

Design and performance of solid-state microwave plasma sources for lab and industrial applications

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INTRODUCTION

Microwaves are frequently used to produce high density plasmas for industrial and laboratory applications. These sources present several advantages when compared to radio-frequency and DC discharges such as high reactive species density and no need for electrodes. Technological advances over the last few years calls for large-scale processing with high density and uniform plasma at reduced and atmospheric pressure.

To meet these industrial requirements **Aura-Wave** [1-2], an electron cyclotron resonance (ECR) coaxial microwave (MW) plasma source working in the 10^{-2} –1 Pa pressure range and **Hi-Wave** [3], a collisional plasma source for higher pressure gas processing, i.e. 1 – 100 Pa have been designed. Each plasma source is powered by its own microwave solid state generator, so multiple sources operating in different conditions (gas type, pressure, MW power) can be distributed together in the same reactor. In this design the solid-state microwave generator can produce a forward wave with variable frequency (2400 MHz – 2500 MHz) which enables an automatic adjustment loop of the reflected power, created occasionally by a change in the operating conditions [4-5].

Atmospheric plasma sources are widely requested in applications such as surface functionalization, elementary analysis, creation of radicals and reactive species as well as a broad use in medicine (sterilization/disinfection, bacterial inactivation, treatment of chronic wounds, etc.). For these purposes, **S-Wave** (a compact plasma source named after “Surface Wave”) has been developed. This plasma source can operate in the range of a few 10^{-2} mbar to atmospheric pressure and is able to create and maintain plasma columns with variable lengths. By positioning the substrate 20 – 30 cm downstream the **S-Wave**, surface treatment by reactive species is possible while avoiding the direct contact with the high temperature plasma column. An ignition system based on dielectric barrier discharge allows to breakdown easily even at atmospheric pressure. **S-Wave** operates optimally in connection with a low ripple 200W or 450W microwave solid-state generator.

METHODOLOGY

The coaxial antenna using the ECR to generate plasma (**Aura-Wave** in Figure 1a) consists of encapsulated cylindrical permanent magnets, mounted in opposition within the coaxial structure. This arrangement enables to generate a magnetic field in the direction of the center of the plasma chamber and hence, limiting losses on the walls. The source was designed to reach plasma densities up to a few 10^{11} cm^{-3} in multisource configuration (Fig. 1b) at 10 cm from the source. The coaxial antenna based on collisional heating called (**Hi-Wave** in Figure 1c) was designed to reach plasma densities of $10^{11}\text{-}10^{12} \text{ cm}^{-3}$ at 10 cm from the source, depending on the gas, in multisource configuration (Figure 1d).

The **S-Wave** plasma source (shown in Figure 1e) is inductively coupled, thus only two tuning adjustments are provided to match the impedance. Generally, nearly 0% of reflected power is achieved using the integrated tuners. The plasma is created in a dielectric tube placed inside the source; the external diameter of the tube is either 6 mm or 8 mm. The microwave electric field propagates longitudinally at the dielectric/plasma interface, i.e. plasma behaves as an electrical conductor; radially the wave is strongly attenuated at skin depth. This principle allows to create and maintain plasma columns with lengths that depend on the operating pressure, microwave power and gas type. For given operator-set discharge conditions, the plasma is fully reproducible without any need for retuning at start-up. Quick connectors are integrated for water cooling and for inlet gas connection.

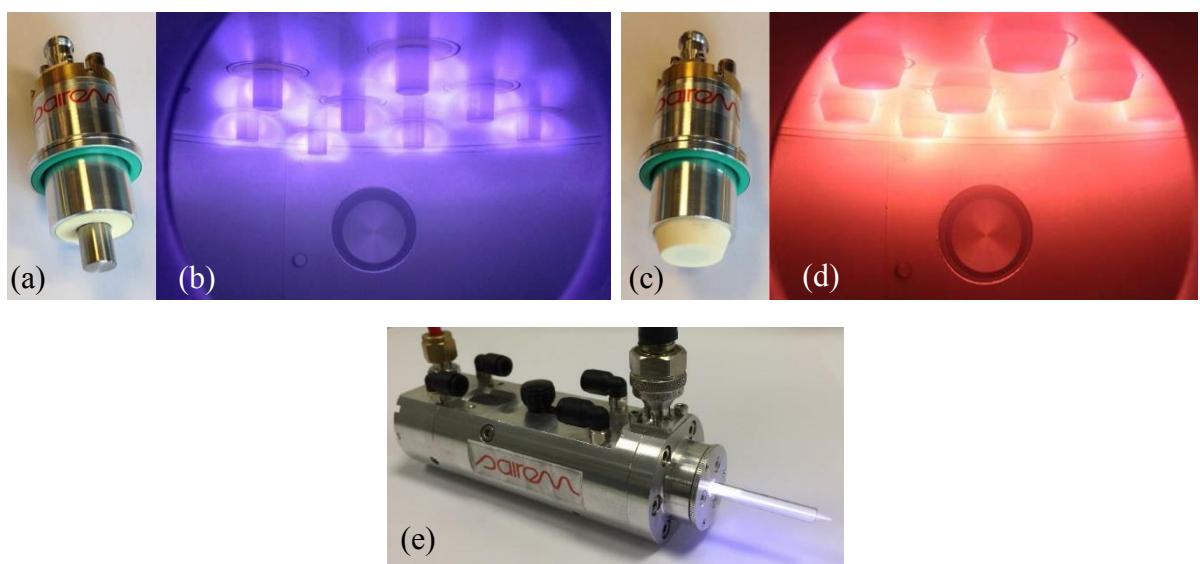


Figure 1. (a) *Aura-Wave* ECR microwave plasma source. (b) Multisource reactor consisting of 8 *Aura-Wave* units (shown in argon for a total microwave power of 160 W at 1 Pa). (c) *Hi-Wave* collisional microwave plasma source. (d) Multisource reactor consisting of 8 *Hi-Wave* units (shown in nitrogen for a total microwave power of 1600 W at 10 Pa). (e) Photo of the atmospheric plasma created by *S-Wave* (without ignition system). Argon, microwave power 200 W.

RESULTS

Plasma parameters - plasma density, electron temperature and uniformity - were measured with a Langmuir probe placed at two heights, $d = 85$ mm and $d = 160$ mm from the plasma sources. In circular matrix, 8 off \times Hi-Wave plasma sources were tested - see the source positioning in the inset of Figure 2(a). The diameter of the circular configuration is 247 mm; 200 W of microwave power supplied to each source, pressure 5 Pa. The plasma density profiles are plotted in Figure 2 for O₂. Plasma uniformity of 1.65 % at $d = 85$ mm and 1.8 % at $d = 160$ mm over 250 mm area diameter was measured. The Optical Emission Spectroscopy (OES) measurements were performed to see the dependence of reactive species line emission on the forward power which has proven to be linear, as shown in Figure 3(b). Optical emission not showing the plateau indicates that the plasma density has not reached the saturation and can be further increased by increasing the forward MW power.

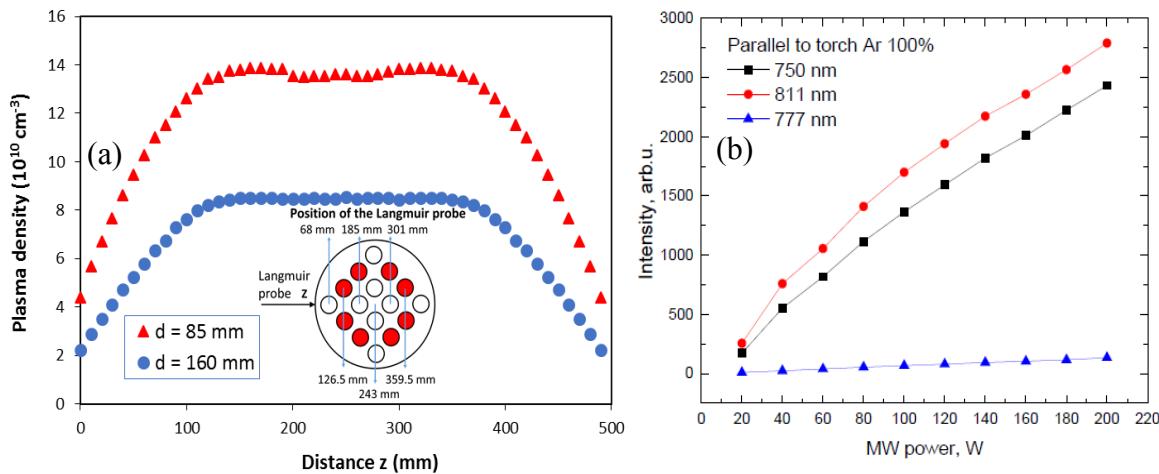


Figure 2. (a) Oxygen plasma distribution uniformity vs. distance and diameter at $d = 85$ mm and $d = 160$ mm from the Hi-wave sources. (b) Evolution of Ar and O₂ emission lines as a function of MW power measured in pure Ar plasma. Fiber orientation: parallel to the torch.

The additional OES measurement have been carried out with USB Verity SD 2048 (200-800nm) spectrometer in order to analyze the spatial distribution of selected argon and nitrogen emission lines. The orientation of the fiber was perpendicular to the plasma jet. The experimental conditions were the following: argon (99.995% purity), gas flux 1.4 l/min, absorbed MW power 100W. Whereas the intensity of Ar atomic emission fades-off at the exit of the dielectric tube as shown in Figure 3(a), the N₂ emission has a maximum at around 8mm from the tube due to interaction with ambient air (see Figure 3(b)). The radiative de-excitation of other species like O, H and OH (hydroxyle) at 8mm from the quartz tube exit (not shown) indicates presence of the region reach in interactions. The demonstrated OE

spectra were correlated with the optical camera images (PIMAX-2K-RB, Pearson Instruments, spectral range 195–920 nm) with the respective filtering applied to the emission lines of interest, confirming the previous observations (Figure 3(c,d)).

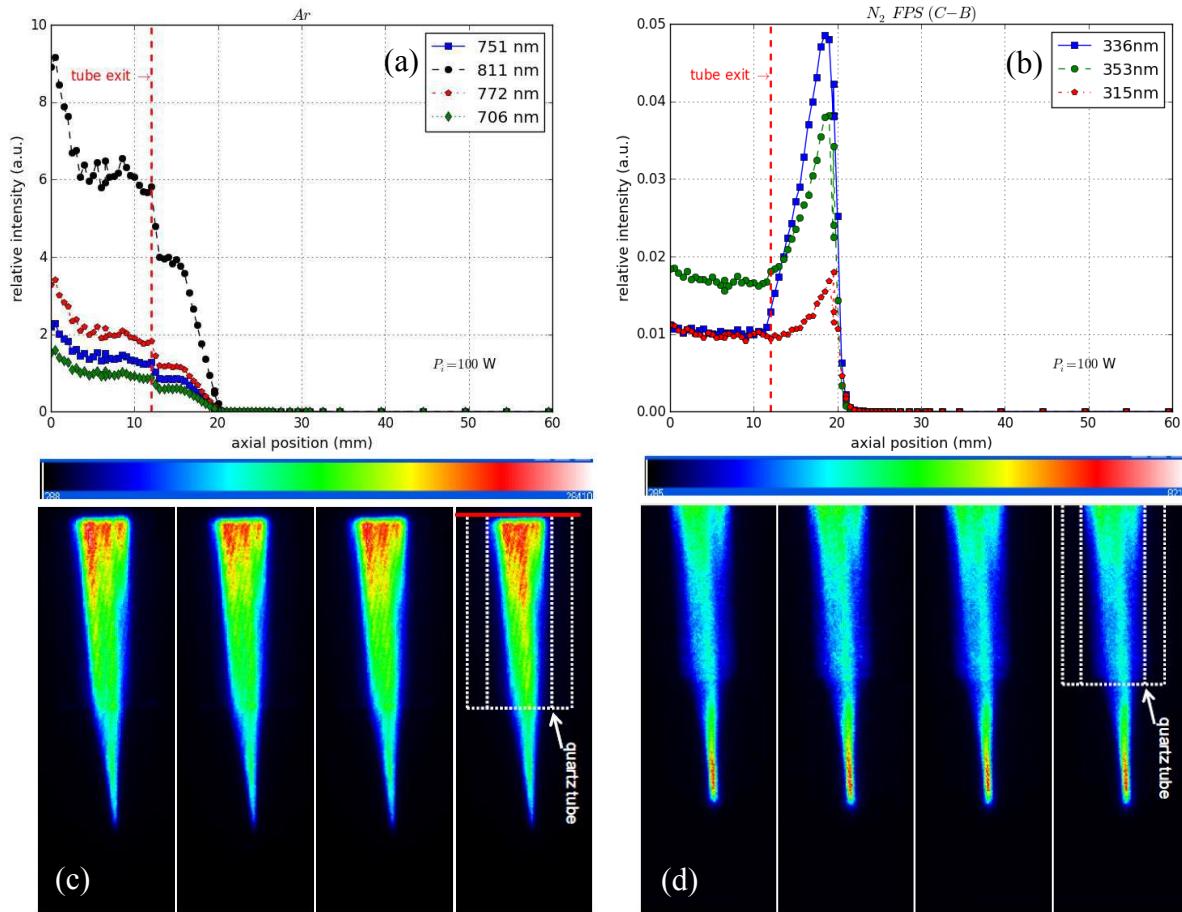


Figure 3. (a,b) Optical emission spectra of Ar and N_2 lines (see insets) as a function of the plasma axial position. The tube exit position is shown by a red dashed line. (c,d) Filtered spatio-temporal evolution of Ar 811nm line (c) and N_2 379-393-399nm emission lines (d). Gate open time $1\mu\text{s}$, with 26ns interval between images.

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