Numerical and Experimental Investigation into the Performance of Plasma Sources for Space Propulsion Systems

Mirko Magarotto

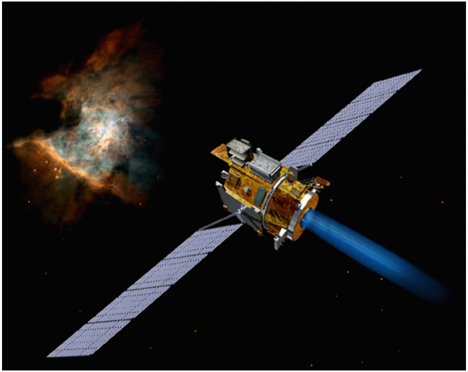
Centro di Ateneo di Studi e Attività Spaziali Giuseppe Colombo
CISAS
University of Padova

Outline

Electric Space Propulsion

Definition

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



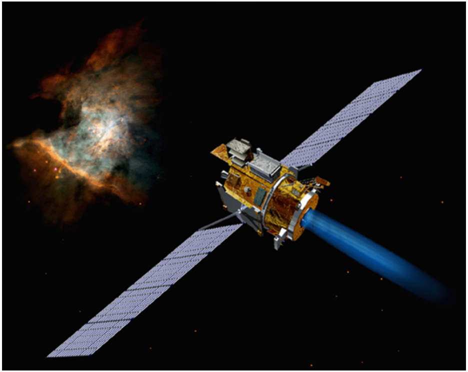
Electric Space Propulsion

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



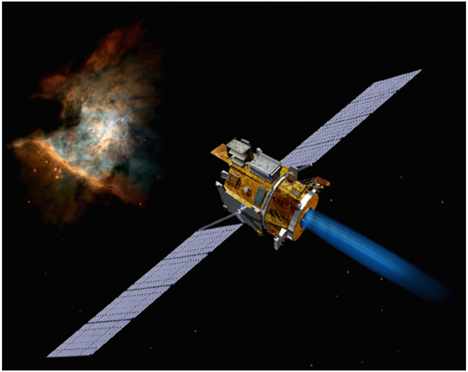
Electric Space Propulsion

Main Features

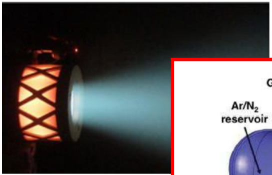
- High specific impulse: higher > 1000 s
- Low thrust: lower < 1 N

Some applications

- Attitude control
- Cubesats
- Interplanetary missions

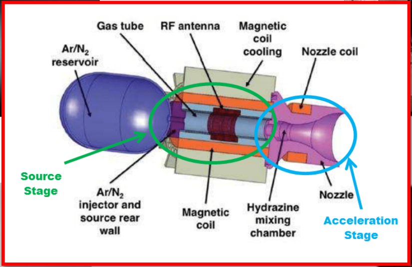


Electric Space Propulsion - State of the art



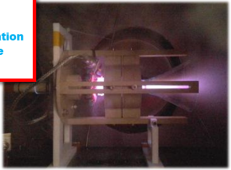
BIT

RIT



ThrustMe

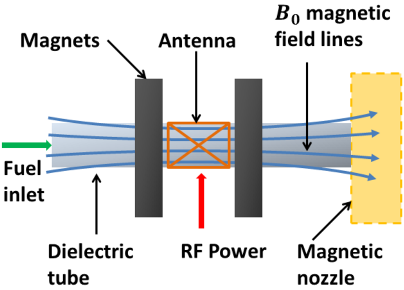
HPH.Com



Helicon Plasma Sources

Main components

- Dielectric Tube
- RF Antenna
- Magnets



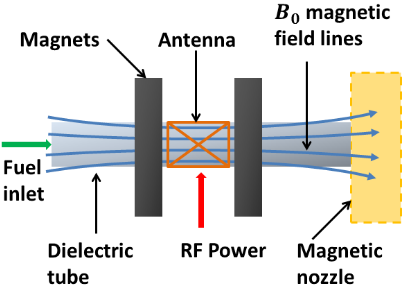
Helicon Plasma Sources

Main components

- Dielectric Tube
- RF Antenna
- Magnets

Main features

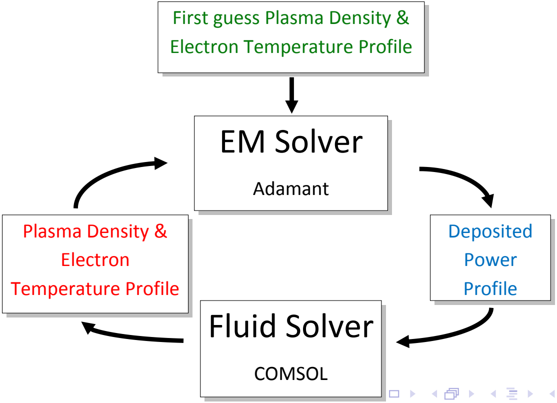
- high density plasma $n \geq 10^{18}\ \mathrm{m}^{-3}$
- simple antenna geometry
- low magnetic field $B_0 \leq 1000$ G



Model of the Source

Coupling FLUID SOLVER and EM SOLVER

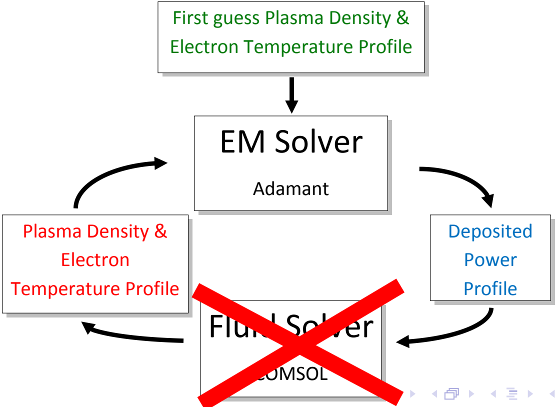
- Reproduction of the transport for high-density plasma
- Computational cost at bay



Model of the Source

Coupling FLUID SOLVER and EM SOLVER

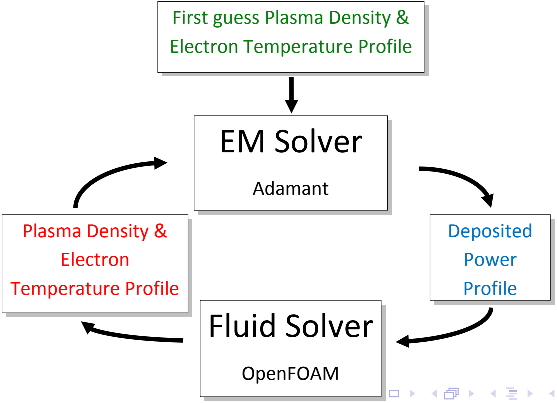
- Reproduction of the transport for high-density plasma
- Computational cost at bay



Model of the Source

Coupling FLUID SOLVER and EM SOLVER

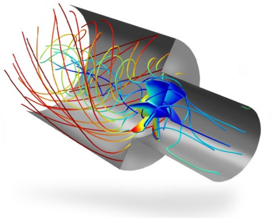
- Reproduction of the transport for high-density plasma
- Computational cost at bay



COMSOL - OpenFOAM Comparison

COMSOL

- Commercial software
- Limited possibility of modifying the model's equations
- Problems with energy equation and boundary conditions



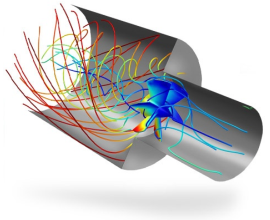
COMSOL - OpenFOAM Comparison

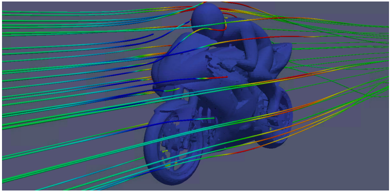
COMSOL

- Commercial software
- Limited possibility of modifying the model's equations
- Problems with energy equation and boundary conditions

OpenFOAM

- Open source C++ library
- Total access to the source code, and to model's equations
- Energy equation and boundary conditions written by user





Fluid Solver implementation in OpenFOAM

Implementation Strategy

1. Implementation in OpenFOAM of the same fluid model of COMSOL, in order to have a consolidated benchmark

Fluid Solver implementation in OpenFOAM

Implementation Strategy

1. Implementation in OpenFOAM of the same fluid model of COMSOL, in order to have a consolidated benchmark
2. Coupling of OpenFOAM and ADAMANT, and benchmark against COMSOL+ADAMANT

Fluid Solver implementation in OpenFOAM

Implementation Strategy

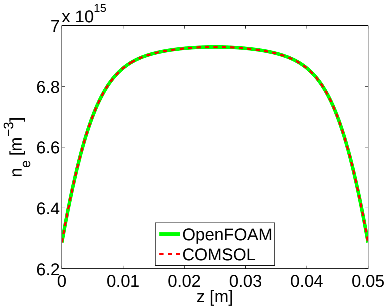
1. Implementation in OpenFOAM of the same fluid model of COMSOL, in order to have a consolidated benchmark
2. Coupling of OpenFOAM and ADAMANT, and benchmark against COMSOL+ADAMANT
3. Update of OpenFOAM with more refined fluid model (e.g. modified energy equation)

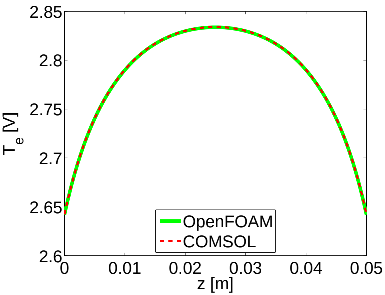
Fluid Solver implementation in OpenFOAM

Implementation Strategy

1. Implementation in OpenFOAM of the same fluid model of COMSOL, in order to have a consolidated benchmark
2. Coupling of OpenFOAM and ADAMANT, and benchmark against COMSOL+ADAMANT
3. Update of OpenFOAM with more refined fluid model (e.g. modified energy equation)
4. Experimental validation

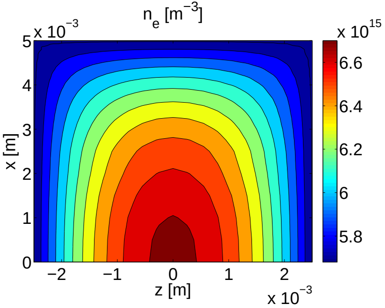
OpenFOAM - COMSOL 1D Simulation Results

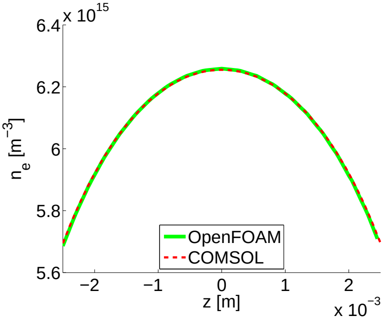




1D Simulation

- Evaluated plasma parameters gradients only along axis of cylindrical plasma source
- Assumed power deposition profile
- Comparison between the two solvers very good





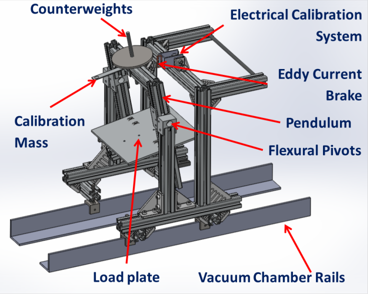
3D Simulation

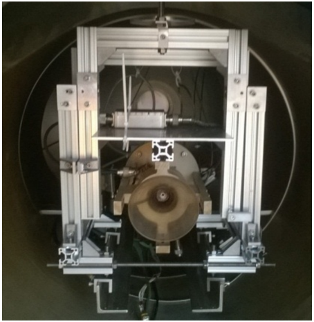
- 3D data sampled on a semi-plane which contains the axis of the plasma source, and on a line into this plane
- Assumed power deposition profile
- Comparison between the two solvers very good

Experimental Setup for Validation and Testing

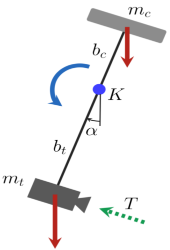
Thruster Diagnostic System

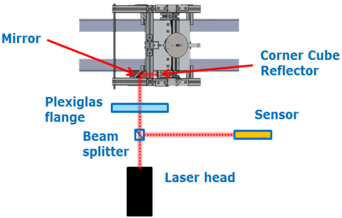
Faraday probe, Retarding Potential Analyzer and Thrust Balance to measure Specific Impulse and Thrust





Thrust Stand Concept





Counterbalanced Pendulum Concept

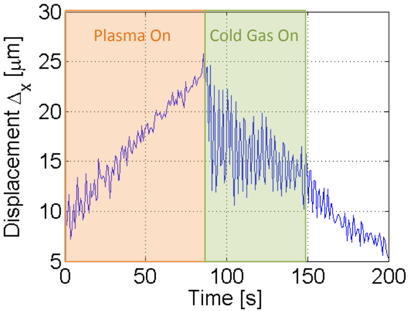
- In accordance with the rotational equilibrium equation a thrust T produces an angular displacement:
$$\alpha = Tb_t/(K + g(m_t b_t - m_c b_c))$$
- Measured, with a laser interferometer, the displacement of a corner cube fastened to the pendulum arm

Thrust Stand Results

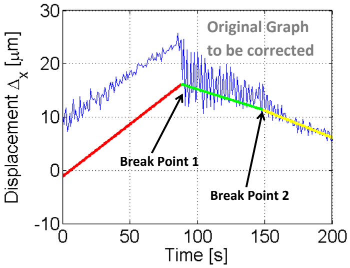
Position Drift

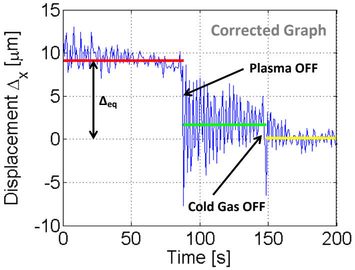
Due to thermal gradients which make the pendulum mass center move

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



Thrust Stand Results





Drift Correction Procedure & Thrust Evaluation

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

Thrust Stand Results

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

Non optimized 50 W Helicon Plasma Thruster, uncertainty in the order of 10%

Thrust Stand Results

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

Non optimized 50 W Helicon Plasma Thruster, uncertainty 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

Stand VS Electrical Measurements

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

Future Expected Results

Future Expected Results

1. Full development of the numerical tool devoted to the source analysis

Future Expected Results

Future Expected Results

1. Full development of the numerical tool devoted to the source analysis
2. Design, optimization, and testing of an high-power Helicon plasma source

Future Expected Results

Future Expected Results

1. Full development of the numerical tool devoted to the source analysis
2. Design, optimization, and testing of an high-power Helicon plasma source
3. Technology exploitation


"That's all Folks!"
Isberg©