Microwave Plasma Simulation Applied to a Double ICP Jet Reactor

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Outline

1. ICP sources, development, structure
2. RF Simulation: Q-factor, matching impedance
3. Plasma simulation for $p=10$ mbar realistic results
4. Plasma simulation for $p=0.1$ mbar, not realistic results
5. Conclusions
Microwave Sources for Inductively Coupled Plasma (I)

3 mm tube

Single ICP

7 mm tube
Microwave Sources for Inductively Coupled Plasma (II)

Double ICP
Microwave Sources for Inductively Coupled Plasma (II)
RF Simulation (I)

RF coupling

Resistive losses

Surface current density
RF Simulation (II)

Behavior of the resonator for homogeneous plasma conductivity

$\alpha = 0.6 \pi$

- $\sigma_p = 0.00 \, (\Omega \text{m})^{-1}$
- $\sigma_p = 0.01 \, (\Omega \text{m})^{-1}$
- $\sigma_p = 0.10 \, (\Omega \text{m})^{-1}$
- $\sigma_p = 1.00 \, (\Omega \text{m})^{-1}$
- $\sigma_p = 10.00 \, (\Omega \text{m})^{-1}$
- $\sigma_p = 100.00 \, (\Omega \text{m})^{-1}$

7 mm

$Q_0 \sim 2000$ (without plasma and influence of the VNA)
RF Simulation (III)

Ideal matching for \( \sigma_{\text{plasma}} = 1 \ (\Omega \text{m})^{-1} \)

\[ \sigma_{\text{plasma}} = 1 \ (\Omega \text{m})^{-1} \]
Plasma Simulation (I): Plasma Parameters

- Electron Temperature
- E and H Fields
- Electron Density
- Electron Potential
Plasma Simulation (II)

Power Dependence of the plasma ignition

\( p=10 \text{ mbar}, \ n_{\text{e, ini}}=10^{14} - 10^{15} \text{ m}^{-3}, \) gas flow=10\(^{-2}\) m\(^3\)/s
Plasma Simulation (II)
Experimental results on transients
Plasma Simulation (III)

Time dependence of the plasma ignition,
P=500 W, p=10 mbar, $n_{e\text{ ini}}=10^{14} - 10^{15}$ m$^{-3}$, gas flow=$10^{-2}$ m$^3$/s

$t=10^{-8}$ s, $n_e=4 \times 10^{19}$ m$^{-3}$

$t=5 \times 10^{-7}$ s, $n_e=3 \times 10^{20}$ m$^{-3}$

$t=2 \times 10^{-6}$ s, $n_e=1.5 \times 10^{21}$ m$^{-3}$
Plasma Simulation (IV)

Gas flow dependence,
P=500 W, p=10 mbar, \( n_e^{\text{ini}} = 10^{14} \text{ m}^{-3} \), Gas Flow= 10\(^{-4}\) - 10\(^{-2}\) m\(^3\)/s

t=2 \( 10^{-6}\) s, \( n_e = 1.5 \times 10^{21} \text{ m}^{-3} \), \( \Gamma = 10^{-2} \text{ m}^3/\text{s} \)

For \( \Gamma = 10^{-2} \text{ m}^3/\text{s} \)
No convergence after t=2 \( 10^{-6}\) s

\( t=7 \times 10^{-6}\) s, \( n_e = 1.4 \times 10^{21} \text{ m}^{-3} \), \( \Gamma = 10^{-4} \text{ m}^3/\text{s} \)

Simulations qualitatively confirmed by experiment
Plasma Simulation (V)

Low pressure behavior, with gas flow
\( p = 0.1 \text{ mbar}, P = 30 - 5000 \text{ W}, n_{e \text{ ini}} = 10^{14} \text{ m}^{-3}, \text{ gas flow} = 10^{-4} \text{ m}^{3}/\text{s} \)

No physical results!

Even for \( P = 5000 \text{ W} \) and \( n_{e \text{ ini}} = 10^{18} \text{ m}^{-3} \) the electron density decreases. The electron density is the smallest in the center of the resonator.
Plasma Simulation (VI)

Low pressure, no gas flow (no gas flow module, only plasma module)
p=0.1 mbar, P=50 W, \( n_{e \text{ini}}=10^{14} \text{ m}^{-3} \),
No physical results!

\[ t=1 \times 10^{-7} \text{ s}, \ n_e=5 \times 10^{13} \text{ m}^{-3} \]

\[ t=1 \times 10^{-6} \text{ s}, \ n_e=8 \times 10^{9} \text{ m}^{-3} \]

Even a finer Mesh (here „extra fine“) does not help neither for better convergence nor for correct physics
Conclusions

1. One can calculate a time evolution of the ignition process for a pressure of 10 mbar
2. According to simulations for Argon it should appear an ICP modus only over 100 W
3. For a pressure of 0.1 mbar it seems to be no interaction between microwaves and plasma. The results are physically not realistic.
4. A finer mesh does not improve neither the convergence nor the physics.