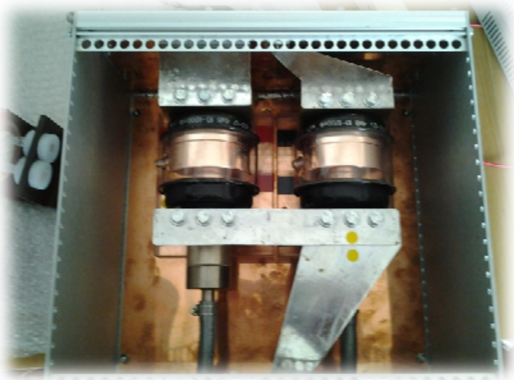
R-Helicon antenna

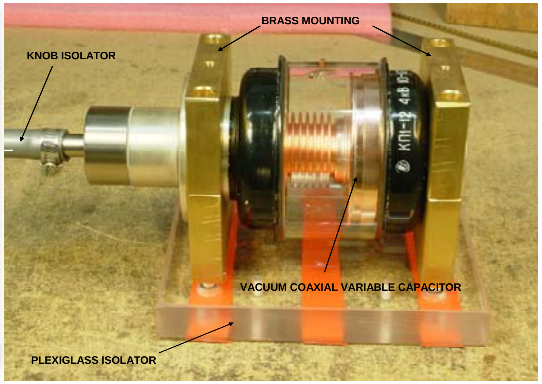
- A matching box is required → mass, complexity, moving parts
- Very low antenna impedance compared to circuital elements → high power losses in the circuit

VS

S-Helicon antenna

- Impedance matching by means of frequency variation
- No matching box is required → no additional mass, no moving parts
- High antenna impedance with respect to circuital elements → low power losses in the circuit





S-HELICON: Plasma Ignition and sustainment

Experimental experience → ignition and operation procedure:

1) the operating frequency is set to the resonant frequency of the antenna → purely resistive load, high impedance, minimal power absorption without plasma
2) mass flow rate is set to 3-4 times its nominal value
3) the antenna voltage is rised to 2-2.5 times its nominal value
4) discharge ignition:
   - phase shift between antenna voltage and current → reactive component
   - antenna impedance drop
5) frequency re-matching → purely resistive load
6) mass flow rate and voltage set to nominal values
7) minor frequency adjustments until temperature stabilizes
8) long term operation without re-matching

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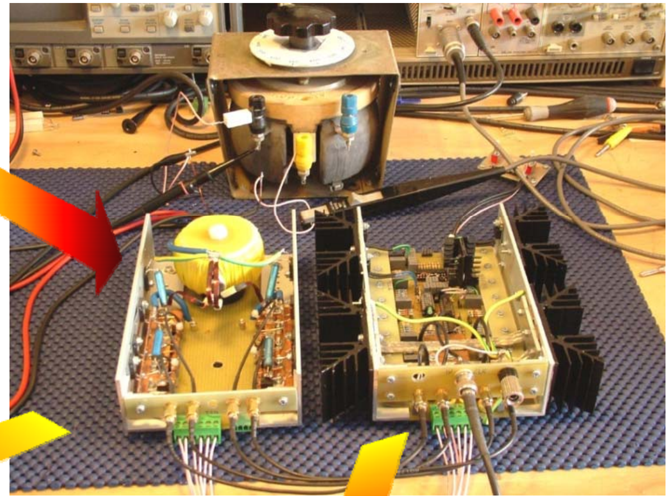
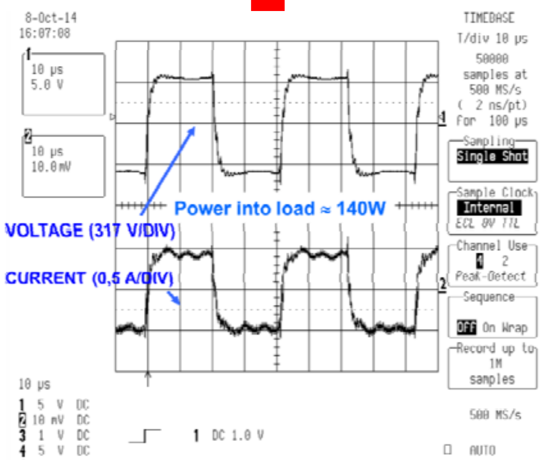
RF electronics design and development: power amplifier preliminary testing

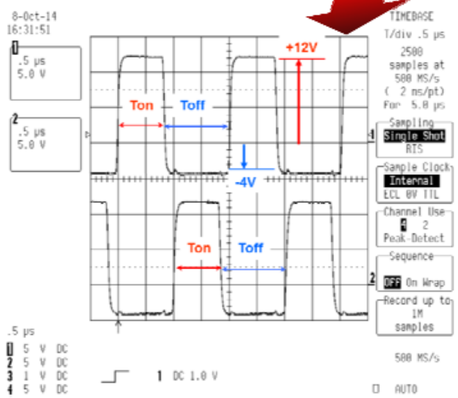
- Prototype tested at ≈ 200 W up to 2 MHz
- Results:
  - Efficiency up to 80-87 % with first prototype
  - Limited waveform distortion

Power from supply ≈ 170 W



Efficiency ≈ 80%





Conclusion

- Helicon thruster could lead to new unconventional feature enabling new innovative mission
- Helicon thruster represent a possible option for satellites currently with no propulsion system enabling new inedit mission