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Microwave Plasma Simulation Applied to a Double ICP Jet Reactor

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Abstract: Inductively coupled plasma (ICP) reactors are usually meter sized and driven at RF frequencies, for example at 13.56 MHz. We developed a miniature resonator allowing an inductive type of coupling of microwaves at 2.45 GHz to a plasma jet, flowing in ceramic tubes. Previous experiments and simulations [1] show an efficient energy transfer of microwaves to plasma of about 80 %. The new development of our ICP structure contains two ceramic tubes and a symmetrical arrangement of two resonators. The present paper concentrates on a study of this plasma source, considering the complex interaction of the electromagnetic field with the plasma and the gas flow, using the plasma module of Comsol. This module gives a realistic picture when the gas pressure is higher than 1000 Pa but fails for values of 1…10 Pa, which is just our range of operation.

Keywords: ICP, microplasma, plasma jet.

1. Introduction

ICP reactors are intended to produce plasma without contact of metallic electrodes with plasma and without ionization mechanism on isolating or conducting walls. Consequently the plasma generated has a high degree of purity. Even when driven at RF frequencies, the penetration depth of the electromagnetic field is relatively small compared with the full depth of the plasma volume. The newly created free electrons reach the center of the plasma volume through diffusion rather than by directly excitation at that place. Even for such RF arrangement, the voltage across the coil may generate undesired capacitively coupled plasma (CCP). Such situation is avoided by a special screening.

The use of microwaves for an ICP source requires an adequate volume where the plasma is generated. The penetration depth has to be comparable with the size of the plasma.

A very economical source is a microwave (2.45 GHz) driven ICP jet produced in a ceramic tube. Using a power of 10-50 W one can create for example an atomic oxygen flux of 10^{16} atoms/s/cm^3 [1]. An array of such sources may replace the kW-power RF-ICP reactor, where plasma is produced in a large volume. Such reactors are currently used in the semiconductor technology.

Our miniature ICP sources have been tested until now with O_2, Ar, H_2, N_2 and He plasmas.

2. Single ICP sources

We performed a large number of experiments and simulations on various ICP sources having one ceramic tube with an external diameter of 3 or 7 mm. All sources consist of a one-turn-coil and a capacitor. The new double ICP is only in the simulation stage. Fig. 1 presents two examples of ICP sources, generating oxygen plasma.

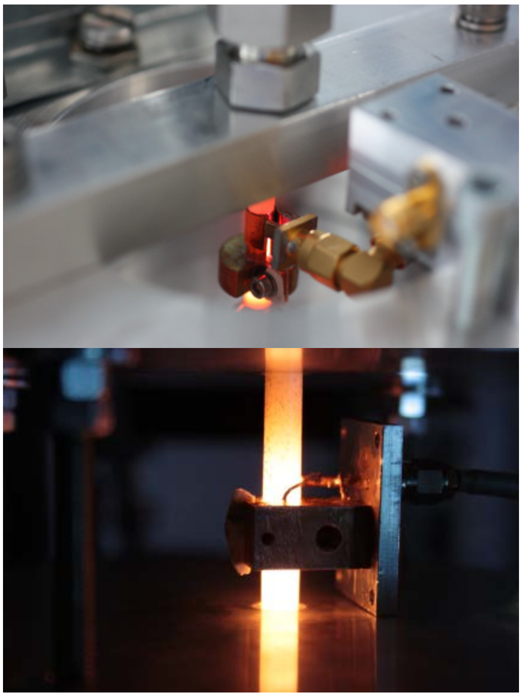

Figure 1. ICP sources generating oxygen plasma jet in a ceramic tube. Top: The 3 mm source, the size of the resonator is 15 mm diameter and 6+10 mm height. Bottom: the 7 mm source, having a thickness of 12 mm.

Depending on the microwave power, the 7 mm source exhibits two regimes of operation: a “CCP” regime, where the discharge takes place in a region of the tube close to the capacitor plates, and an “ICP” regime, in which plasma is generated homogeneously in the volume of the tube. Fig. 2 shows the two regimes of the plasma.

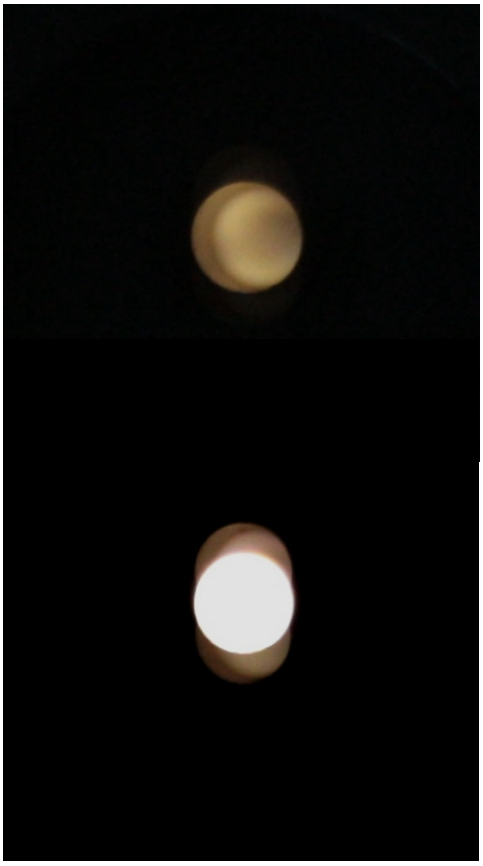

Figure 2. Photographs of the plasma jet from the bottom of the ceramic tube, both with the same exposure time. Top: “CCP” regime with partially filled tube, bottom: “ICP” regime with intense plasma and homogeneously filled tube.

Using a simple RLC lumped equivalent circuit model we can estimate the absorbed power in the plasma and in the metallic resonator. The diagrams in Fig. 3 show the behavior of the resonator at different powers. Although plasma is less dense in the “CCP” regime and has low light intensity, it appears like very small impedance parallel with the RLC resonator. On the Smith diagram the loaded resonator is quasi short-circuited by such a plasma. On the contrary, in the “ICP” regime the microwave equivalent impedance of the plasma is higher, the loaded resonator matches with its impedance the oscillator resonance and therefore the microwave power transfer is optimal. This feature still has to be understood theoretically.

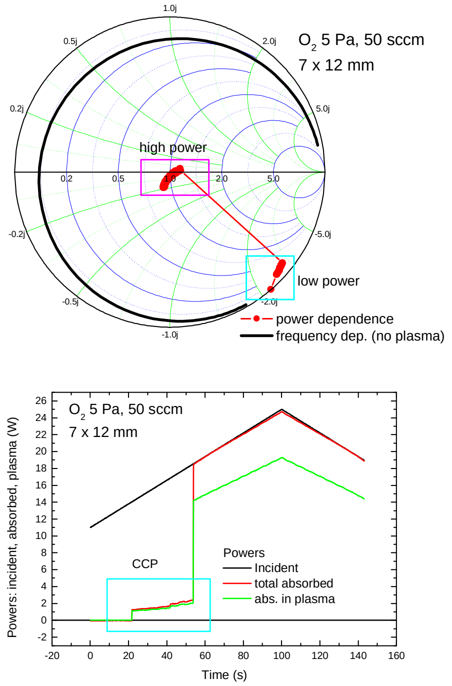

Figure 3. Top: frequency and power dependence of the S_{11} parameter for the 7 mm ICP source generating oxygen plasma. At low power (“CCP”) the ICP resonator is short-circuited by plasma, while at high power (“ICP”) it is well matched with the generator. Bottom: power balance of the system showing how much of the incident and total absorbed power is transferred to plasma.

3. Double ICP source

The single ICP source is not suitable for building arrays due to its asymmetric shape. Moreover, the screening of such a simple ICP resonator requires a relatively large volume in front of the capacitor in order to prevent a large detuning of the resonator. Therefore we developed a double ICP resonator.

The geometrical arrangement is presented in Fig. 4. There is only one common capacitor for the two coils. The coaxial coupling is realized on the plates of the capacitor.

3.1 RF analysis

The primary analysis of this resonator has been performed using the RF module of Comsol. The main information concerns the matching property, the Q-factor and the resonance frequency for different homogeneously distributed conductivities of the plasma. Knowing the resonance frequency as a function of plasma conductivity, one can set up the plasma module of Comsol.

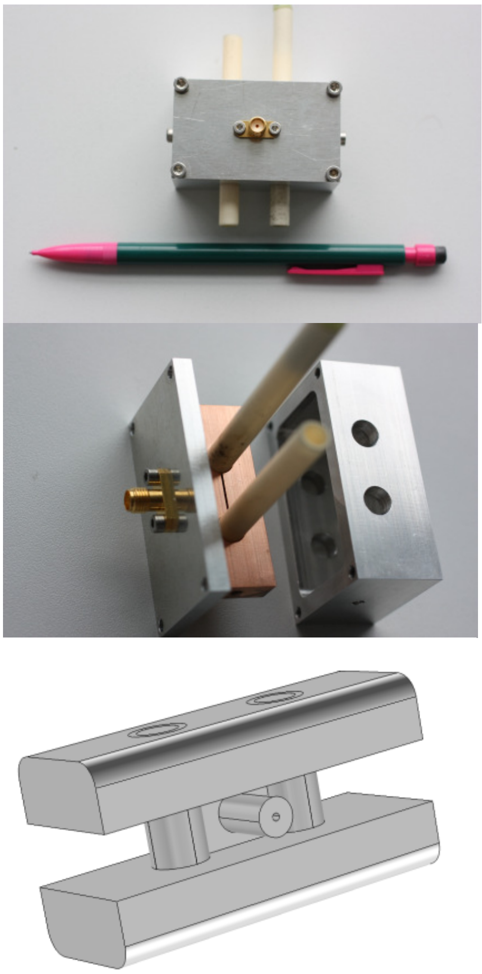

Figure 4. Top: photographs of the practical realization of the double ICP resonator. Bottom: Comsol geometry illustrated by the external view of the inner surface.

Fig. 5 shows the S_{11}-parameter, the Q-factor and resonance frequency dependence on the plasma conductivity considered as homogeneous in the whole volume of the tube. The ideal uncoupled and unscreened resonator radiates slightly. Therefore, if the "screening" consists of a perfectly matched layer (PML) the corresponding Q factor is slightly lower (green dashed line compared with the black dashed line, corresponding to the perfect electric conductor (PEC) screening). However, if the resonator is coupled to the 50 Ω generator the situation is reversed. Especially for the low conducting plasma during the ignition, the Q-factor for the unscreened resonator (solid green line) is much higher. This feature is experimentally confirmed by the single ICP structure. Presently, we try to optimize the structure so that the screened resonator has a similarly high Q-factor as in the unscreened case.

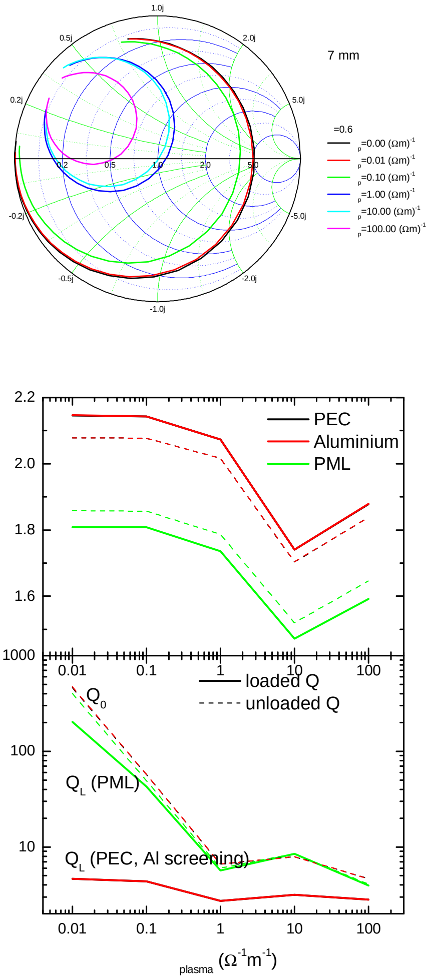

Figure 5. Top: Smith diagram showing the resonance curves for different plasma conductivities. Ideal matching occurs for relatively high plasma conductivity, σ=1 - 10 $(\Omega m)^{-1}$.
Bottom: the dependence for the Q-factor and resonance frequency.

Fig. 6 presents the electric and magnetic field distributions. As expected, the electric field has its highest intensity between the capacitor plates and the magnetic field lines close between the two coils.

For a homogeneous conductivity of plasma of 1-10 $(\Omega m)^{-1}$, we expect a relatively good matching of the resonator with the generator. In this case the resonance frequency is about 2.0 GHz. We chose for the plasma transient analysis a fixed driving frequency of 2.08 GHz.

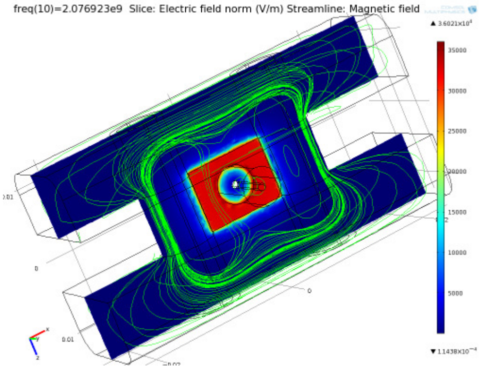

Figure 6. Slice: normalized electric field distribution. Green streamline: magnetic field lines in the double ICP resonator.

3.2 Plasma analysis

The numerical analysis was performed for different conditions, considering various microwave powers, gas pressures, and gas flow rates for Argon. Generally, the plasma module does not reach the convergence for times longer than 10^{-6} s. We considered a stationary gas flow defined by the gas pressure and the flow rate. For plasma, we used the microwave plasma module, which considers the interdependence of the Maxwell equations with particle and energy conservation.

Changing the microwave input power, according to the model only the delay of the ignition changes. No sudden jump from one mode to the other is predicted like that observed in measurements in Fig. 3.

Fig. 7 presents the time evolution of the S_{11} parameter for different powers.

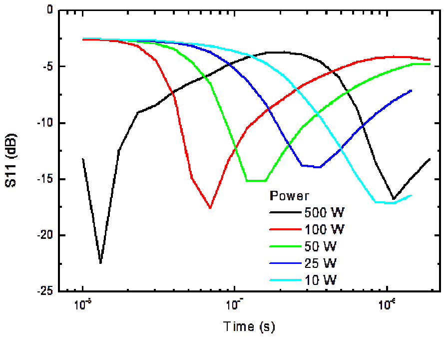

Figure 7. Time evolution of the S_{11} parameter as a function of microwave power.

The time evolution of the electron density and other parameters was studied in detail. For example, for an input power of 500 W one observes the evolution of the electron density from 10^{19} m^{-3} at t=10^{-8} s to 10^{21} m^{-3} at t=10^{-6} s (Fig. 8). Inspecting the spatial distribution of the free electrons and of the current density, one may conclude that the plasma is initially in the "CCP"-state and after 10^{-6} s it reaches the "ICP"-state.

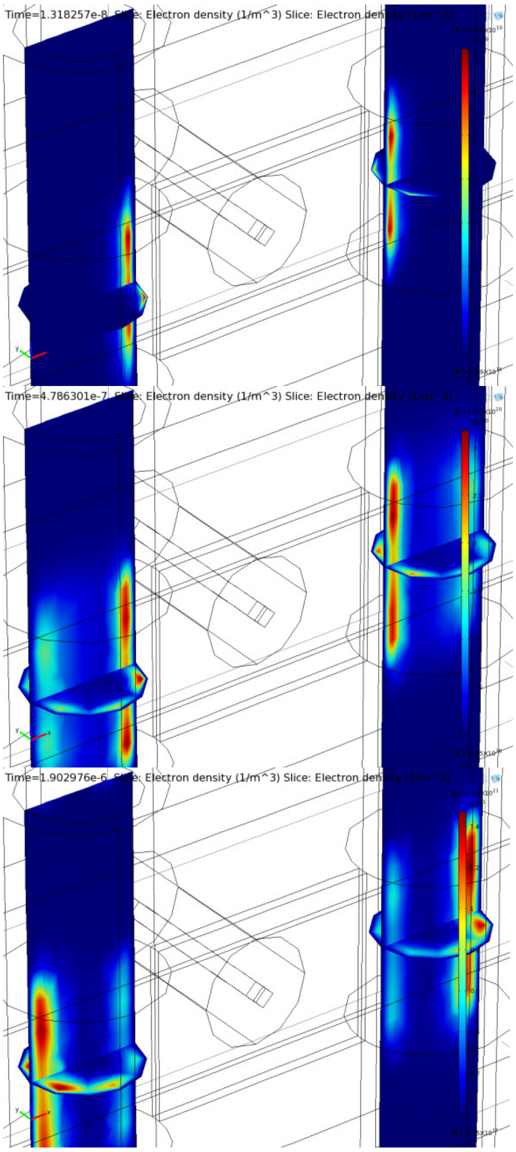

Figure 8. Time evolution of the electron density for P=500 W and a gas flow of 10^{-2} m^3/s.
Top: t=1.3 10^{-8} s, $n_{e,max}$=4 10^{19} m^{-3}.
Middle: t=5 10^{-7} s, $n_{e,max}$=3 10^{20} m^{-3}.
Bottom: t=2 10-6 s, $n_{e,max}$=1.5 10^{21} m^{-3}.

The electron density forms a hollow cylinder for a gas flow of 10^{-2} m^3/s. Fig. 9 demonstrates that by decreasing the gas flow from 10^{-2} m^3/s to 10^{-4} m^3/s the electron density transforms from a hollow to a full cylinder. This is confirmed by our experiments.

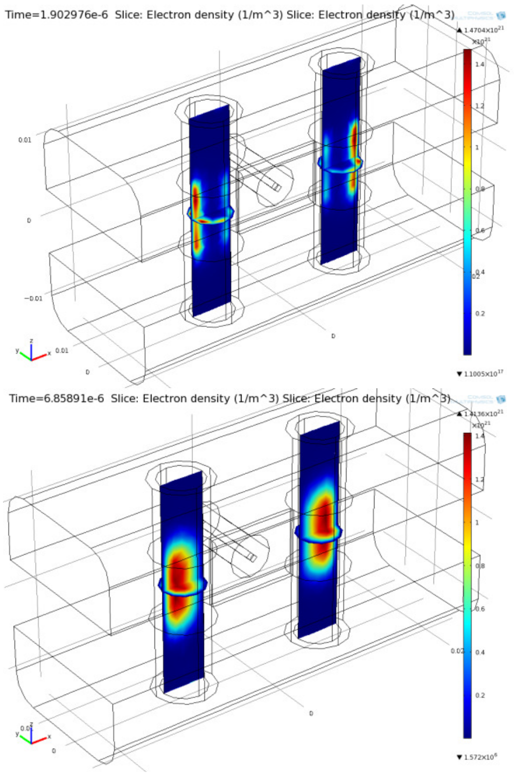

Figure 9. Electron density as a function of the gas flow after 10^{-6} s. Top: 10^{-2} m^3/s, bottom: 10^{-4} m^3/s

3.3 Plasma simulation for pressures < 10 Pa

We tried to use the plasma module for different pressures, especially in the range we are interested in, i.e., 1…10 Pa. It turns out that even for very high microwave powers (5000 W) the electron density decreases just in front of the coil (Fig. 10), which does not agree with the experimental findings.

4. Conclusions

We find that our RF simulations using Comsol give results that are in agreement with experiment. For the plasma module, situation is different. In some cases we studied qualitative agreement is found, in other cases (unfortunately just those we are interested in here) simulations yield physically incorrect results.

5. Acknowledgements

We acknowledge useful discussions, consulting and help of Prof. Dr. Klaus Wandel and of Dipl. Ing. Silvio Kühn.

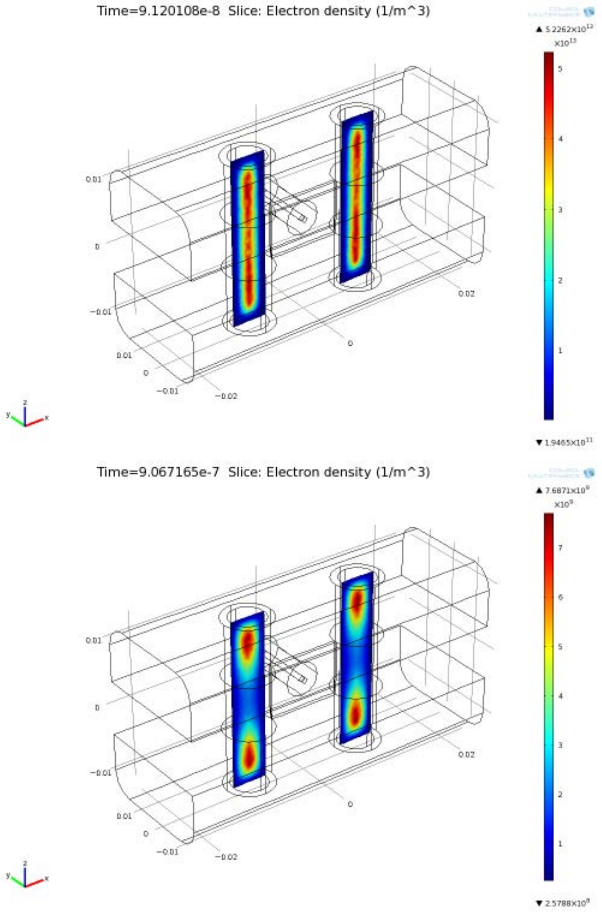

Figure 10. Unusual decrease of the electron density as a function of time for a pressure of 10 Pa. Top: $t=10^{-7}$ s, $n_{e,max}=5\ 10^{13}$ m^{-3}.
Bottom: $t=10^{-6}$ s, $n_{e,max}=8\ 10^{9}$ m^{-3}.

6. References

1. H.-E. Porteanu, S. Kühn, R. Gesche, and K. Wandel, „ICP Mikroplasmaquelle für die erzeugung von Sauerstoff Plasma“, Plasma Technology Conference PT 15, Stuttgart 2011.