Numerical and Experimental Investigation into the Performance of Plasma-Based Thruster for Space Propulsion

Mirko Magarotto

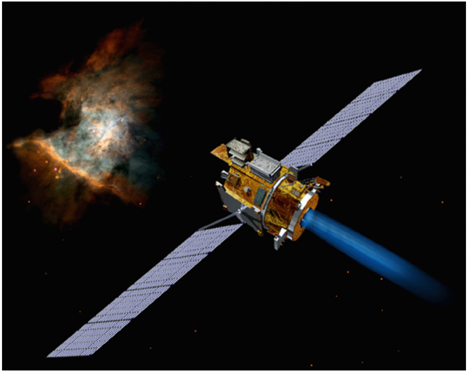
Centro di Ateneo di Studi e Attività Spaziali Giuseppe Colombo
CISAS
Università degli Studi di Padova

Outline

Electric Space Propulsion

Definition

- Electric power employed to generate thrust
- Usually plasma is operation fluid



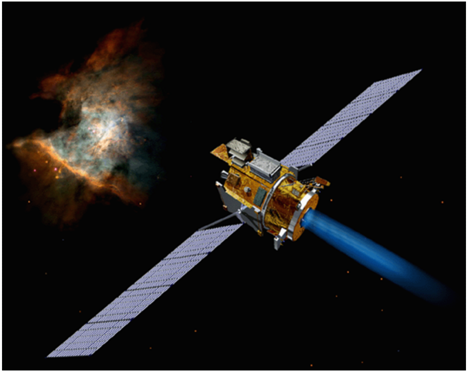
Electric Space Propulsion

Definition

- Electric power employed to generate thrust
- Usually plasma is operation fluid

Main features

- High specific impulse: higher > 1000 s
- Low thrust: lower < 1 N



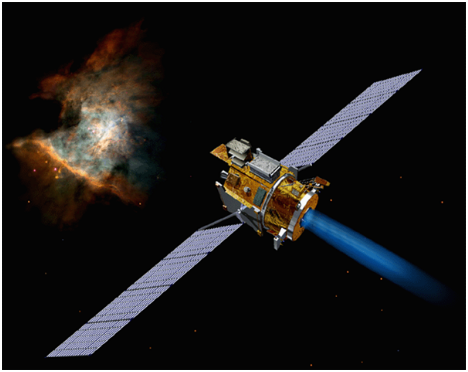
Electric Space Propulsion

Main features

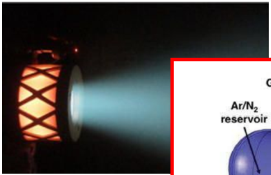
- High specific impulse: higher > 1000 s
- Low thrust: lower < 1 N

Some applications

- Attitude control
- Cubesats
- Interplanetary missions

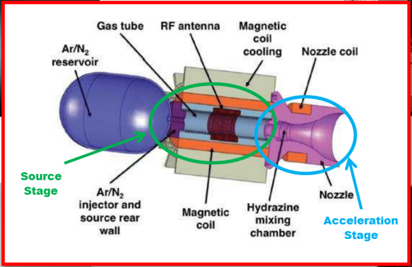


Electric Space Propulsion - State of the art



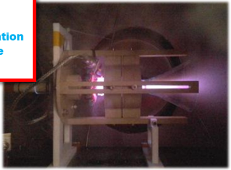
BIT

RIT



ThrustMe

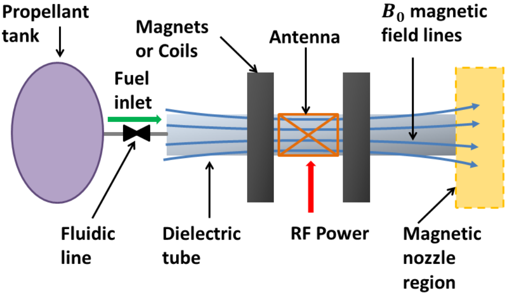
HPH.Com



HPT Concept

Main components

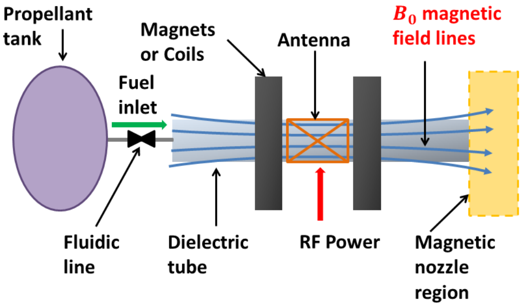
- **Propellant tank** and **fluidic line**
- **Dielectric tube**
- **RF antenna**, provide power
- Coils or permanent **magnets**



HPT Concept

Magnetic field

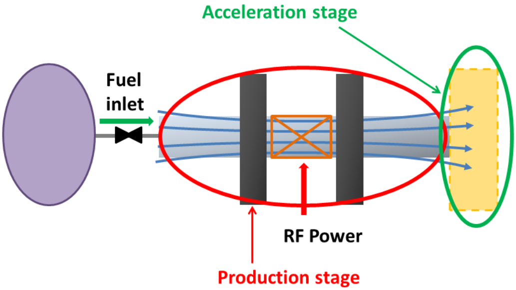
- Create a **magnetic nozzle** region at the source outlet
- Enhanced **plasma confinement**
- **Efficient power deposition**



HPT Concept

Thruster stages

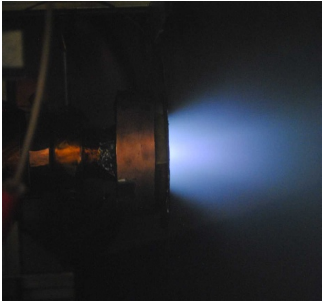
- ***Production stage***, Helicon source inside which plasma is generated
- ***Acceleration stage***, magnetic nozzle region where plasma is accelerated



HPT Performances

Advantages

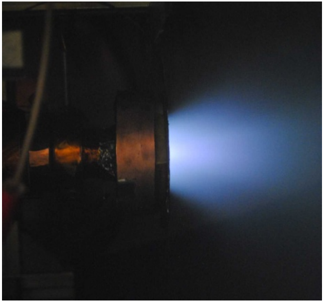
- Simple geometry ⇒ **low cost**
- No needs of grids and electrodes ⇒ **long life**
- **Design robust** to scaling and multiple gases operation



HPT Performances

Issues

- Never tested in space missions $\Rightarrow$ only theoretic reliability
- Performances lower than Ion and Hall thrusters, $I_{sp} \leq 1500$ s



Objectives

Objectives

- Grasp the main physical phenomena which govern the behaviour of both the *Production Stage* and *Acceleration Stage*
- Ultimately, **improve the performances of HPTs**

Objectives

Objectives

- Grasp the main physical phenomena which govern the behaviour of both the *Production Stage* and *Acceleration Stage*
- Ultimately, **improve the performances of HPTs**

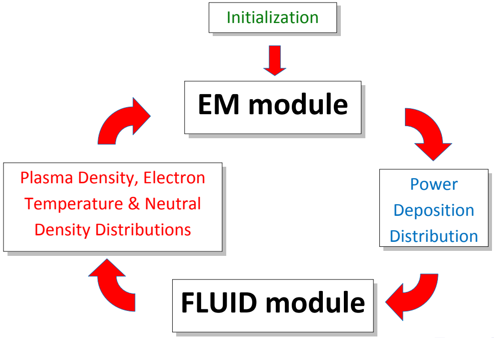
Methodology

- Develop a **numerical tool** able to predict the propulsive performances of a HPT
- Employ a **thrust stand** to obtain reliable measurements of the actual thrust produced by HPT prototypes

Production Stage

3D-VIRTUS

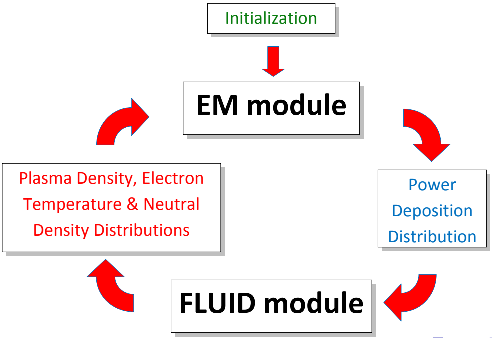
- **Self-consistent** model of Helicon plasma source
- EM module ⇒ **wave-plasma coupling**
- FLUID module ⇒ **macroscopic plasma transport**



Production Stage

EM module

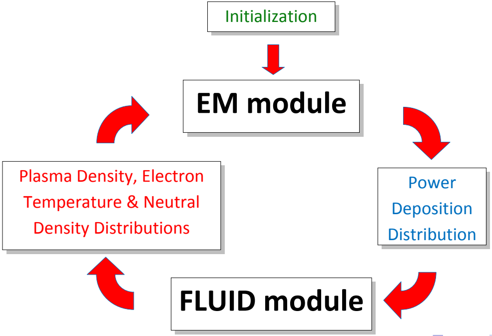
- Relies on the well established code **ADAMANT**
- Generic shape of RF antenna can be handled
- The antenna current is computed and not assumed



Production Stage

FLUID module

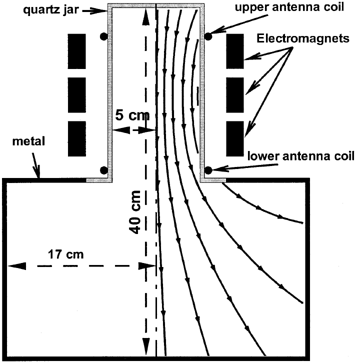
- Implemented in the **OpenFOAM** C++ library
- Easily reconfigurable from 1D to 3D
- Computational cost at bay because of the fluid approach



Production Stage - Validation

Benchmark

- Plasma reactor for material processing
- System simulated with the self-consistent code SEMS
- 2D-axisymmetric simulation



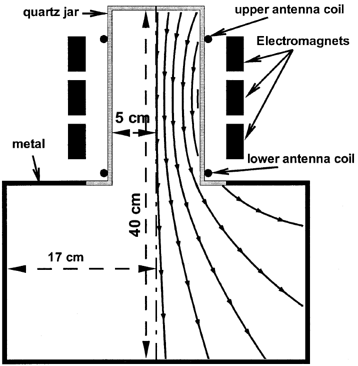
Production Stage - Validation

Benchmark

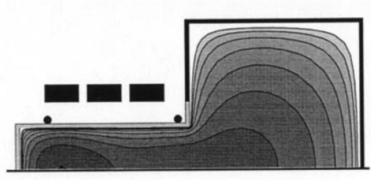
- Plasma reactor for material processing
- System simulated with the self-consistent code SEMS
- 2D-axisymmetric simulation

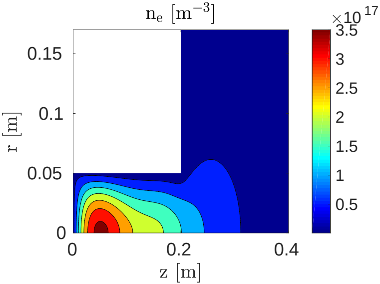
Error sources

- Different numerical approaches
- SEMS chemical reactions and boundary conditions unknown



Production Stage - Validation

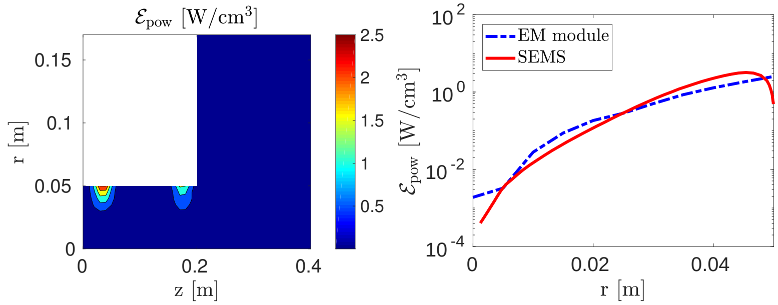




Electron density n_e

- Similar trend predicted
- Difference of 50% between the predicted peak values
- Good agreement between the two codes

Production Stage - Validation



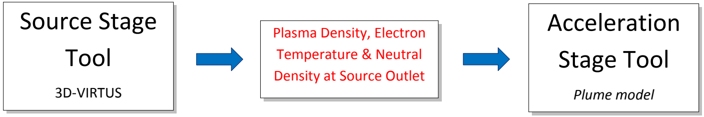
Power deposition $\mathcal{E}_{pow}$

- Good qualitative and quantitative agreement
- The agreement between the two solvers is very good despite the two different solution methods adopted

Coupling of Production and Acceleration Stages

Numerical model of HPT

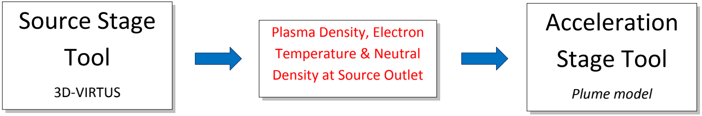
- The source stage is solved with 3D-VIRTUS
- The momentum flux of the plasma ejected from the outlet of the source is computed
- An analytical quasi-one dimensional model of the plume is applied to calculate the thrust and the specific impulse



Coupling of Production and Acceleration Stages

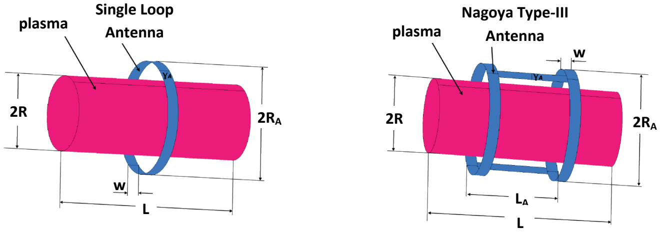
Numerical model of HPT

- The source stage is solved with 3D-VIRTUS
- The momentum flux of the plasma ejected from the outlet of the source is computed
- An analytical quasi-one dimensional model of the plume is applied to calculate the thrust and the specific impulse



Results

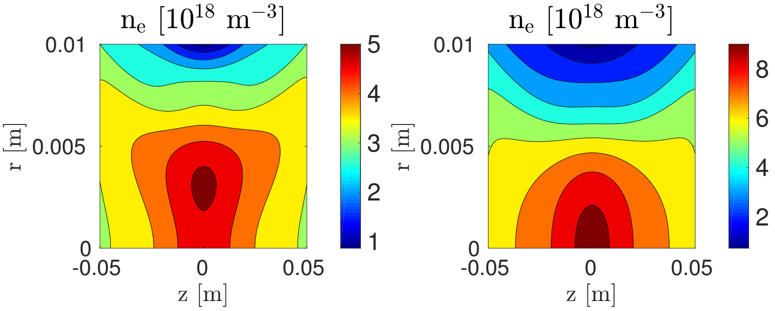
- Accurate description of the **plasma source**
- Preliminary estimations of **propulsive performances**



Analysis

- Performed a parametric analysis to identify how the configuration of the source influences the plasma parameters
- Here the influence of the antenna geometry is analysed

Numerical Results - 3D-VIRTUS



Electron density n_e results

- The n_e peak is higher if the discharge is driven by a *Nagoya Type-III Antenna*, rather than a *Single Loop Antenna*
- In the *Single Loop Antenna* case the peak is not in correspondence of the axis of the discharge

Numerical Results - HPT model

Analysis

The same configurations analysed with 3D-VIRTUS have been simulated with the numerical model of HPT to evaluate the attainable thrust T

Analysis

The same configurations analysed with 3D-VIRTUS have been simulated with the numerical model of HPT to evaluate the attainable thrust T

Results

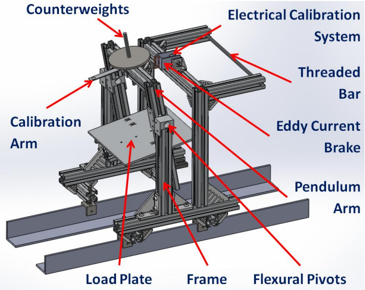
	Single Loop	*Nagoya Type-III*
T [mN]	1.73	2.21

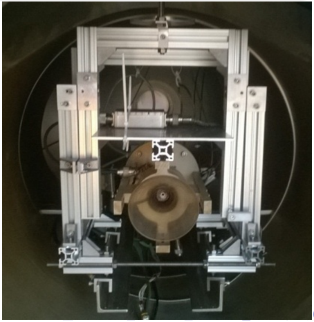
- T is significantly higher if the discharge is driven by *Nagoya Type-III Antenna*
- The *Nagoya Type-III Antenna* is also the case of higher n_e

Counterbalanced Pendulum Thrust Stand

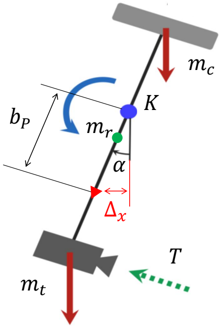
Main features

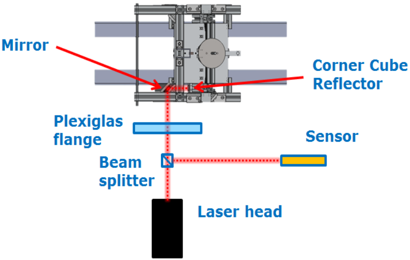
- Developed to test **small-medium HPTs** (up to 10 kg)
- Thrust measured in the range from μN up to **tens of mN**
- **Tens of measurements** per day can be accomplished
- **Uncertainty** in the range of **10%**





Counterbalanced Pendulum Concept





Counterbalanced pendulum concept

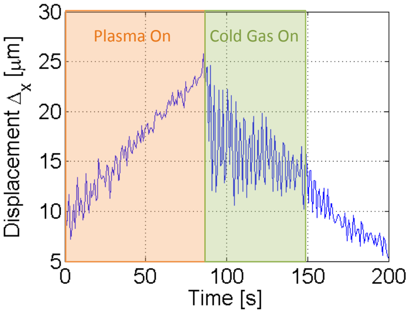
- The thrust T produces an horizontal displacement Δ_x of the pendulum arm $\Delta_x \propto T$
- The **displacement** is measured with a **laser interferometer** focused on a corner cube

Zero-Position Drift Correction & Thrust Evaluation

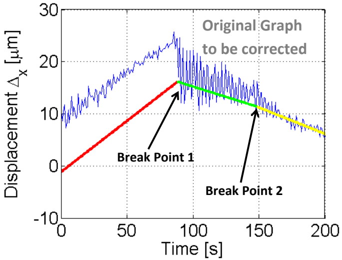
Zero-position drift

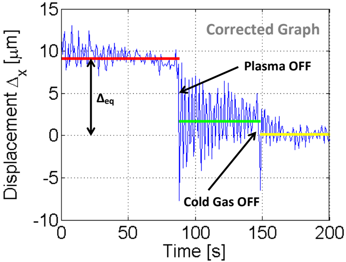
Due to **thermal gradients** which make the centre of mass of the pendulum move

- Plasma heat losses major drift source
- Electrical cables and gas adduction tube are other important drift sources



Zero-Position Drift Correction & Thrust Evaluation





Procedure for drift correction & thrust evaluation

- Identification of intervals where heating conditions uniform
- Drift contribution approximated with interpolation lines
- Thrust evaluated from Δ_{eq}, difference between corrected mean values

Uncertainty Evaluation & Benchmark

Test	1	2	3	4	5
Thrust [mN]	0.278	0.426	0.380	0.252	0.405
Uncertainty [mN]	±0.020	±0.023	±0.047	±0.024	±0.054

Thrust measurement

Uncertainty of the measurements in the order of **10%**

Uncertainty Evaluation & Benchmark

Test	1	2	3	4	5
Thrust [mN]	0.278	0.426	0.380	0.252	0.405
Uncertainty [mN]	±0.020	±0.023	±0.047	±0.024	±0.054

Thrust measurement

Uncertainty of the measurements in the order of **10%**

Test	1	2	3	4
T electrical [mN]	0.203	0.254	0.147	0.180
T stand [mN]	0.178	0.208	0.172	0.192
Relative Difference [%]	-12.4	-18.2	16.6	6.8

Thrust stand VS Faraday probe measurements

Agreement within the **20%**, in line with the uncertainty of the electrical measurements in the order of 30-40%

Conclusions and Future Work

Conclusions

- **The model of HPT** predicts accurately the *Production Stage* and preliminary the propulsive performances
- Both **3D-VIRTUS and the model of HPT** have been **exploited** to analyse a wide range of source configurations
- A **counterbalanced pendulum thrust stand** for HPTs testing has been characterized and exploited
- Qualitative agreement of numerical and experimental data

Conclusions and Future Work

Conclusions

- **The model of HPT** predicts accurately the *Production Stage* and preliminary the propulsive performances
- Both **3D-VIRTUS and the model of HPT** have been **exploited** to analyse a wide range of source configurations
- A **counterbalanced pendulum thrust stand** for HPTs testing has been characterized and exploited
- Qualitative agreement of numerical and experimental data

Future work

- To simulate the *Acceleration Stage* with a more accurate tool; e.g., the **PIC code F3MPIC**
- To **optimize** the tested HPT with the updated code that gives accurate predictions of the propulsive performances


"That's all Folks!"
I s b e r g©