Plasma density measurement using a surface-wave transmission probe

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1 Introduction

- A new technique for measuring the absolute electron densities in low-pressure plasmas using microwaves is described [1].
- It is based on observing the propagation of electromagnetic surface waves (SW) at the plasma-sheath boundary, guided by a dielectric cylinder immersed in the plasma.
- The transmission spectrum is measured between two antennas situated at either end of the dielectric cylinder and connected to a network analyser.
- The lowest frequency at which the surface waves can propagate is equal to $1/\sqrt{2}$ of the plasma frequency ω_p, which is directly related to the electron number density n_e.
- We call this probe the Plasma Transmission Probe (PTP) in contrast to the Plasma Absorption Probe (PAP) proposed by Sugai and co-workers [2].

2 Experimental set-up

- A schematic drawing of the first PTP, seen from above, is shown in Fig. 1. The probe head (see Fig. 1a) consists of a teflon (relative dielectric constant $\epsilon_r = 2.07$) cylinder of 1.67 mm diameter into which antennas of length $d = 1.4$ mm are inserted at either end. The teflon cylinder ensures the continuity of the plasma-sheath boundary from one antenna to the other, excluding plasma.

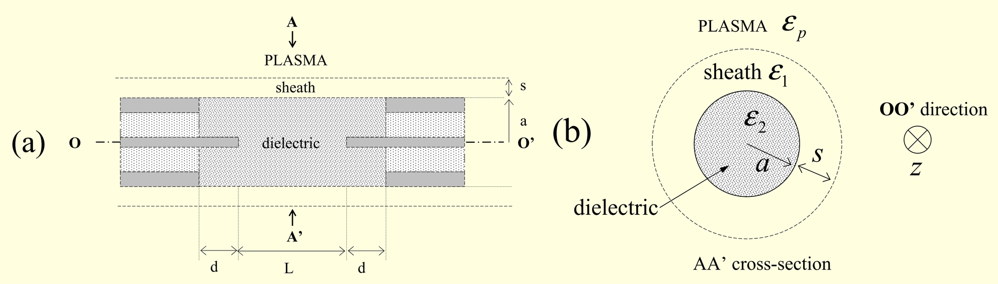

Fig. 1
Schematic of the PTP head — *Cross-section between antennas*

- Experimental transmission spectra were measured in a CCP discharge in argon (40.68 MHz) at various plasma densities and pressures (40–750 mTorr). Plasma density was also measured in an ICP discharge in argon at 5 mTorr and compared with the one measured with a microwave 1/4-wave resonator (hairpin probe [3]). A second PTP was used (see Fig. 2b).

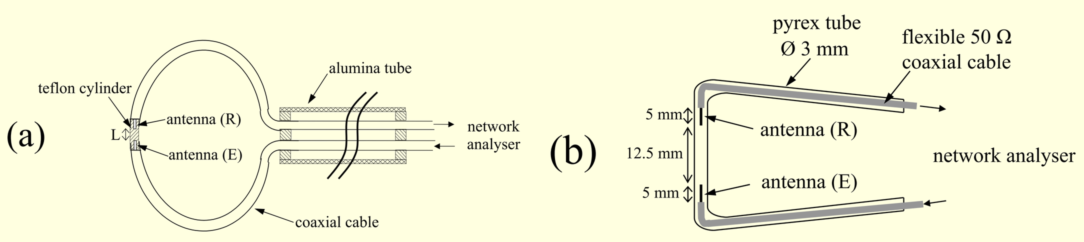

Fig. 2
First plasma transmission probe used in CCP — *Second plasma transmission probe used in a ICP*

3 Theory and model

- Analytical theory based on the work of Trivelpiece-Gould [4] indicates that the lowest frequency at which surface waves can propagate is equal to plasma-vacuum resonance frequency $f_{res} = f_{pe}/\sqrt{2}$.
- This latter frequency is directly related to the electron density by the relation : $n_e = 2.5 \times 10^{10} f_{res}^2$, where n_e is the plasma density in cm^{-3} and f_{res} the SW resonance frequency given in GHz.
- Using the *electrostatic approximation* and treating the plasma as an unlossy dielectric, Kokura et al [2] have shown that SW propagating along the direction OO' (see Fig. 1b) can be guided by the plasma-sheath boundary.
- Calculated normalized dispersion relations of the first three azimuthal SW modes ($n_e = 10^{10}$ cm^{-3}, $s = 5$ mm, $a = 1$ mm) are shown in Fig. 3a for two different dielectric between antennas (teflon or vacuum).

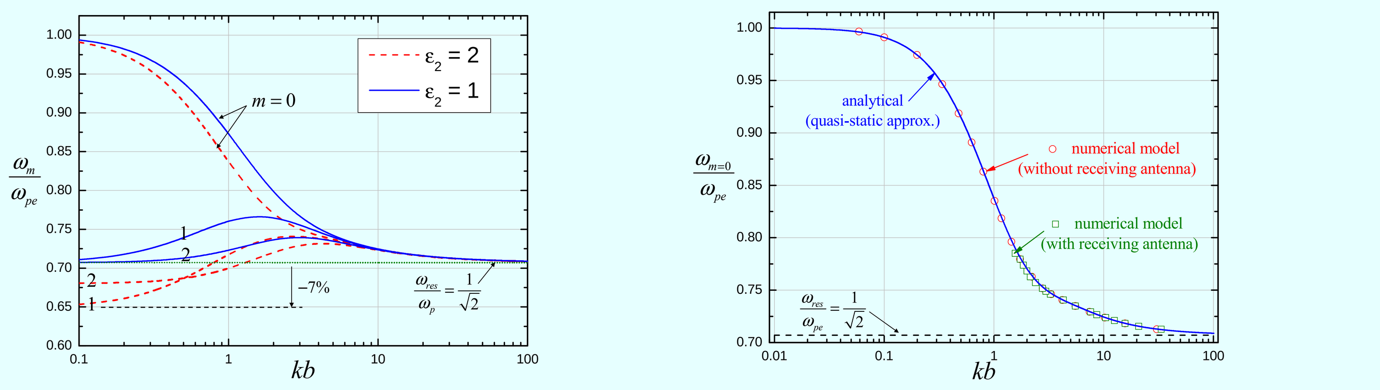

Fig. 3
Analytical dispersion relations — *Numerical and analytical dispersion relation (TM, $m = 0$, unlossy plasma)*

- For $\epsilon_2 = 1$, waves are excited between $f_{pe}/\sqrt{2}$ and f_{pe}. Therefore the transmitted power should increase abruptly for frequencies above $f_{pe}/\sqrt{2}$ and decrease above f_{pe} during the frequency swept. For $\epsilon_2 = 2$ (teflon), the resonance frequency for $m = 0$ is unchanged, but the higher order modes can propagate at frequencies slightly lower than $f_{pe}/\sqrt{2}$. However in a good axi-symmetrical system, excitation of such modes is not expected.
- An axi-symmetric finite element model of the probe was used to calculate transmission spectra where the plasma is treated as a lossy dielectric.
- The overall model geometry is shown in Fig. 4a. An incident TEM wave is injected at the input of the cable connected to the emitting antenna (E). The *full set of Maxwell's equations* is then solved numerically by the FEM method using a commercial software package (FEMLAB). The solution was assumed to be a transverse magnetic (TM) wave. Due to the axial symmetry, only the azimuthal mode $m = 0$ is allowed. Amplitude of the calculated EM field is shown in Fig. 4b in an unlossy plasma for 20 dBm input power between f_{res} and f_{pe} ($f = 0.655$ GHz, $n_e = 10^{10}$ cm^{-3}, $f_{res} = 0.64$ GHz, $s = 5$ mm, $a = 1$ mm).

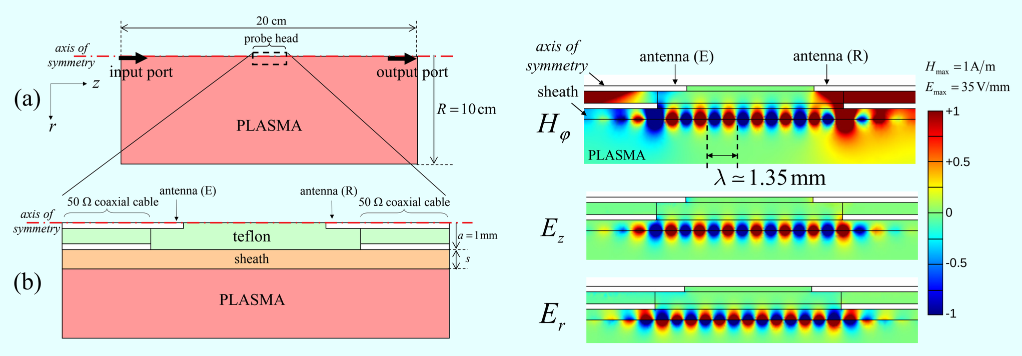

Fig. 4
Overall model geometry and prope head close-up — *Amplitude of the EM fields between f_{res} and f_{pe}*

- A TM ($m = 0$) SW mode excited, guided by the plasma-sheath boundary between antennas is clearly identified on Fig. 4b. The wavelength can be derived from the field amplitudes. Thus, the dispersion relation calculated with the full set of Maxwell equations can be determined and compared with the analytical results using the electrostatic approximation in Fig. 3b. A very good agreement is found between the analytical and numerical results justifying the calculated dispersion relation and the use of the electrostatic approximation.

4 Experimental results

- A typical transmission coefficient spectrum measured in the CCP discharge is shown in Fig. 5a, for an argon pressure of 40 mTorr and an RF power of 50 W. The spectrum is characterized by the presence of an intense peak between 0.9 GHz and 1.3 GHz.
- The threshold frequency above which transmitted microwave power significantly increases is assumed to be equal to the plasma-vacuum SW resonance frequency $f_{res} = f_{pe}/\sqrt{2}$. The plasma density is then derived ($n_e \simeq 2.10^{10}$ cm^{-3}) using the above formula. The transmission coefficient spectrum was calculated with the finite element model and is compared to the measured one on the same figure. Both frequencies $f_{pe} = 1.28$ GHz and $f_{pe} = 0.91$ GHz are indicated with dashed vertical lines.

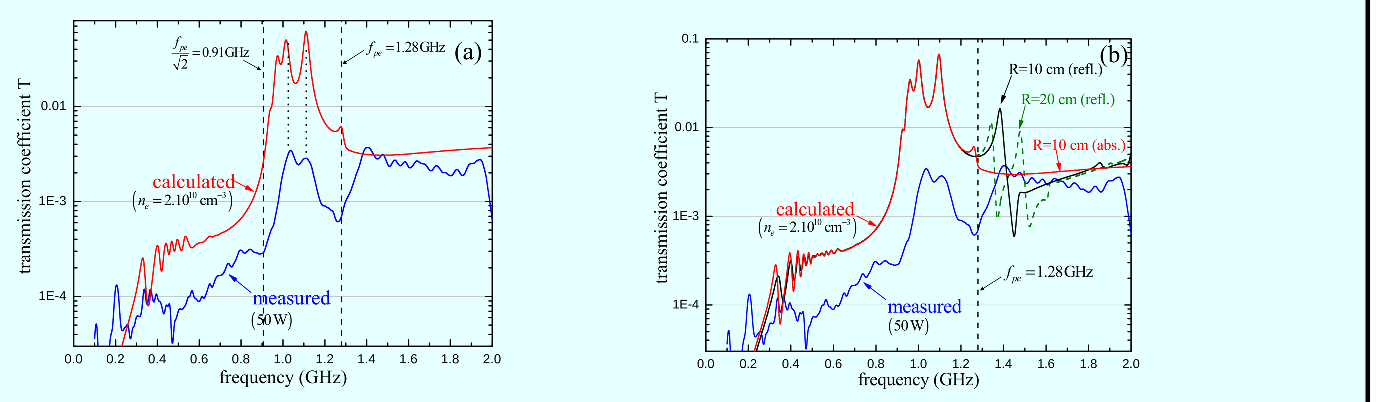

Fig. 5
Comparison between the measured and calculated spectrum Effect of probe environment (model size R and boundary conditions)

- Reasonable agreement is found despite some differences above the plasma frequency. The difference between the experimental and model spectra above the f_{pe} can be attributed to external factor. The transmission spectra calculated with different model radii R or boundary conditions (absorbing or reflecting) at the model radial boundary are shown on Fig. 5b.
- Figure 6a shows how the spectra change when the plasma density is increased by increasing the RF power in argon at 40 mTorr. The calculated transmission coefficient spectra shown in Fig. 6b were calculated at 40 mTorr using the determined densities as described previously.

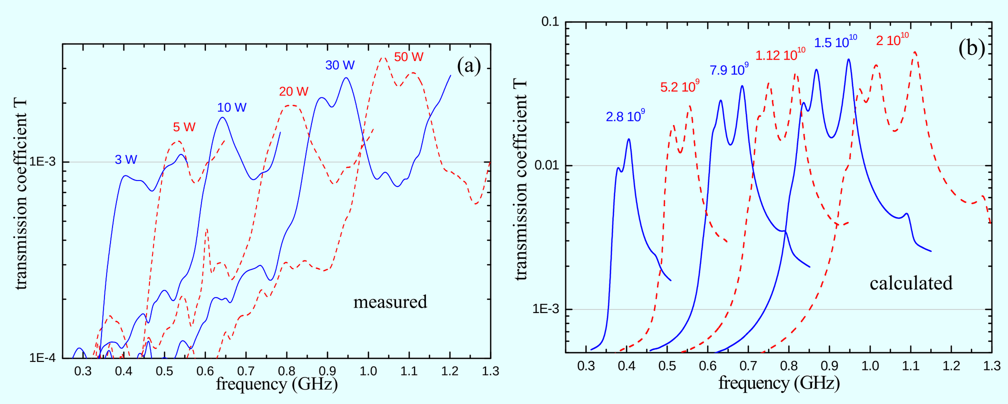

Fig. 6
Plasma density (or RF power) dependency in argon 40 mTorr (a) measured and (b) calculated

- The pressure dependence (40–750 mTorr) at constant plasma density of the transmitted power spectrum is shown on Fig. 7. The peaks due to resonances are not discernible at higher gas pressures and lower density, and cannot be used to derive the plasma density as in the PAP technique. The direct measurement of the plasma frequency becomes difficult at low density or high pressure, whereas the detection of f_{res}, remains possible. The decrease of the transmission with decreasing electron density or with increasing gas pressure is due to the decrease of the plasma conductivity. This attenuation can be mitigated by increasing the emitted microwave power.

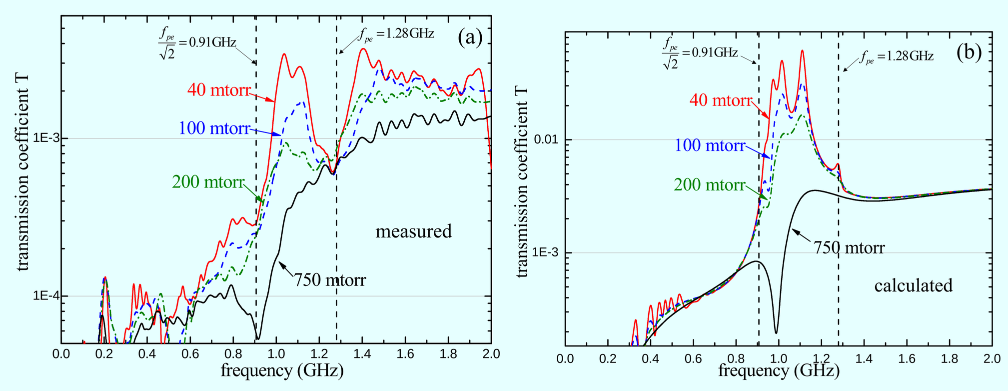

Fig. 7
Pressure dependency (40–750 mTorr) of the transmission coefficient spectrum at constant plasma density in argon (a) measured (RF power $\simeq$ 50 W) and (b) calculated ($n_e = 2.10^{10}$ cm^{-3}).

- A comparison of the plasma densities determined with the PTP and with the hairpin probe in the ICP is shown in Fig. 8a. The ratio of the measurements is shown in Fig. 8b. The ratio is constant and less than 1. The discrepancy between the PTP and hairpin probe is that the PTP is mainly sensitive to the plasma density at the plasma-sheath boundary. The EM fields of surface waves are evanescent in the plasma. The measured SW resonance frequency is therefore *dependent on the plasma density at the plasma-sheath boundary*, which is known to be less than the plasma density in the bulk.

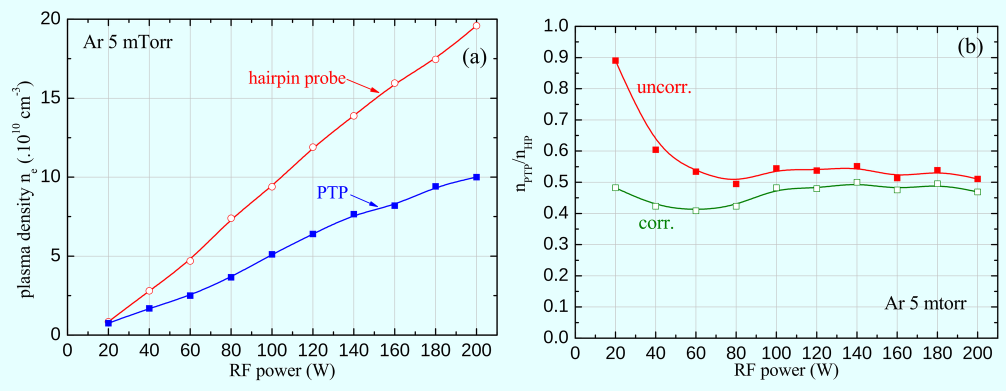

Fig. 8
Comparison of high plasma densities measured with a hairpin probe and a PTP versus RF power in argon at 5mTorr.

5 Conclusions

- A new microwave technique for measuring the local electron density in plasmas has been developed, based on a SW probe used in transmission.
- This probe, which we call the PTP, is promising for the measurement of relatively low plasma density ($\geq 10^9$ cm^{-3}) at higher pressure (≤ 1 Torr).
- The determination of the plasma density is based on the direct determination of the resonance frequency of a SW propagating along the plasma sheath interface surrounding the probe, which is directly related to the plasma frequency, i.e. the plasma density.
- The effect of the plasma density distribution around the probe, the sheath thickness and the permittivity of the dielectric cylinder have been investigated using both modeling and experiments and will be discussed in a further publication.

References

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