Power balance in microwave microplasmas generated in capillary tubes

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Context

Over the last years, we have designed and tested several launchers able to generate microwave microplasmas in dielectric capillary tubes.

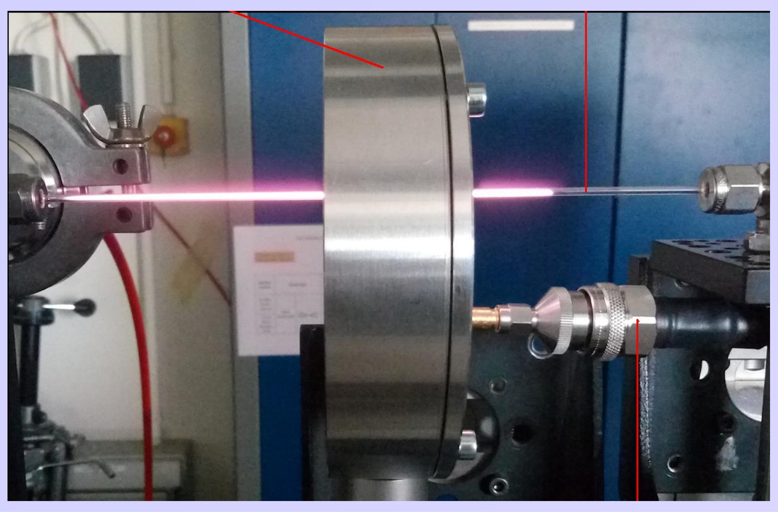
Advantages of microwaves are numerous: plasmas can operate over a large range of pressures (from 10^{-4} mbar to atmospheric pressure), with very low power (a few W to a few tens of W), in continuous mode, and electrodeless.

The obtained microplasmas turn out to produce high electron and ion densities (10^{14} cm^{-3} range), high power density (up to 10 $kW.cm^{-3}$), high amount of active species (10^{12} cm^{-3} range for argon metastable states) and high amount of photons, all of them interesting for a large panel of potential applications.

Motivation to our study comes from the fact that the power balance in microwave microplasmas is almost never discussed.

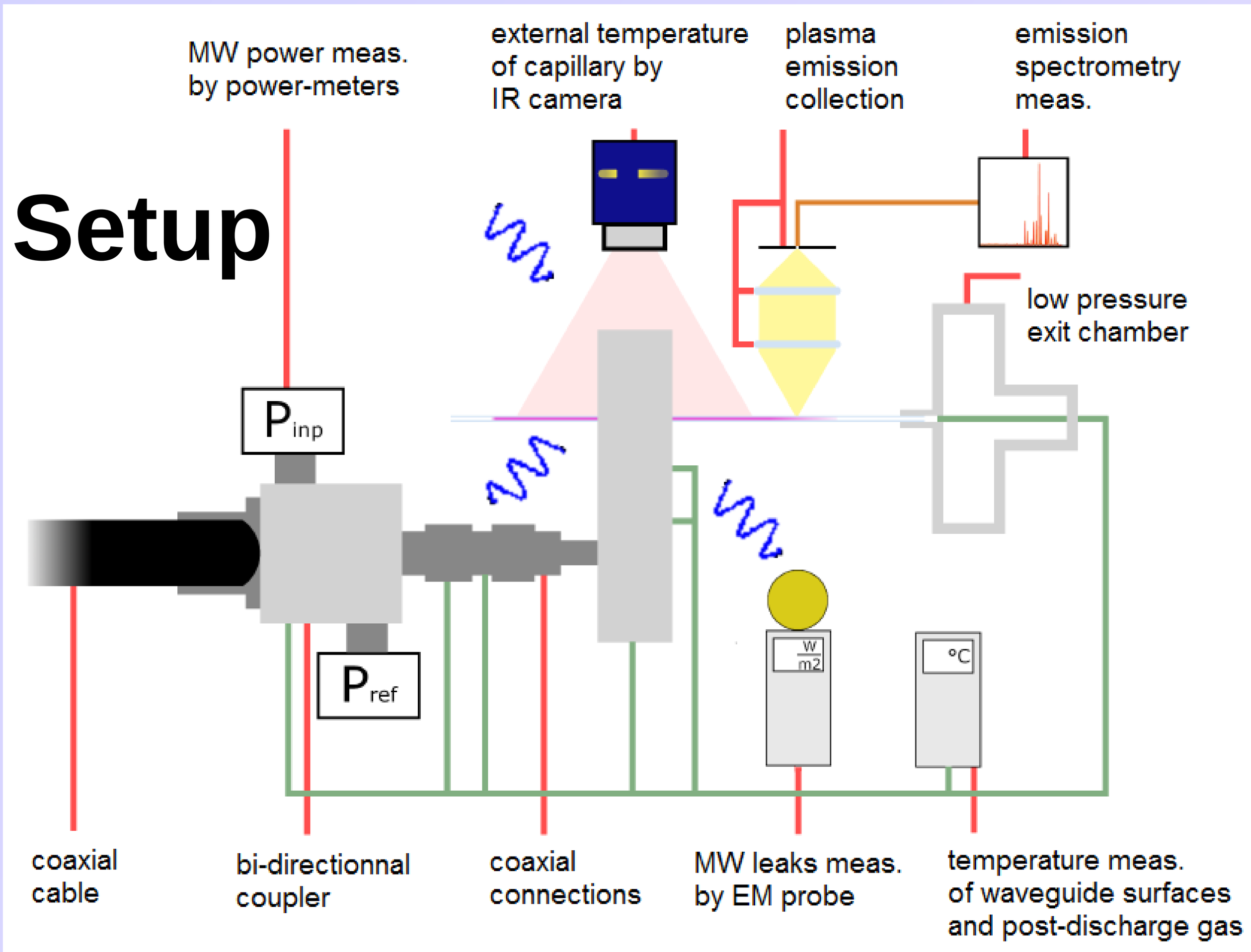
In the best cases, authors only report input and reflected measured powers and suppose that the difference is coupled to the plasma leading to a >90% coupling efficiency.

The current work is thus dedicated to determine the microwave power really coupled to the plasma.
It requires a complete power balance study taking into account all the power loss possibilities.



Surface wave launcher

The launcher is a cavity with a leak which enables the propagation of a surface wave azimutally homogeneous (m=0 mode) along a dielectric (silica) capillary tube (ϕ_{int} = 1 mm / ϕ_{ext} = 2 mm) into which a gas (pure argon, or with a fraction of air) is injected, leading to the ignition and sustainment of a plasma column whose length is proportionnal to microwave power.



Power loss terms

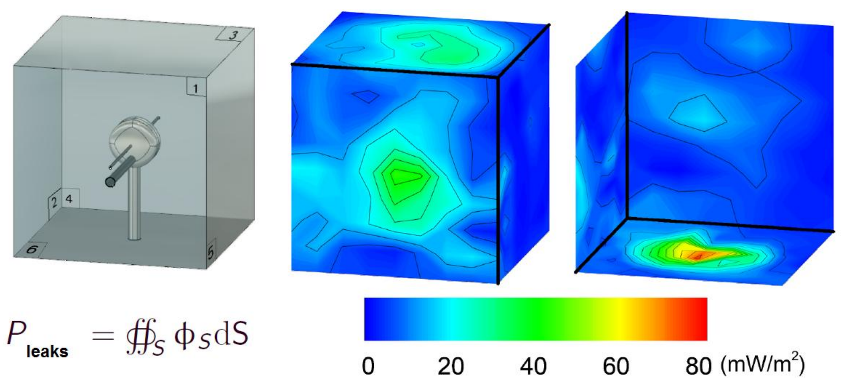
1- Microwave leaks
2- Reflected power
3- Heating of microwave coupling elements

Power coupled to the plasma

4- Optical radiation from the plasma
5- Post discharge heating & chemistry
6- Heating of the capillary tube

Measurement of the power loss terms

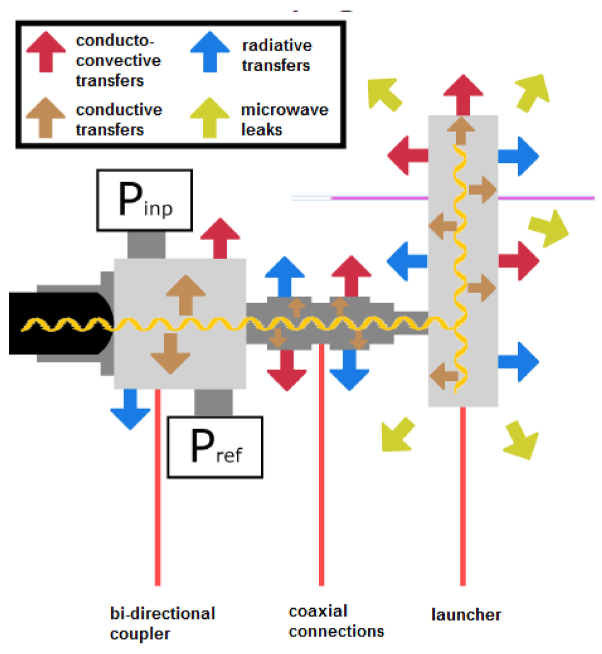
1- Microwave leaks



$P_{leaks} = \oiint_S \phi_S dS$

ϕ_S measured by EM probe on virtual cube centered on the launcher.

P(leaks) = 95mW for P(inc)=15W — *negligible*



2- Reflected power)

Measurements of:
incident & reflected powers near the launcher
with bi-directional coupler & power-meters
to limit coaxial losses and to get rid of generator low accuracy

Typical values for P(inc)=15W :
P(ref) = 14 W (without plasma)
P(ref) = 4 W (with plasma)

3- Heating of microwave coupling elements

Conducto-convective power

$P^{CC}_{heating} = h(T_{surface} - T_{air})S$

Heat transfer coefficient

$h = \frac{Nu(T, L_c)\lambda(T)}{L_c}$

With Nu: Nusselt number

Thermal radiative power

$P^{rad}_{heating} = \epsilon\sigma(T^4_{surface} - T^4_{walls})S$

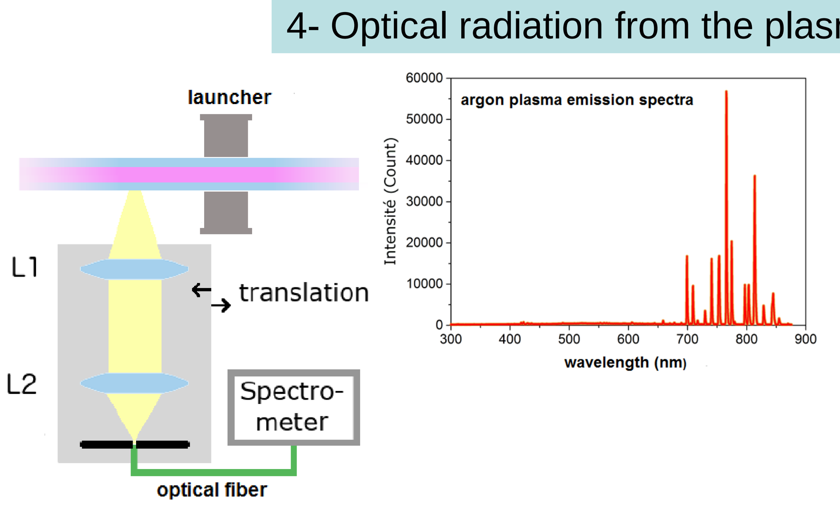
T(surface) measured by thermocouple
Graphite coating on the launcher to have an high and known value of emissivity ε

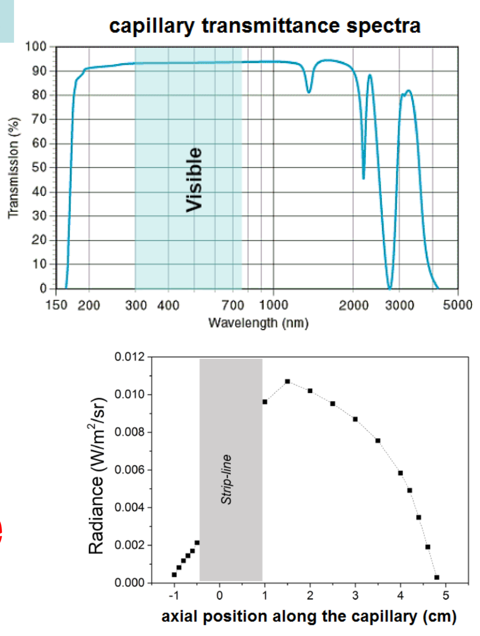
$\rightarrow P_{heating} = P^{CC}_{heating} + P^{rad}_{heating}$

Typical values for P(inc) = 15 W : P(heating) = 1 W (without plasma)
P(heating) = 3,5 W (with plasma)

Measurement of the power coupled to the plasma

4- Optical radiation from the plasma

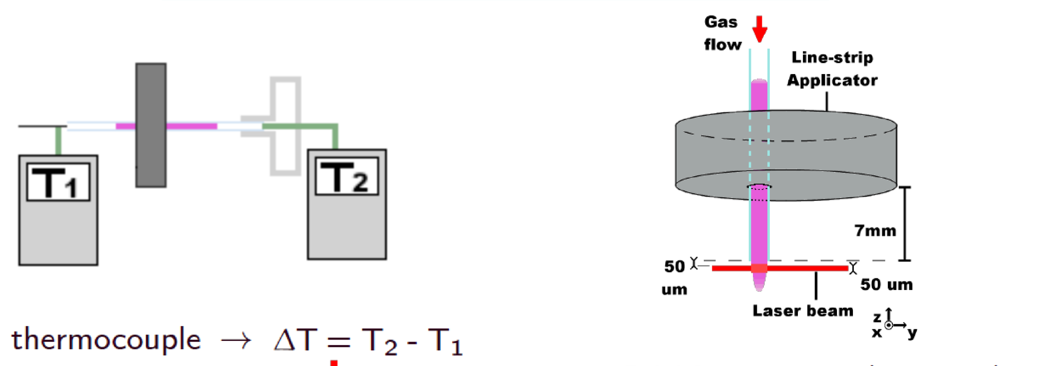




$P_{rad} = \iiint_{V_{Plasma}} \int_{\nu} \int_{\Omega} e_{\Omega}(\nu) dV d\nu d\Omega$

P(rad)=15 µW for P(inc)=15W — *negligible*

5- Post discharge heating & chemistry



thermocouple $\rightarrow$ $\Delta T = T_2 - T_1$

- $P_{heat.} = \dot{m}_{gaz} C_{p,gaz} \Delta T_{gaz}$

- $\Delta T_{gaz} \in [0 ; 100 \text{ K}]$
$\rightarrow P_{heat.} < 10$ **mW** — *negligible*

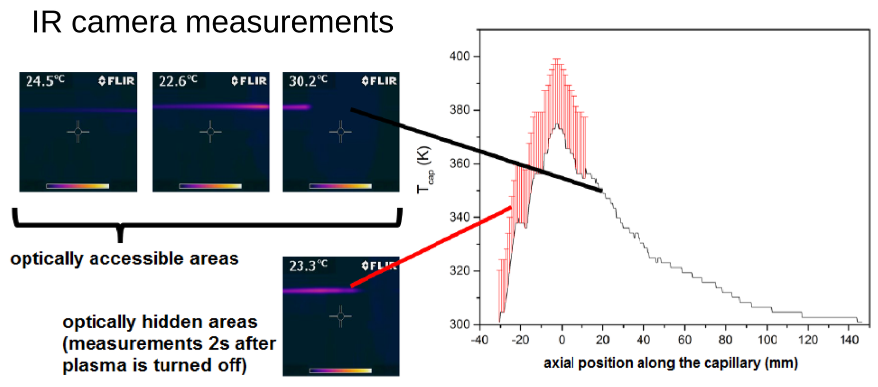
TD:LAS diagnostics (801,6 nm)

- $P_{Chem.} = [Ar^m] \Delta E \text{ v S}$

- $[Ar^m] \simeq 10^{12}$ cm^{-3}
$\rightarrow P_{Chem.} < 10$ **mW** — *negligible*

6- Heating of the capillary tube

IR camera measurements

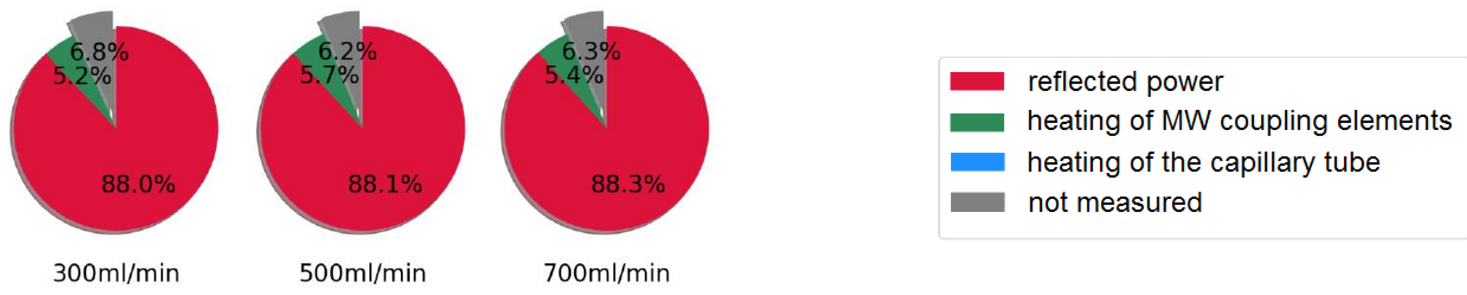


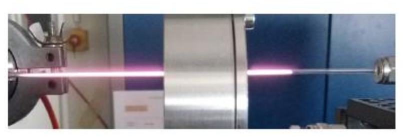
$P_{heat\_cap} = [h(T_{surface} - T_{air}) + \epsilon\sigma(T^4_{surface} - T^4_{walls})]S$

P(heat_cap)=2-3 W for P(inc)=15W

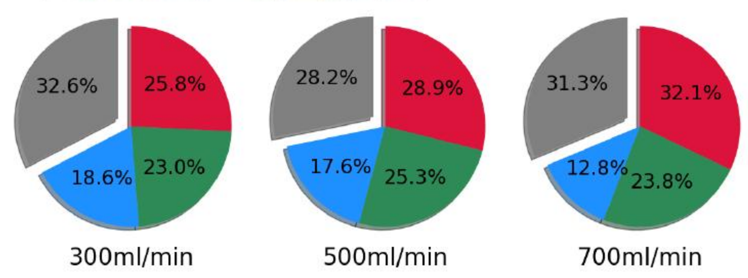
Conclusions

Power balance without plasma





Power balance with plasma



We show the negligible nature (< 1%) of a large part of the loss & coupled channels: microwave field leakage, optical radiation from the plasma, chemistry and post-discharge heating.
The power balance can thus be made solely from measurements of incident and reflected powers, heating of the microwave coupling elements and heating of the external walls of the capillary tube.

Without plasma, almost all the incident microwave power is back reflected (> 90%) and about 5% is lost in heating of the microwave coupling elements.
With plasma, overall, the reflected power becomes lower (25-60% of the incident power), the heating of the microwave coupling elements higher (15-30%) and the power transmitted to the plasma, measured via capillary heating, is relatively low (5-20%).

This is striking different compared to numerous studies considering only the incident and reflected measured powers, giving power coupled to the plasma of the order of 90 % of the incident power.
Strong conclusion : **the real power coupled to the plasma is, in the best case, lower by a factor of 2 to 3 compared to what is traditionally reported in the literature, especially for the surface loss dominated configurations like small diameter and capillary tubes.**