A numerical and experimental study of the curling probe: application to electron density measurements in ECR and ICP plasma sources

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Introduction

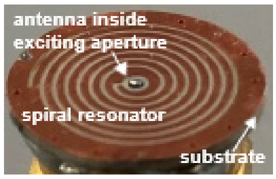


Figure 1: *One of the manufactured CPs.*

The diagnosis of plasma parameters, such as the electron density and temperature, is a key issue in understanding and controlling EP systems. To date, electron density is mostly measured with electrostatic probes, such as Langmuir probes (LP), which may be quite invasive, due to the collection of charges (up to several mA), or with spectroscopy methods, such like Thomson scattering, though needing complex optical benches and long acquisition times when applied to low dense plasma (<10^{10} cm^{-3}). In 1976, Stenzel [1] proposed a microwave resonant probe to measure electron density: the hairpin (HP), which is a U-shaped antenna to be immersed in plasma. In 2011, Liang et al. [2] proposed a new type of microwave resonant probe, the curling probe (CP), a spiral slot-type antenna, which has several advantages: compactness, embeddable in a reactor/thruster wall and the capacity to perform electron density measurements through a dielectric wall. Later works [3-5] show the interest and capabilities of such diagnostic tool.

Microwave resonant probes rely on the creation of a stationary volume wave in-between resonator ends at a given resonance frequency, from which plasma properties can be evaluated. The hairpin is a quarter-wavelength resonator. In the case of a CP, the spiral resonator is capacitively coupled with an exciting aperture (Fig. 1): we found that the resonator does not behave either as a half- or a quarter-wavelength type. Therefore, a numerical study is carried out to investigate its nature. Simulations results have been validated with experimental data.

Numerical study

The behavior of the CP is studied numerically both in 2D and 3D configurations, based on electro-magnetic FEM-based simulations. 2D simulations show that the nature of the resonator depends on the geometry of the spiral: an analytical equation for the resonance frequency as a function of the 2D spiral parameters is established [5]. For typical spiral dimensions, the curling probe behaves in-between a quarter- and a half-wavelength resonator. In the 3D case, additional couplings from the underlying structure slightly shift the 2D resonant frequency (of a few hundreds of MHz) depending on probe 3D structure, yet, the nature of the resonator in 3D is consistent to the 2D case. The 3D resonant frequency is described with a correlation by introducing two coefficients (α and β) accounting for the 3D structure and materials. A calibration procedure using solid dielectric etalons of known permittivity has been established from simulations, and later experimentally verified [5]. The resulting calibration equation (Eq. 1) is combined with the cold collisionless plasma permittivity model ($\varepsilon_p = 1 - (f_p/f)^2$) to obtain the plasma electron density.

$$\varepsilon_r = (1+\alpha)\left(\frac{f_0}{f_r}\right)^2 - \alpha \tag{1}$$

where f_r is the resonance frequency in presence of the probed medium (ε_r) and f_0 is the vacuum reference frequency.

Experimental study

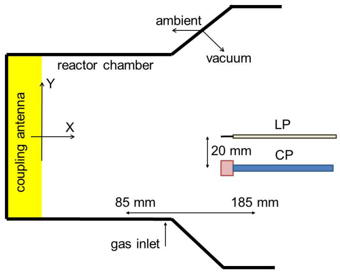
The probe consists of a PCB spiral resonator: a 35 μm-thick copper layer etched on a dielectric substrate as shown in Fig. 1. Three curling probes have been manufactured varying vacuum resonance frequency (approximately 700, 1400 and 3000 MHz) and substrate thickness and material (RO4003 and FR4). The vacuum frequency drives probes performances in terms of sensitivity to plasma density, accuracy of the measurement and sensitivity to sheath thickness. Low frequencies CPs (f_0 ~1000 MHz) have proven to be more sensitive and accurate in low density plasmas with respect to high frequency probes (f_0>3 GHz). Nonetheless, the maximum measurable density is limited by the analyzing microwave frequency ($f_p \leq f$ for an EM-wave to propagate inside plasma), so that high frequency probes are needed for performing measurements in high density plasmas. To overcome this issue, we propose to use the second harmonic resonance (SHR). Its larger resonant frequency allows to extend the measurable density range ([6] conducted a similar investigation on a HP). The calibration procedure can be applied to the SHR as well, though the SHR comes with reduced performances in terms of reflectance peak quality factor leading to a lower sensitivity to plasma density with respect to its first harmonic. More details can be found in ref. [5].

Plasma sheath effect

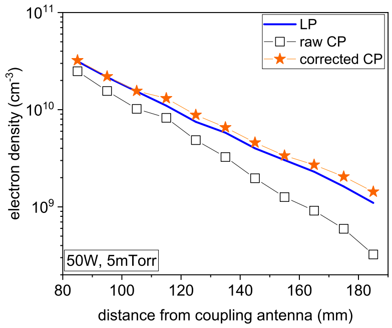
When operating, the curling probe is left floating within the plasma, so that an electron-depleted plasma sheath surrounds the probe surface, resulting in a lower measured density with respect to the unperturbed bulk density. A correction method, built from simulations, is currently being developed. This method is based on a simple plasma-wall interaction model for the sheath structure, and the capability of the CP to probe a medium some mm away from its surface, thanks to the radiated E field. The sheath model is based on classical sheath equations within the following hypothesis: collisionless and weakly magnetized plasma and sheath, cold and singly charged ions with a Dirac energy distribution (E_{ki}) and Maxwellian electron energy distribution at a uniform bulk electron temperature (T_{bulk}). In addition, secondary electron emission is neglected and Bohm criterion is assumed for the ions entering the sheath. In the case of sub-sonic ions, a presheath is considered based on the correlation given in [7]. Numerical results show that as the ion beam velocity increases, the sheath thickness decreases following a logarithmic law as a function of the ion Mach number, $M_i = f(E_{ki}, T_{bulk})$. Inputs of the correction method are the raw measured density, an estimation of the ions beam energy (if any, otherwise immobile ions are considered) and an estimation of the bulk electron temperature; the unperturbed bulk density being the output. The correction method has been tested by comparing corrected CP densities with LP measurements.

Application to ICP and ECR plasma sources

The CP was tested in the ICP source (LPP lab, Ecole Polytechnique) in parallel with a RF-compensated Langmuir probe, as showed in the measurement setup in Fig. 2a. The reactor is excited at 4 MHz and fed with Argon at flowrates from 7 to 60 SCCM, operating pressures range from 2 to 15 mTorr (0.3 to 2 x10^{-2} mbar). Fig. 2b shows the longitudinal profile along plasma expansion: raw CP density diverges from LP measure far from the coupling antenna due to the increase in sheath thickness (estimated values varied from 0.2 to 1.2 mm). The correction method seems to properly account for the sheath increase and a worthy agreement is obtained between the two probes. In general, the correction method has proven to be valid within the validity of the sheath model. It is noteworthy that the CP capability to probe a medium far from its surface has been confirmed.



(a)



(b)

Figure 2: *(a) Measurement setup. (b) Longitudinal profile along plasma expansion.*

The CP was also tested on the ECR (Electron Cyclotron Resonance) thruster (Fig. 3a) in the B09-ONERA facility (Palaiseau). The ECR is a cathode-less thruster developed at ONERA since 2010 [7-14]. The thruster is fed with Xenon at flowrates between 1 and 2 SCCM and it is powered at 2450 MHz at around 30W. Pressures during thruster operation are around 10^{-6} mbar. The thruster is based on the resonant absorption of microwaves by electrons and the acceleration of electrons and ions in a magnetic nozzle. Among the very few studies reporting electron density measurements in cathode-less thruster, Correyero et al. [11] used a LP to probe the far field region of the nozzle. LP measurements in the near field were not possible due to strong plasma perturbations and probe damaging. Fig. 3b shows the longitudinal profiles along the nozzle axis: raw CP densities are corrected with the presented correction method and a good agreement is observed with the LP. Lower perturbation on thruster functioning was observed when approaching the CP rather than the HP at the thruster exit plane. Fig. 3c shows the first (to our knowledge) *in-situ* measurement of electron density (as time evolution after ignition) in the source of a cathode-less thruster, made possible by flush-mounting the CP (of 10 mm in diameter) in the walls of the ECR source (of 27 mm in diameter). The steady-state density value is consistent with other CP measurements performed at the thruster exit plane at same operating conditions.

Conclusions and on-going works

We showed the capability of the curling probe for EP systems diagnostics in terms of low intrusivity and possibility to perform measurements in harsh environments for conventional electrostatic probes (electron temperatures in the ECR source are estimated at 30 to 50 eV). Current investigations on the CP focus on the possibility to perform measurements through a dielectric wall: first experimental tests of a CP embedded in a 0.7 mm-thick BN wall were consistent with results obtained from an immersed-in-plasma CP and with simulated behavior. In addition, the large measurable density range of the CP (possible with the combination of the FHR and SHR) makes it a suitable candidate to 2D-map the ECR nozzle where densities vary from 10^{11} (in the near field) to 10^{7} cm^{-3} in the far field. This may allow the estimation of plasma variables (e.g. the electron magnetic moment) and behavior in the nozzle (for example electrons detachment), leading to a better physical understanding of ECR thruster working principle.

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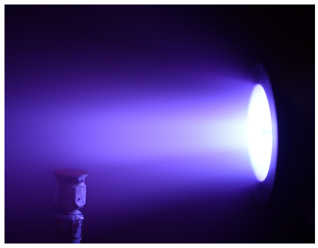

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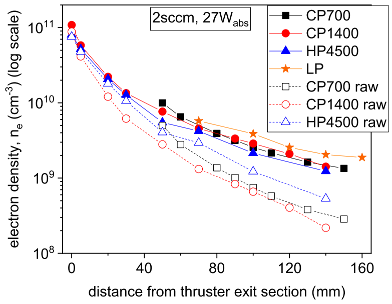

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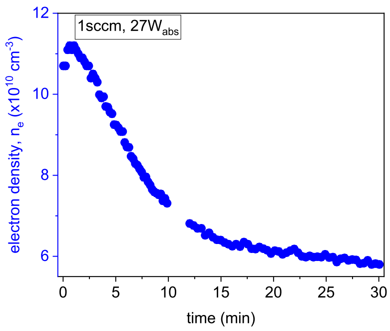

(c)

Figure 3: *(b) Longitudinal profile along the nozzle axis. (c) Time evolution of density inside the ECR source.*

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