Microwave coaxial plasma sources: design and performances

Microwave plasma for low pressure surface treatment using solid state technology

Today, uniform plasma processing over large dimensions, and most often requiring strong ionic assistance, are essential for surface treatments at industrial level which require higher etching or deposition rates, such as **PECVD** (Plasma Enhanced Chemical Vapor Deposition) or **deep etching**. These requirements have stimulated the development of uniform plasma sources, of high density, and moreover capable of delivering **high concentrations of reactive species**.

Microwave plasma sources are well known for their performance in terms of creating high densities of species, but have often been considered a second choice given the difficulty of implementing them in an industrial process. For example, such sources often require an impedance adaptation system that is difficult to automate. In addition, to create a large volume of plasma by overcoming the critical density limiting the propagation of waves, it is necessary to wisely distribute the plasma sources, thus adding a strong constraint on the control of the power transmitted to each source.

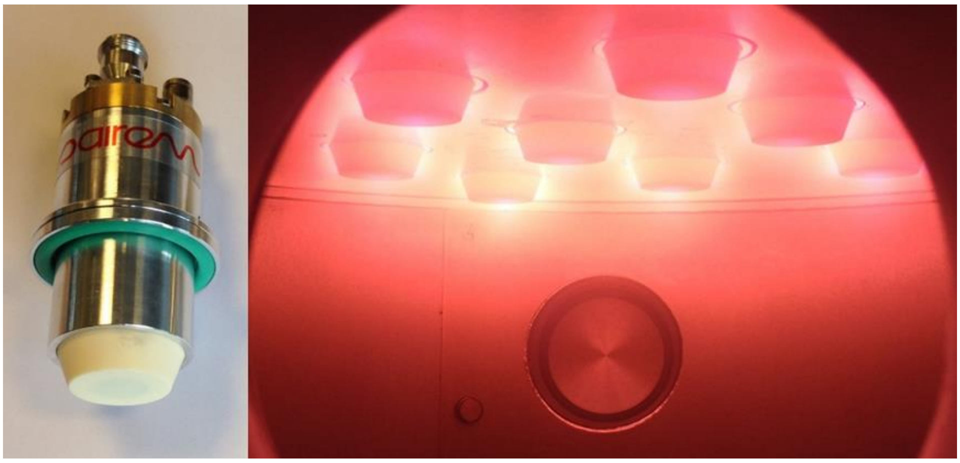
To overcome these constraints, SAIREM has developed two types of innovative microwave plasma sources operating with solid state generators:

Self-matching plasma sources using 2.45 GHz solid state generators

- **Aura-Wave** is an **ECR** (Electronic Cyclotron Resonance) microwave coaxial plasma source which can sustain stable plasmas from **a few 10^{-4} to 10^{-1} mbar** (a few 10^{-2} Pa to a 10 Pa) depending on gas nature (see details in section "Recommendations"). Permanent cylindrical magnets are encapsulated and mounted in opposition inside the coaxial structure [1], allowing the generation of a magnetic field towards the plasma chamber in order to limit losses to the walls. The source makes it possible to reach plasma densities of **a few 10^{11} cm^{-3}** in multisource configuration at 10 cm from the sources plane.

Aura-Wave ECR coaxial plasma source; 25 x 400 W (10 kW), oxygen, 1 Pa

- **Hi-Wave** is a collisional type microwave plasma source operating from a few **10^{-2} to 1 mbar** (a few Pa to 100 Pa). It is thus intended to operate without magnets in the collisional regime. Plasma densities **greater than 10^{12} cm^{-3}** can be achieved in multisource configuration at 10 cm from the sources plane.



Hi-Wave coaxial plasma source; 8 × 200 W, nitrogen, 10 Pa.

Both sources have been designed to avoid internal power losses and to be used **without** the need for **any impedance matching system** over the entire operating range of each plasma source [2-4]. The sources are said to be **self-adapted**. To do this, a long microwave modeling step was performed, the principle was to avoid any abrupt impedance change inside the source. Also, the shape of the dielectric allowing the transmission of waves in the plasma chamber has been carefully modeled to favor the penetration of microwaves into the plasma. Thus, **each plasma source is linked directly by a simple coaxial cable to its own solid-state generator** with adjustable power between 0 and 450 W and tunable frequency from 2.4 to 2.5 GHz. The adjustable frequency of the generator is intended to be used as backup matching means if the reflected power increases above a set value; an automatic adjustment loop enables the microwave generator to start sweeping the frequency band until the lowest reflected power level is found [2].

Patents

[1] S Béchu, A Bès, A Lacoste, J Pelletier, Device and method for producing and/or confining a plasma, Patent WO 2010/049456.

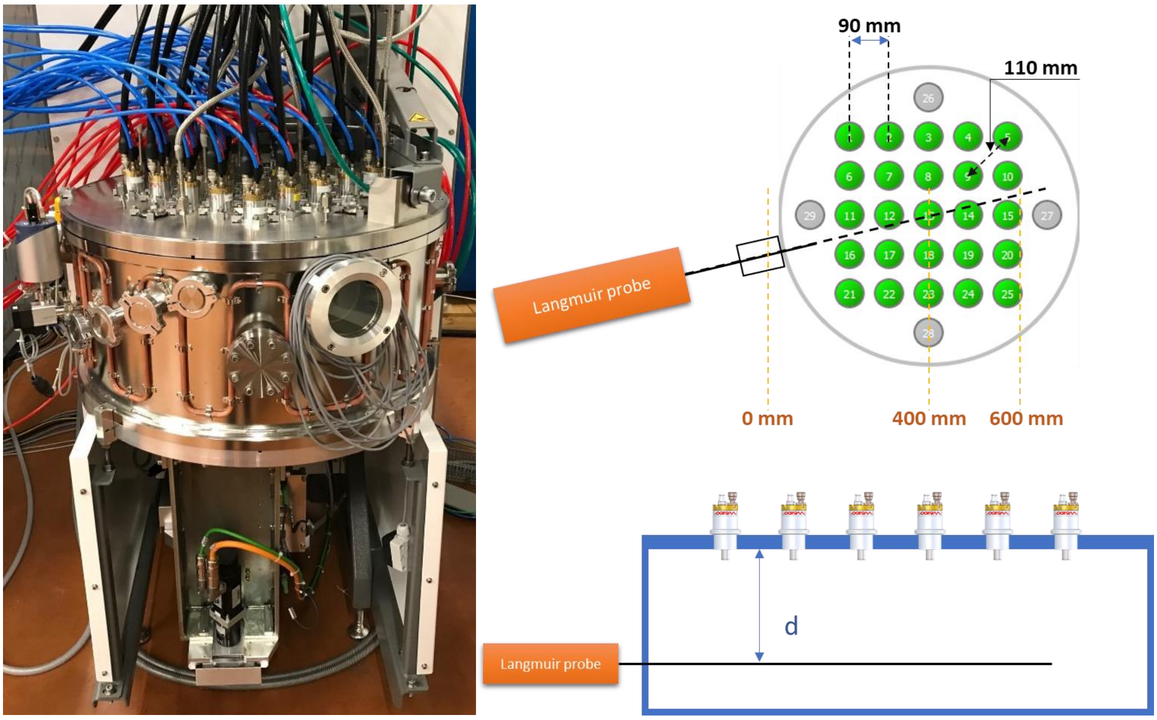
[2] A Grandemenge, J-M Jacomino, L Latrasse, M Radoiu, Facility for microwave treatment of a load, Patent WO 2012/146870.

[3] L Latrasse, M Radoiu, Elementary device for applying a microwave energy with coaxial applicator, Patent WO 2017/060611.

[4] L Latrasse, M Radoiu, Elementary device for producing a plasma, having a coaxial applicator, Patent WO 2017/060612.

Surface treatment over large dimensions with Aura-Wave

Concerning surface treatment over large areas, the sources could be distributed in different configurations, as in matrix, circular, or circular centered configurations for example. Below are examples of some measurements tested on a demonstrator located at SAIREM. This demonstrator, presented in the figure below, allows to integrate up to 25 sources distributed in matrix configuration with a lattice mesh a= 90 mm (i.e. the distance between 2 sources). Plasma density measurements were performed using a Langmuir probe including a translation system, the density profiles were measured at a fixed distance from the sources plane d (10 and 14 cm in examples presented here), as shown in the figure below, right.



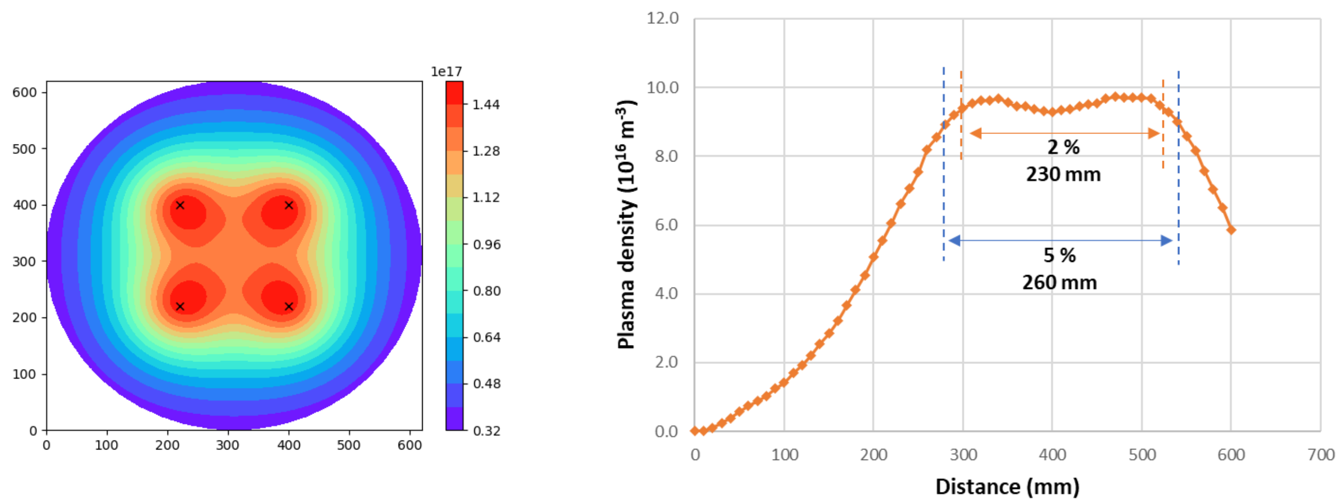
Left: demonstrator for large surface treatment. Right: Sketch representing density profiles measurement setup.

Previous plasma measurements have shown that the radial density profile of several plasma sources measured at a fixed distance from the source plane corresponds to the algebraic sum of all the density profiles obtained for each source individually. Thus, the profile obtained for a single source could be used to extrapolate the density profiles for an unlimited number of plasma sources. Thanks to this result, a simulation software was developed, which is very helpful to predict a distribution as a function of the specification of the customer (number of sources i.e. budget, distance to the substrate holder, gas nature, working pressure, requested plasma density, treatment surface…).

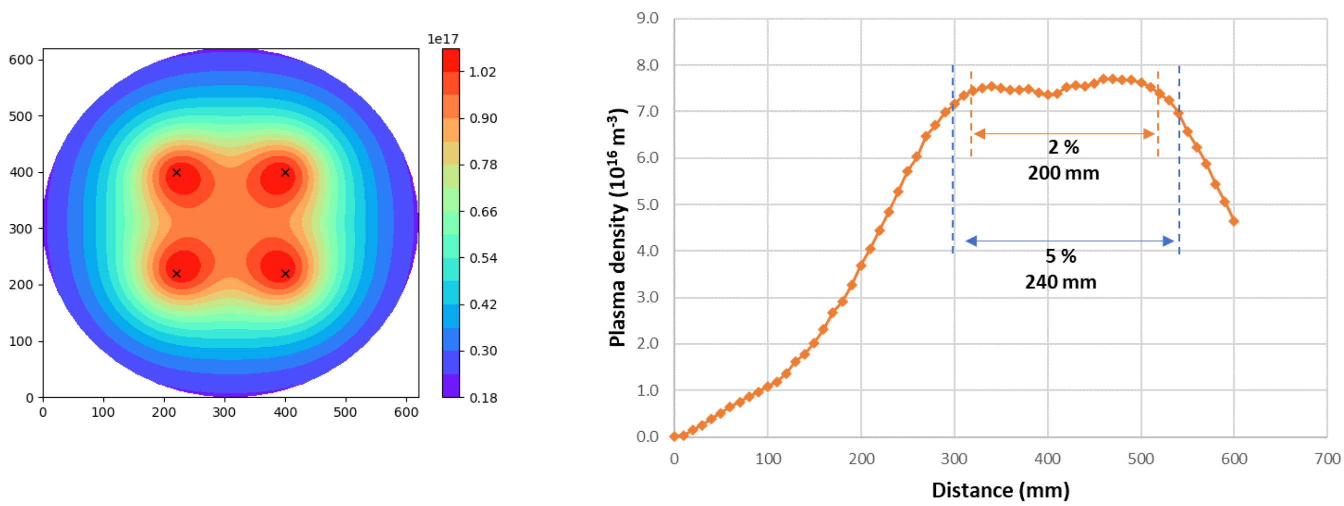
This software showed very satisfying coherence with experimental results.

4 plasma sources in matrix configuration

Figure below, left, represents the plasma density calculated for a plasma sustained by 4 Aura-Wave in matrix configuration with a lattice mesh a= 180 mm and at a distance from the source plane d = 10 cm. Plasma operating conditions are N_2 at 1 Pa and 400 W per plasma source. Figure on the right shows the corresponding measurement in the demonstrator. The simulation is a top view map and the measurement was performed in one dimension but could be assume to be quite symmetric in revolution, i.e. whatever the Langmuir probe position around the plasma chamber.



Distribution of the plasma density, matrix configuration, 4 sources a = 180 mm, d = 10 cm, N_2, 1 Pa, 400 W/source. Left: simulation. Right: measurement.

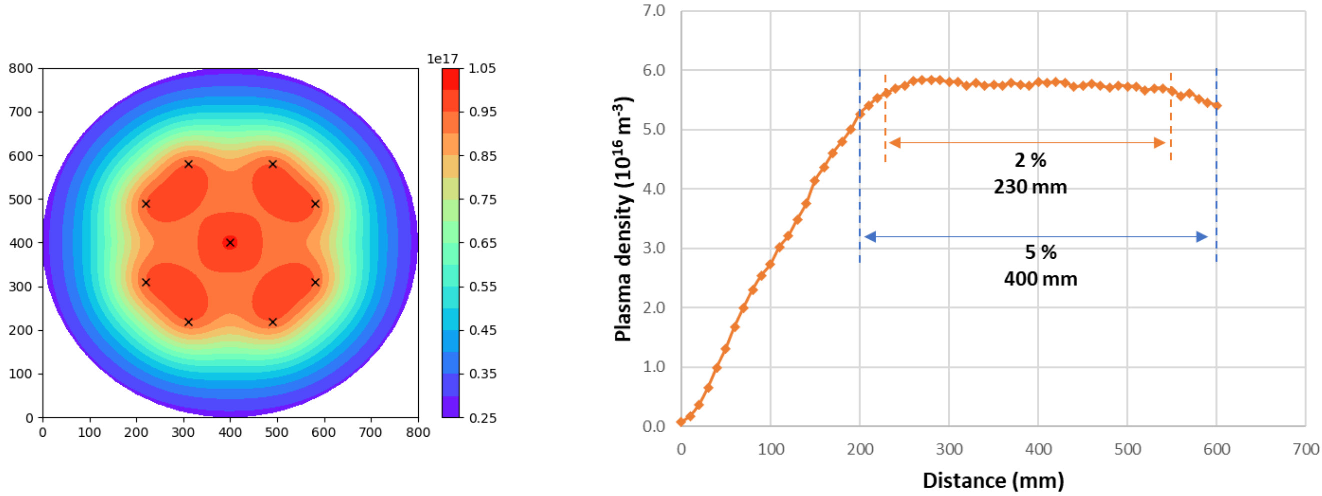


Distribution of the plasma density, matrix configuration, 4 sources, a = 180 mm, d = 10 cm, O_2, 1 Pa, 400 W/source. Left: simulation. Right: measurement.

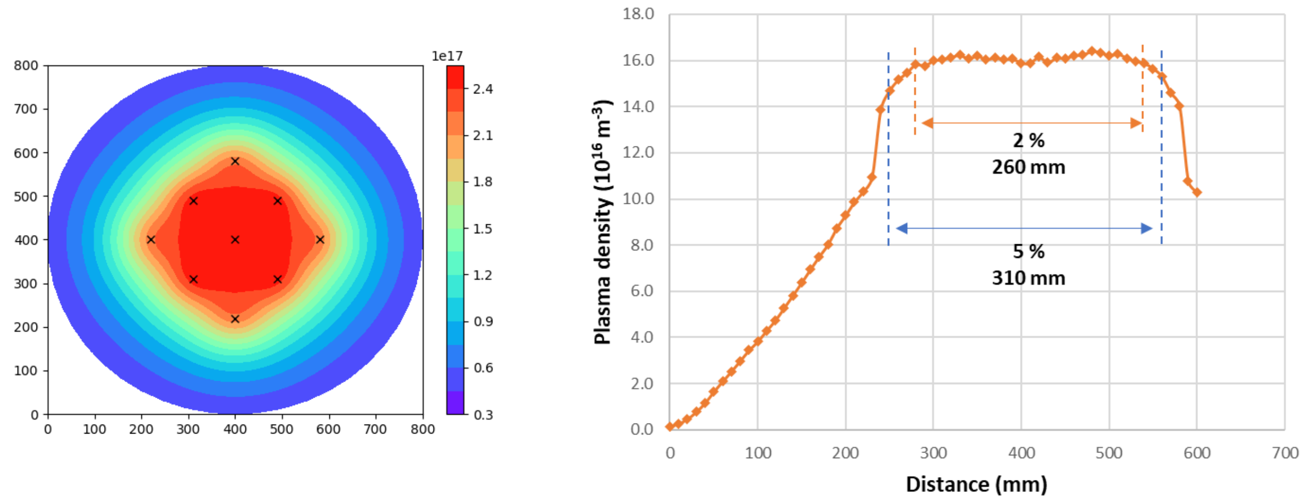
The same simulation and measurement were performed in O_2, as shown above. In both cases, a good correlation is observed and 4 plasma sources allow to generate a very uniform and dense plasma. A uniformity of 2 % is obtained over a diameter of 200 mm and 5 % around 250 mm. The plasma density reaches around 10^{11} cm^{-3}.

9 plasma sources

Figure below, left, represents the plasma density calculated for a plasma sustained by 9 Aura-Wave in circular centered configuration on a diameter around 400 mm and at a distance from the source plane d = 14 cm. Plasma operating conditions are N_2 at 1.5 Pa and 400 W per plasma source except for the centered one which has half the power. Figure on the right shows the corresponding measurement in the demonstrator.



Distribution of the plasma density, circular centered configuration with 9 sources on a diameter of 400 mm, d = 14 cm, N_2, 1.5 Pa, 400 W/source and 200 W for the centered one.
Left: simulation. Right: measurement.



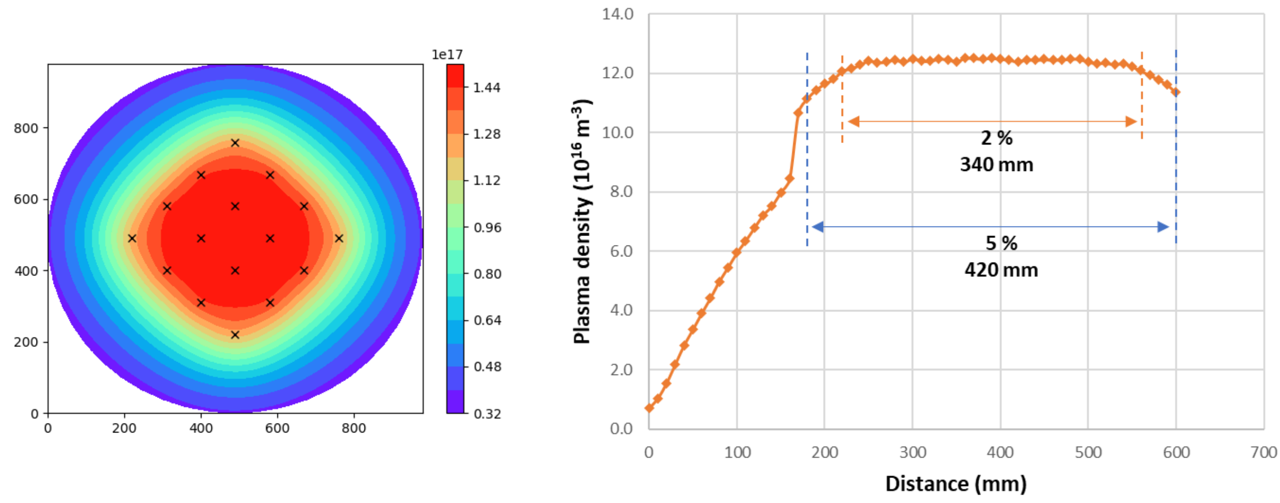
Distribution of the plasma density in matrix configuration, 9 sources, a = 110 mm, d = 10 cm, N_2, 1 Pa, 400 W/source, 100 W for the central one. Left: simulation. Right: measurement.

Simulation and measurement with 9 plasma sources distributed in matrix configuration with a lattice mesh a = 110 mm is represented above. Operating conditions are N_2 at 1 Pa and 400 W per source (except the central sources).

Results show that with 9 sources it is possible to be uniform on 400 mm with 5 % of uniformity, using a circular centered configuration. A matrix configuration with a = 110 mm is more compact and allow to work closer to the source plane, it reduces the uniformity diameter to around 300 mm with a uniformity of 5 % but increases the plasma density by a factor of 3.

16 plasma sources distributed in matrix configuration

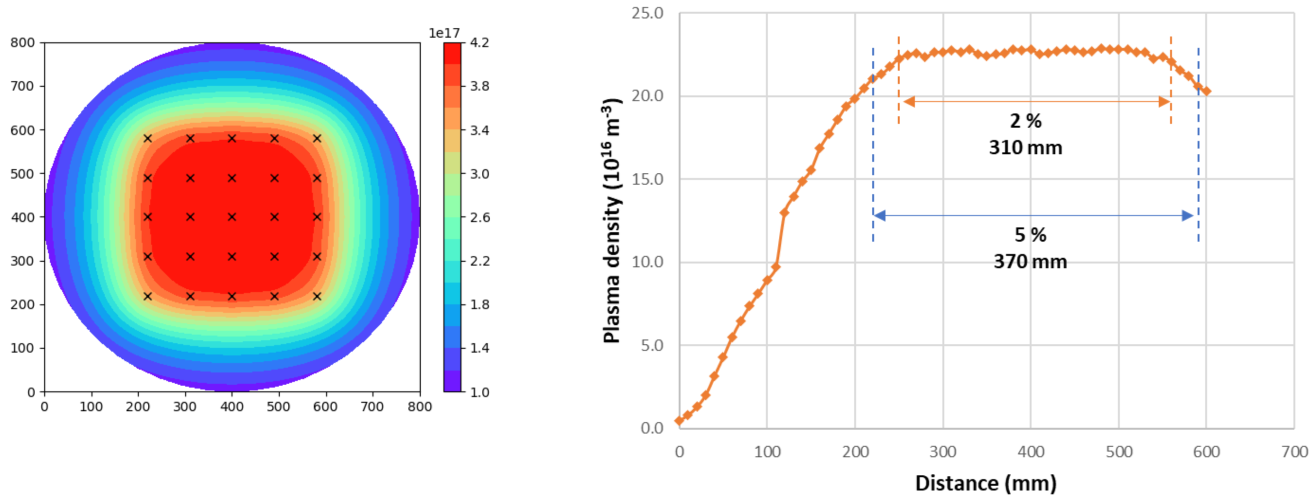
Figure below, left, represents the plasma density calculated for a plasma sustained by 16 Aura-Wave in matrix configuration with a lattice mesh a = 110 mm at a distance from the source plane d = 10 cm. Plasma operating conditions are Ar at 0.1 Pa and 400 W per plasma source on the peripherical sources and 50 W in the 4 central ones. Figure on the right shows the corresponding measurement in the plasma chamber.



Distribution of the plasma density, matrix configuration, 16 sources, a = 110 mm, d = 10 cm, Ar, 0.1 Pa, 400 W/source for the peripherical sources, 50 W for the 4 central ones.
Left: simulation. Right: measurement.

This configuration allows to obtain high density with a uniformity of 5 % on 420 mm in diameter.

25 plasma sources distributed in matrix configuration



Distribution of the plasma density, matrix configuration, 25 sources, a = 90 mm, d = 10 cm, N_2, 1 Pa, 400 W/source for the peripherical sources, 100 W for the 9 central ones.
Left: simulation. Right: measurement.

Figure above, left, represents the plasma density calculated for a plasma sustained by 25 Aura-Wave in matrix configuration with a lattice mesh a= 90 mm and at a distance from the source plane d = 10 cm. Plasma operating conditions are N_2 at 1 Pa and 400 W per plasma source on the peripherical sources and 100 W in the 9 central ones. Figure on the right show the corresponding measurement in the plasma chamber.

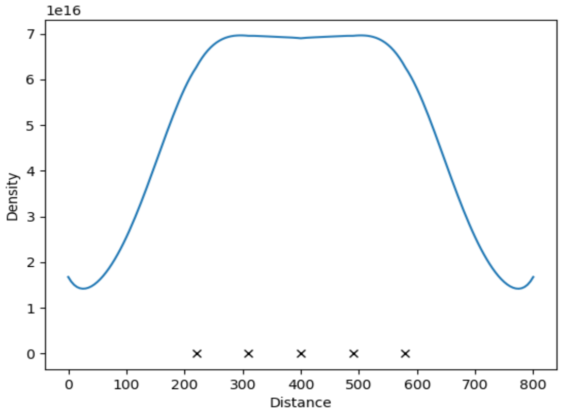
This configuration allows to obtain very high density with a uniformity of 5 % on 370 mm in diameter and 2 % on 310 mm.

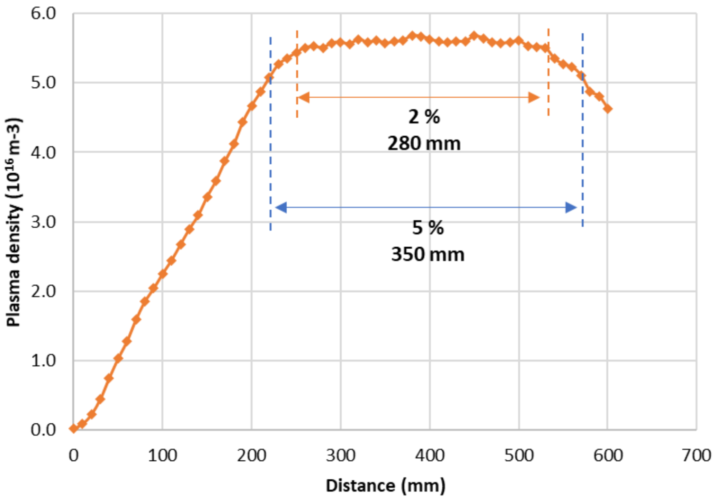
Conclusion on large area treatment

It is possible to create uniform plasma with a reduced number of plasma sources. 4 plasma sources allow to be uniform on more than 200 mm, 9 plasma sources for 300 to 400 mm, 16 for more than 400 mm. Roughly, the maximum distance between the peripherical sources allows to cover the same area, but the lattice mesh should not exceed 220 mm. Increasing the number of plasma sources while keeping the distance between the peripherical sources, i.e. increasing the compactness, allows to work closer to the source plane. Both the compactness and the shorter distance help to increase a lot the plasma density and thus to achieve very high reactive species density essential for plasma processes such as CVD, Reactive Ion Etching, deep etching, or functionalization….

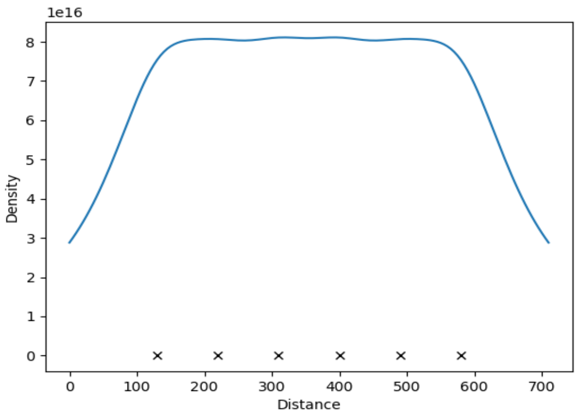
Linear treatment over large length

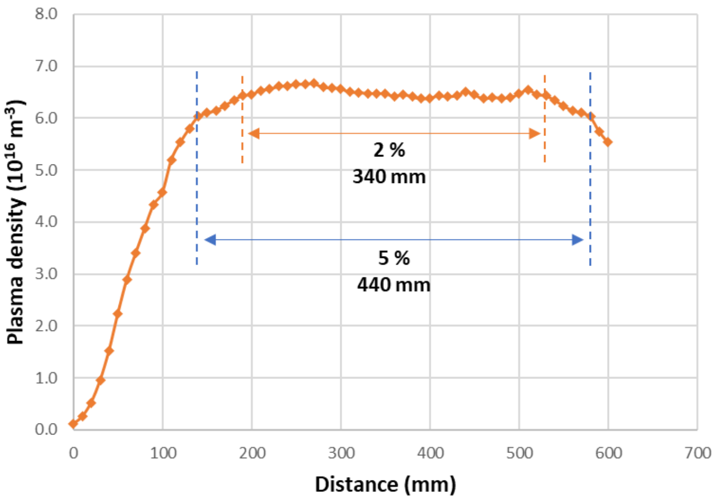
Other measurements were performed in linear configuration. Figures below show, on the left, the plasma density calculated for a plasma sustained by 5 Aura-Wave in linear configuration with a distance between sources b = 90 mm and at a distance from the source plane d = 14 cm. Plasma operating conditions are N2 at 1 Pa and 400 W per plasma source on the edge sources and half the power in the 3 central ones. On the right, the corresponding measurement in the plasma chamber.





Distribution of the plasma density, linear configuration, 5 sources, b = 90 mm, d = 14 cm, N_2, 1 Pa, 400 W/source for the edge sources, 200 W for the 3 central ones.
Left: simulation. Right: measurement.





Distribution of the plasma density, linear configuration, 6 sources, b = 90 mm, d = 14 cm, N_2, 1 Pa, 400 W/source for the edge sources, 200 W for the 4 central ones. Left: simulation. Right: measurement.

Figures above show, on the left, the plasma density calculated for a plasma sustained by 6 Aura-Wave in linear configuration with a distance between sources b = 90 mm and at a distance from the source plane d = 14 cm. Plasma operating conditions are N_2 at 1 Pa and 400 W per plasma source on the edge sources and half the power for the 4 central ones. Figure on the right shows the corresponding measurement in the plasma chamber.

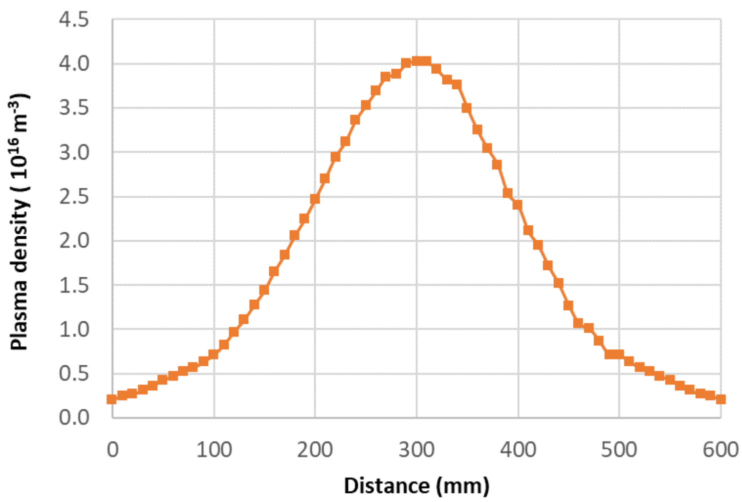
Correlation between measurements and simulation is quite satisfying. 5 plasma sources allow to be uniform with 5 % uniformity on 350 mm and 6 plasma sources on 440 mm. As for area treatment, the distance between the edge sources allows to cover the same distance, roughly, as b = 90 mm, adding a plasma source allows to increase uniformity on additional 90 mm.

Other measurements and simulation were performed with larger distance b, less compactness allows to cover higher length but decreases the plasma density.

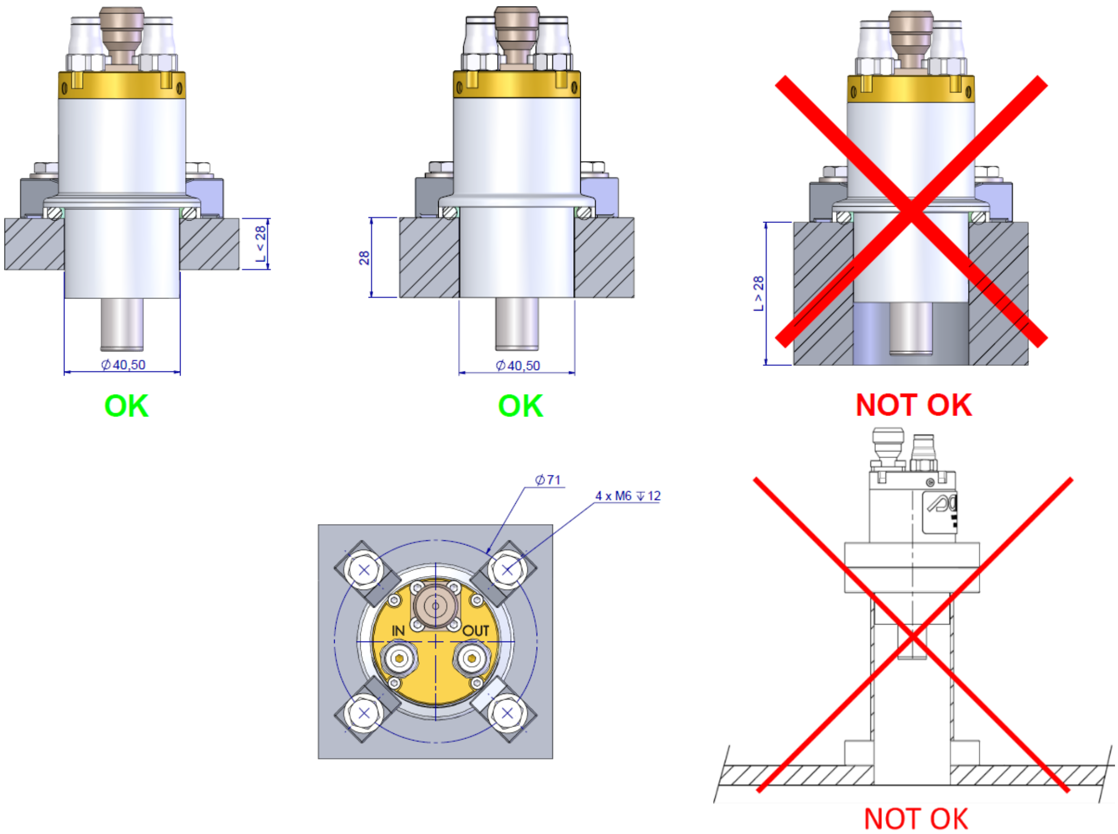
Recommendations and advices

Implementation

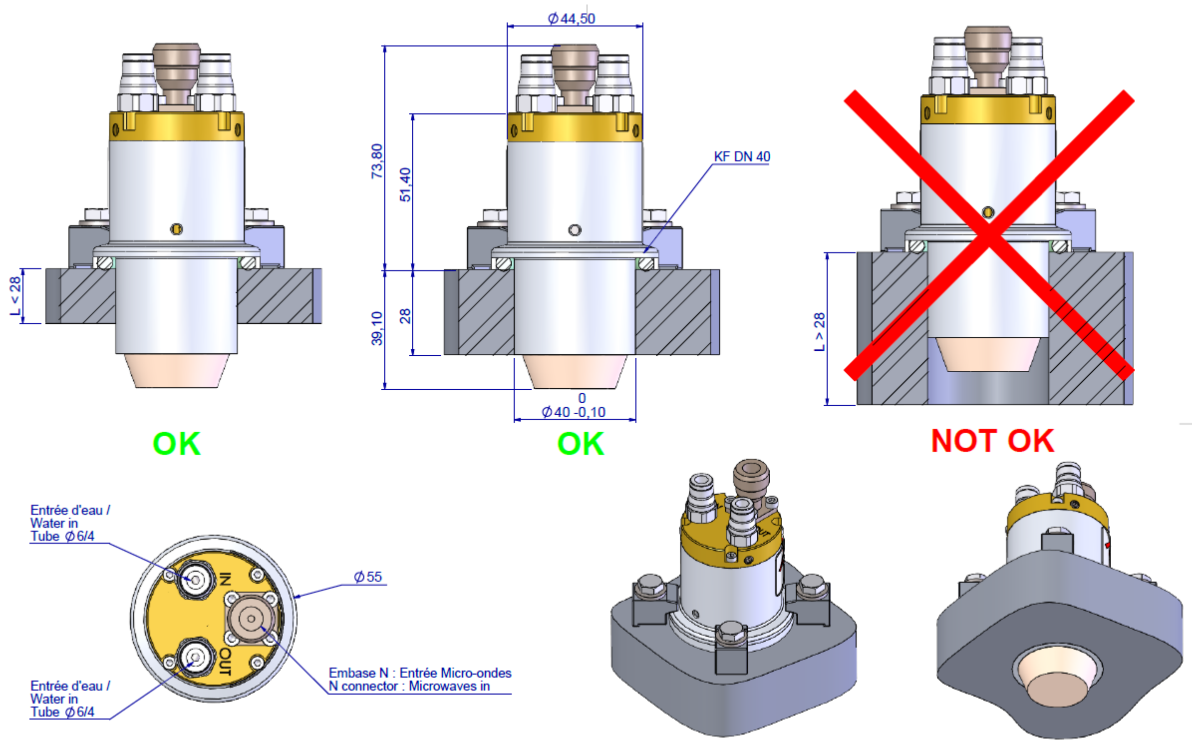
The plasma sources spread a lot; it means that the ion production volume is quite large. An example of plasma density measured by one plasma source at a distance from the source plane d = 14 cm is presented below for pure N_2 at 1 Pa and 400 W. In this case, on 250 mm in diameter (125 mm from the center), the plasma density drops only by 50 %. At lower pressure, diffusion is higher so this diameter is increased.



Density profile measured for one Aura-Wave at d = 14 cm, N_2 – 400 W.



Implementation of the Aura-Wave plasma source.



Implementation of the Hi-Wave plasma source.

Consequently, if the chamber is too small or if the source is confined in a connection flange or a wall (see implementation figures of Aura-Wave and Hi-Wave above), edge effect will appear leading to a quick drop of the density on the wall, creation of reflected power, and an increase of pollution due to wall sputtering. For this reason, we recommend to implement the source at least 150 mm from the wall, i.e., for a single source integration, i.e. in a plasma chamber at least 300 mm in diameter.

Operating pressure depending on the source type and the gas nature

Operating pressure ranges are presented below for both Aura-Wave and Hi-Wave as a function of the gas nature.

Source type	**Gas**	**Operating pressure range (Pa)**
Aura-Wave	H_2, He	0.1 to a few 10s Pa
	O_2, N_2	10^{-2} to a few Pa
	Ar	10^{-2} up to 1 Pa
Hi-Wave	H_2	10 to 100 Pa
	O_2, N_2	A few 10^{-2} to a few 10s Pa
	Ar	A few 10^{-2} to a few Pa

These pressure ranges could vary with measurement gauges and also with number and compactness of the plasma sources in multisource configuration.

Concerning Aura-Wave, from a general point of view, when the pressure is too high the plasma loose its “Aura shape” or “donuts shape” due to magnetic confinement and the plasma start to stick to the alumina. The ECR heating is not any more efficient. The plasma becomes dense, not confined and it leads to an increase of the reflected power (the plasma acts as a sheet of metal).

From a general point of view, whatever the source used, a consequent reflected power increase (5-10 % after frequency scan) means that the source is working in its upper pressure limit.

Water cooling and microwave connections

It is mandatory to cool the plasma sources during processes. At least 1 l/min is necessary to cool each source. Quick connectors for 6 mm OD tubing IN and OUT are implemented on the rear of the source. The flow direction of water should be respected.

The coaxial cable should be well screwed on the N connectors of both the microwave module and the plasma source to prevent arcing.

Scan frequency

After plasma ignition, always perform a frequency scan to decrease reflected power.

Hi-Wave particularity

The Hi-Wave is more efficient than the Aura-Wave in terms of performance (plasma density and reactive species production) as it works at higher pressure. Nevertheless, it is also more delicate to use, indeed collisional heating is less efficient than ECR, and it operates on a shorter pressure window because the plasma is created directly in contact with the alumina (leading to high variation of impedance with pressure). Consequently, it is more difficult to ignite and sustain the plasma. Thus, we strongly recommend not to use the Hi-Wave in single set up. The Hi Wave should be used in a setup of, at least, four sources with their corresponding microwave modules.