Advanced plasma sources for space applications

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Outline

Framework

Plasma exhibits complex Electromagnetic (EM) wave phenomena.
It can be exploited in a broad range of advanced application:

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It can be exploited in a broad range of advanced application:

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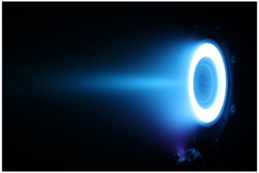
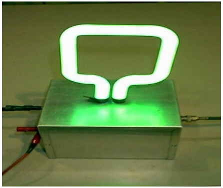
Space Propulsion:

Plasma Thrusters



Space Communication:

Gaseous Plasma Antennas



Framework

Plasma propulsion systems

Use electric power to ionize the propellant and impart kinetic energy to the plasma.

Critical issues:

- Limited lifetime
- Need for an external cathode
- Low power density.

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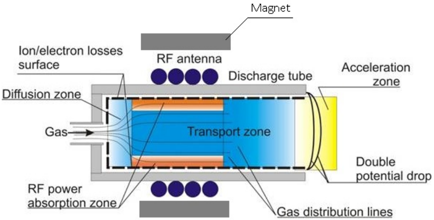
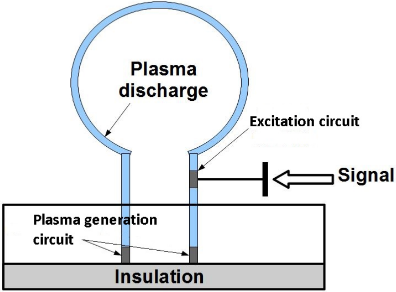
Helicon Plasma Thruster (HPT)



Framework



Gaseous Plasma Antennas (GPAs)

Devices relying on an ionized gas to radiate EM waves.

Feautures:

- Electrically reconfigurable;
- Low RCS, and thermal noise;
- Minimize co-site interference and signal degradation;
- Virtually *transparent* above the plasma frequency and *invisible* once turned off.

Motivation, and Objectives

Although different in shape, fields of applications, and working conditions, GPAs and HPTs share:

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Plasma generation

Wave-plasma coupling

Plasma transport

Motivation, and Objectives

Objectives

- Physical investigation into plasma generation, charged particle transport in a magnetized plasma, and wave-plasma coupling mechanism
- Clarify the role of the antenna in the source of HPTs, and the behavior of GPAs taking into account realistic excitation circuit and plasma transport
- Coupling of the EM solution with the plasma transport
- Design, and development of innovative plasma sources to be exploited as a GPA.

Global Model

Plasma transport within a plasma source modeled by a 0-D fluid model.

Input

- Source Geometry: R, L;
- Neutral pressure p_n;
- Deposited power P;

Output

- Average plasma density $n_e = n_i$;
- Average electron temperature T_e.

From input to output

System at equilibrium:

- Particles produced chemically = Particles lost in walls
- EM deposited power = Chemical losses + wall losses

ADAMANT

Wave-plasma coupling modeled by an EM solver.

- Full-wave approach
- Coupled surface and volume integral equations
- Arbitrarily-shaped circuit
- Inhomogeneous and anisotropic plasma

Plasma Model

- cold, and collisional
- multispecies
- non-uniform
- if magnetized, $B_0 \parallel z$ axis

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Dyadic Permittivity Function

$$\bar{\varepsilon}_{rk} = \begin{bmatrix} S_k & jD_k & 0 \\ -jD_k & S_k & 0 \\ 0 & 0 & P_k \end{bmatrix}$$

ADAMANT

Input

- Plasma mesh;
- PEC mesh;
- Source type, number of feeding points, f;
- Gas Type;
- n_e, n_i, T_e, T_i, B_0, p_n.

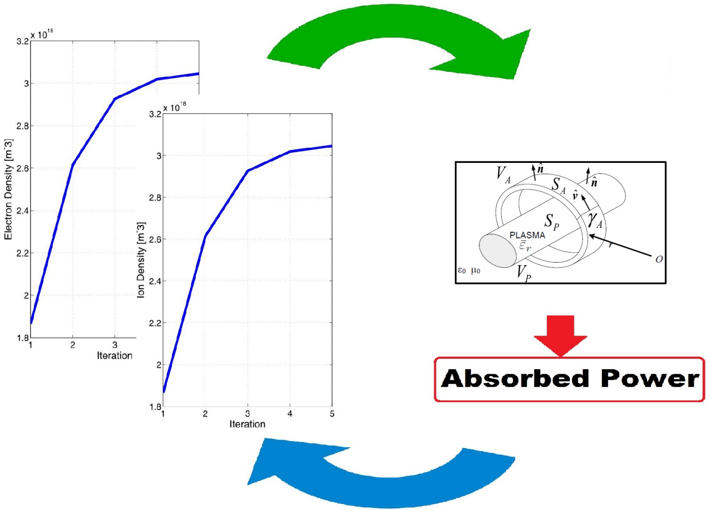
Output

- Current distributions;
- Z-matrix, S-parameters;
- Scattered fields;
- Input, absorbed, and radiated power.

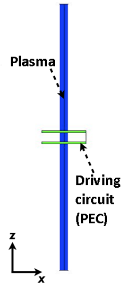
From input to output

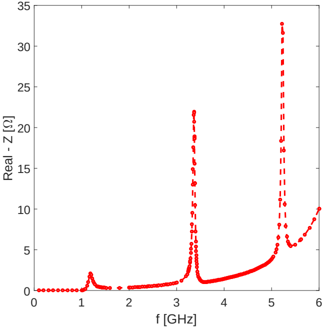
- Surface Integral Equation
- Volume Integral Equation
- Excitation on the feeding port (voltage-gap approximation)

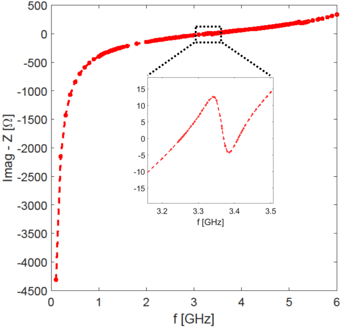
Global Model and ADAMANT coupling



Antenna Input Impedance, and Current Distribution

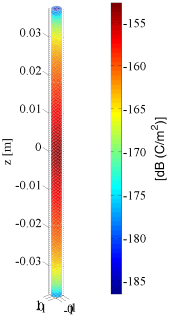




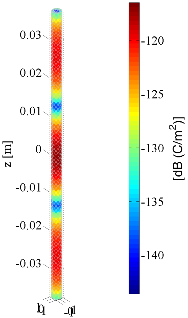


Cylindrical argon plasma column with: $n_0 = 1 \cdot 10^{19}$ m^{-3}, $T_e = 3$ eV, $p_n = 0.02$ mbar, $L = 75$ mm, and $\Phi = 2.5$ mm

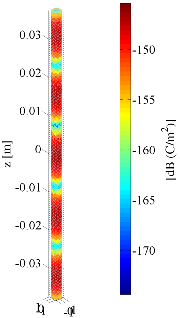
Antenna Input Impedance, and Current Distribution



$f = 1.37$ GHz



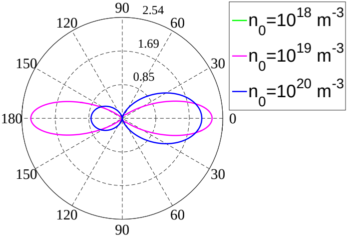
$f = 3.62$ GHz

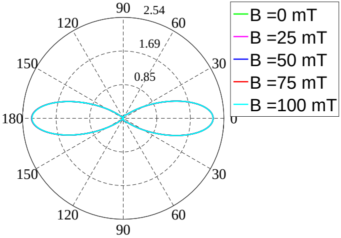


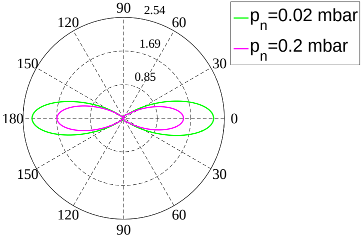
$f = 5.51$ GHz

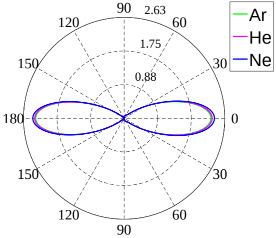
Cylindrical argon plasma column with: $n_0 = 1 \cdot 10^{19}$ m^{-3}, $T_e = 3$ eV, $p_n = 0.02$ mbar, $L = 75$ mm, and $\Phi = 2.5$ mm

The GPA Radiation Pattern

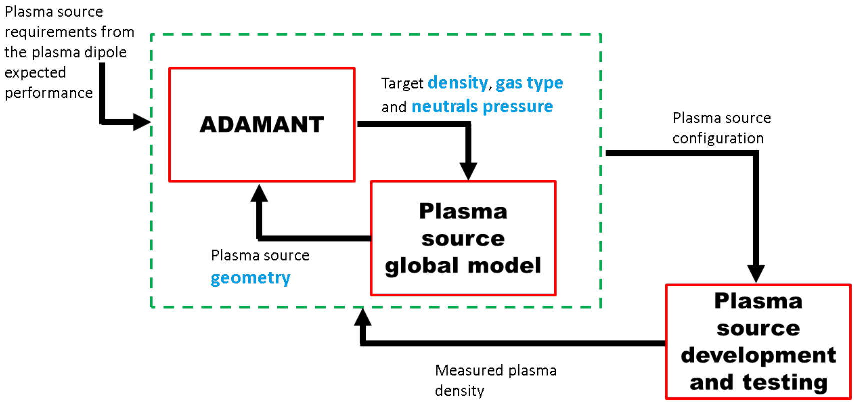








Numerical, and Experimental Approach



Numerical Analysis - Plasma Source

Matlab genetic algorithm + Global Model

Decision-space variable	**Optimization parameters**
Plasma Radius Plasma Length	Plasma density of 10^{19} m^{-3}
Neutral Pressure Input Power	Minimize input power

Plasma Radius [mm]	5 - 10
Plasma Length [mm]	50 - 75
Neutral Pressure [mbar]	0.06 - 0.5
Input Power [W]	20 - 100

Numerical Analysis - Plasma Source

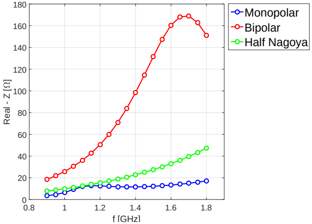
Matlab genetic algorithm + Global Model

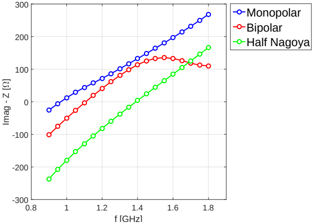
	Case 1	**Case 2**	**Case 3**	**Case 4**
Plasma Radius [mm]	8.7	6.6	7.5	6.42
Plasma Length [mm]	54.6	56.2	78.9	72.5
Neutral Pressure [mbar]	0.75	0.39	0.09	0.4
Input Power [W]	84.1	23.8	94.2	28.9

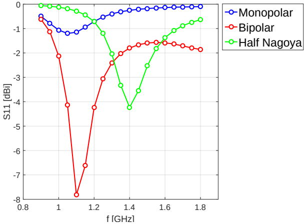
Numerical Analysis - Antenna Performances

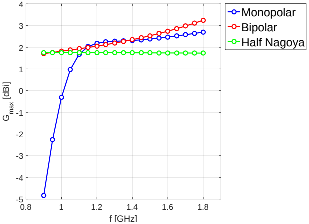
Coupler	Sleeve, Half-Nagoya
Metal-coupler length	30 – 42 mm
Metal-coupler Φ	14 – 30 mm
Antenna Configurations	Monopolar, Bipolar
Plasma Φ	3 – 10 mm
Column length	50 – 130 mm
Column distance	0 – 12 mm
Neutral gas	Ar, He, Ne
Electron temperature	3 eV
Neutral pressure	0.5 – 10 mbar
Plasma density	$10^{18} - 10^{19}$ m^{-3}
Working frequency	0.8 – 1.8 GHz
Voltage	1 V

Numerical Analysis - Antenna Performances









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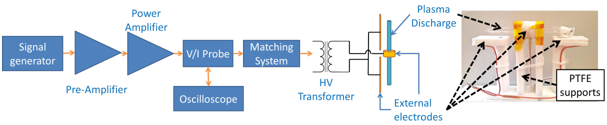
Generation Method

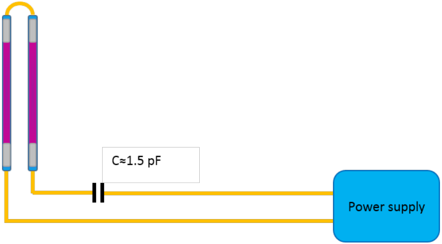
Plasma generation: 2 techniques

RF - External Electrodes



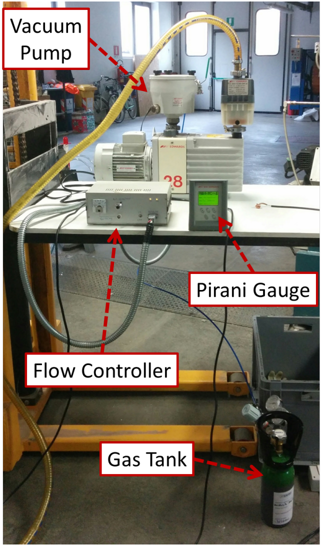
$p_n = 1 - 10 mbar$
$\phi = 3 - 10 mm$
Not-uniform n_e
$n_e < 1 \cdot 10^{19}\ \mathrm{m}^{-3}$

HF - Internal Electrodes



$p_n = 1 - 2 mbar$
$\phi = 5 - 6 mm$
Higher, and more uniform n_e
Dirty atmosphere

Manifacturing



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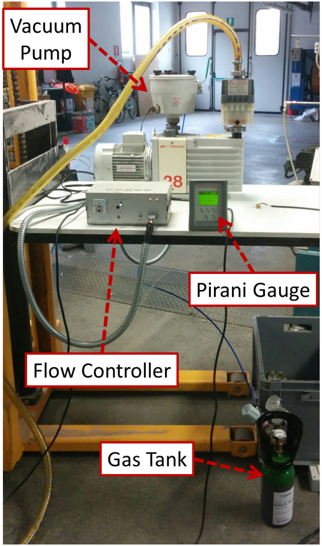
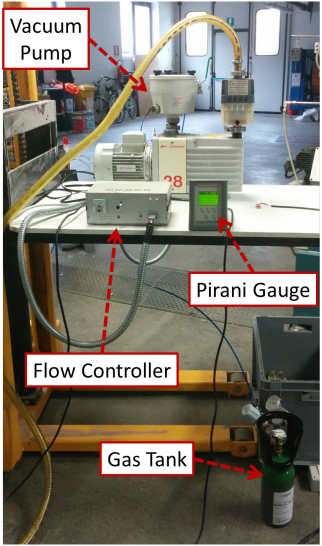


Pyrex vessel with *ad hoc* interface

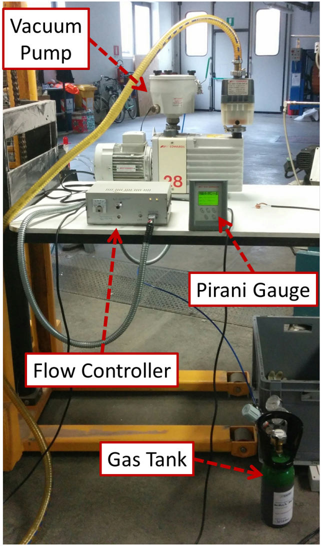
Manifacturing



Pyrex vessel with *ad hoc* interface

Sealing process

Manifacturing



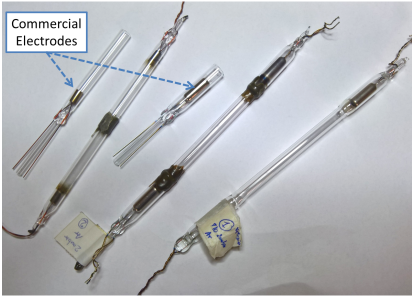
Pyrex vessel with *ad hoc* interface

Closed vessels

Manifacturing

Vessel Preparation

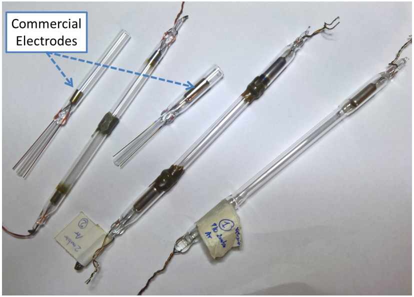
Commercial electrodes sealed with a tube of the desired dimensions



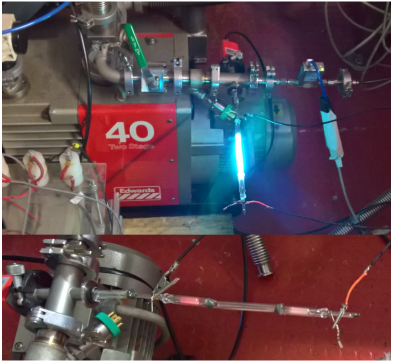
Manifacturing

Vessel Preparation

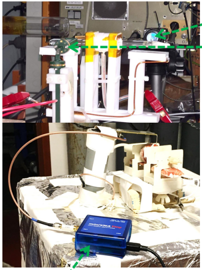
Commercial electrodes sealed with a tube of the desired dimensions



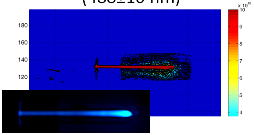
Aging process



Diagnostic

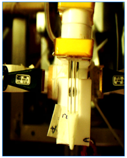


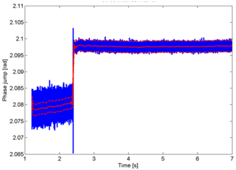
Basler Camera with BP filters (488±10 nm)



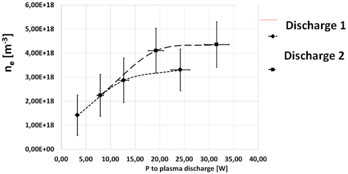
Filtered image of a plasma discharge, and plasma density map.

MW Interferometer



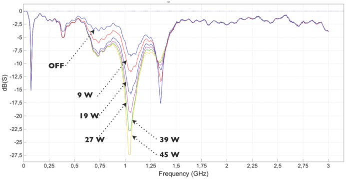


Plasma density value is correlated to the phase jump.



Plasma density against the net power to plasma.

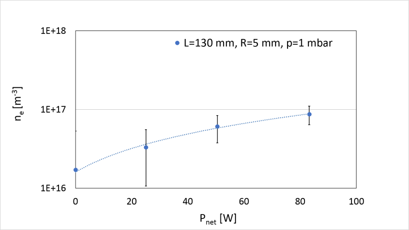
VNA

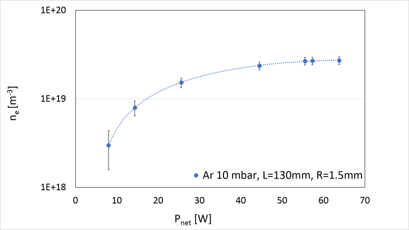


Magnitude of the reflection coefficient of the plasma dipole without plasma ("OFF"), and at different net power to plasma

Source Characterization

RF Discharges



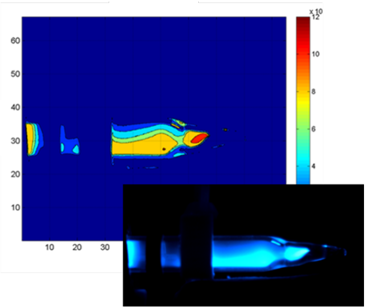


Argon, $p_n = 1$ mbar,
$\Phi = 10$ mm, $L = 130$ mm.

Argon, $p_n = 10$ mbar,
$\Phi = 3$ mm, $L = 130$ mm.

Source Characterization

RF Discharges



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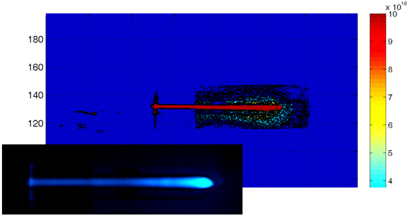


Argon, $p_n = 10$ mbar,
$\Phi = 3$ mm, $L = 130$ mm.

Source Characterization

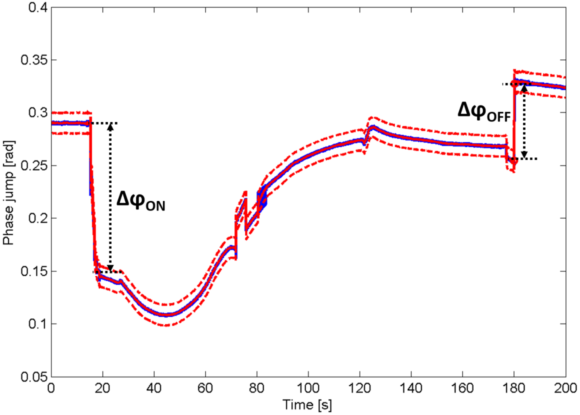
HF Discharges

We explored different gas pressures, and mixture

Gas	p_n **[mbar]**	n_0 $[\mathbf{m}^{-3}]$
Ar	1	$3.70 \cdot 10^{18} \pm 1.84 \cdot 10^{17}$
Ar - Ne	2	$3.84 \cdot 10^{18} \pm 8.57 \cdot 10^{16}$
Ar	2	$4.40 \cdot 10^{18} \pm 5.09 \cdot 10^{17}$
Ar - Hg	2	$3.18 \cdot 10^{18} \pm 5.88 \cdot 10^{16}$
Ar - Hg	1	$2.59 \cdot 10^{18} \pm 1.50 \cdot 10^{17}$

Source Characterization

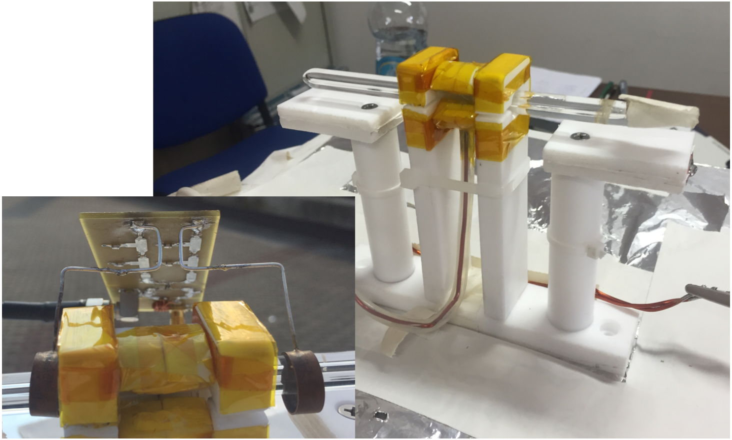
HF Discharges



$$n_{ON} = 5.08 \cdot 10^{18} \pm 3.38 \cdot 10^{17} \text{ m}^{-3}.$$
$$n_{OFF} = 2.83 \cdot 10^{18} \pm 4.11 \cdot 10^{17} \text{ m}^{-3}$$

Antenna Characterization - Reflection Coefficient

Argon, $p_n = 10$ mbar, $\Phi = 3$ mm, $L = 130$ mm.



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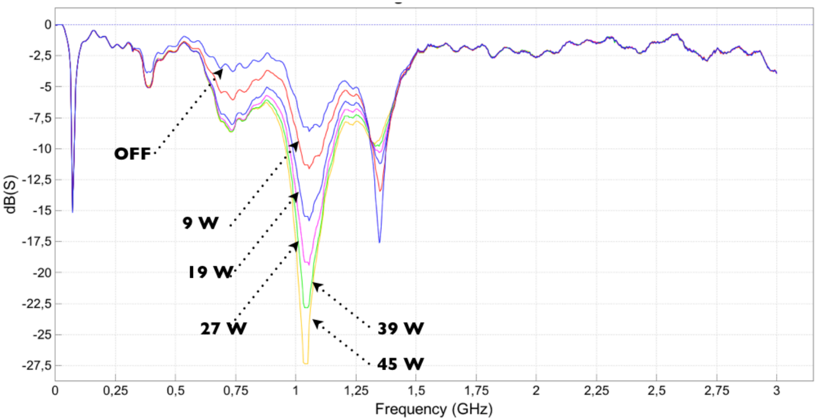
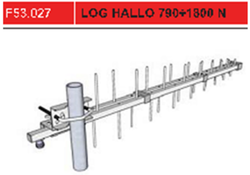
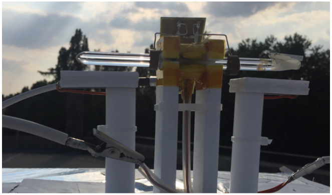
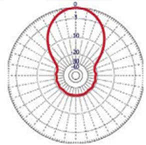


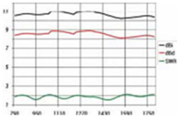
Antenna Characterization - Gain Pattern

Antenna testing with a well-known Log-Hallo Antenna as transmitter.







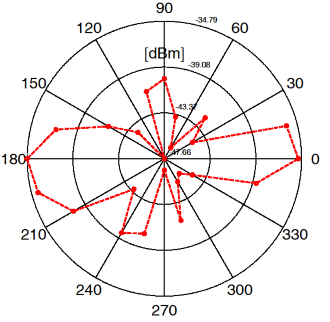


Friis Transmission Equation:

$$G_r = P_r - P_t - G_t - 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2$$

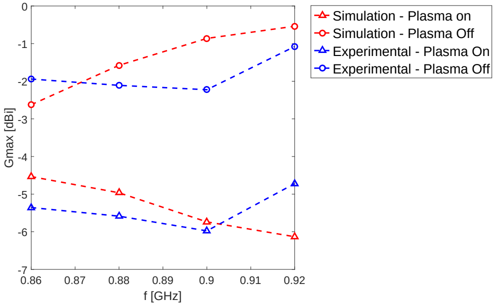
Antenna Characterization

P_r on the E-plane



$G_{max} = -6$ dBi

G_{max} on the E-plane



Conclusions

- Development of a tool that couples the EM solution with the plasma transport, useful to study both GPAs, and Plasma Thrusters.
- Physical assessment on wave propagation in a plasma column.
- Physical assessment on the radiation properties of a plasma dipole.
- Design of 2 plasma sources to be exploited in a GPA.
- Preliminar assessment on the antenna performance of a GPA.

Publications

- Trezzolani, F., Magarotto, M., Manente, M., Moretto, D., Bosi, F.J., Gallina, G., De Carlo, P., Melazzi, D., Pavarin, D., Pessana, M., *Development of a counterbalanced pendulum thrust stand for electric propulsion*, (2017) 4th IEEE International Workshop on Metrology for AeroSpace, MetroAeroSpace 2017 - Proceedings, art. no. 7999554, pp. 152-157.
- Melazzi, D., De Carlo, P., Trezzolani, F., Lancellotti, V., Manente, M., Pavarin, D., Rigobello, F., Capobianco, A.-D., *First experimental characterization of a gaseous plasma antenna in the UHF band*, (2017) 2017 11th European Conference on Antennas and Propagation, EUCAP 2017, art. no. 7928419, pp. 3213-3217.
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Thanks for your Attention