

Microwave frequency sweep interferometer for plasma density measurements in ECR ion sources: Design and preliminary results

Giuseppe Torrisi,^{1,2} David Mascali,¹ Lorenzo Neri,¹ Ornella Leonardi,¹ Gino Sorbello,^{1,3} Luigi Celona,¹ Giuseppe Castro,¹ Riccardo Agnello,¹ Antonio Caruso,¹ Santi Passarello,¹ Alberto Longhitano,¹ Tommaso Isernia,² and Santo Gammino¹

¹INFN - Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy

²University Mediterranea of Reggio Calabria, Reggio Calabria, Italy

³University of Catania, Catania, Italy and INFN-LNS, Catania, Italy

The Electron Cyclotron Resonance Ion Sources (ECRISs) development is strictly related to the availability of new diagnostic tools, as the existing ones are not adequate to such compact machines and to their plasma characteristics. Microwave interferometry is a non-invasive method for plasma diagnostics and represents the best candidate for plasma density measurement in hostile environment. Interferometry in ECRISs is a challenging task mainly due to their compact size. The typical density of ECR plasmas is in the range 10^{11} – 10^{13} cm⁻³ and it needs a probing beam wavelength of the order of few centimetres, comparable to the chamber radius. The paper describes the design of a microwave interferometer developed at the LNS-INFN laboratories based on the so-called “frequency sweep” method to filter out the multipath contribution in the detected signals. The measurement technique and the preliminary results (calibration) obtained during the experimental tests will be presented.

I. INTRODUCTION AND MOTIVATION

In the last three decades, the performance of the electron cyclotron resonance ion sources (ECRISs) has been dramatically improved. In the next generation ECRIS, plasma diagnostic for density measurement will represent an important feedback for a correct understanding of the role of the key components (magnetic field configuration, gas pressure, microwave frequency, etc.). In this paper, we propose an interferometric method to measure the line-average plasma density in ECRIS. Preliminary results obtained during the experimental tests will be presented. As in the classical scheme of a microwave Mach-Zender type interferometry,¹ a microwave signal at frequency larger than any cut-off/resonance frequency of the plasma under investigation is splitted into two different branches: the first one crosses the plasma, the second one is used as reference signal, propagating into a waveguide of calibrated length. In the typical arrangement of the torus geometry of the fusion experiments, a probing wave propagating perpendicular to the magnetostatic field² is used and the density can be determined from phase shift which explicitly depends on the natural plasma oscillation ω_p , i.e., the electron density, as depicted by the mathematical relation below,

$$\Delta\phi = \int_0^L \frac{\omega}{c} \left[1 - \left(1 - \frac{\omega_p^2}{\omega^2} \right)^{1/2} \right] dl, \quad (1)$$

where L is the plasma length along which the integral is calculated, c the speed of light, ω the probing microwave pulsation, $\omega_p^2 = \frac{ne^2}{m_e\epsilon_0}$ the plasma oscillation, and the other quantities are the standard fundamental physical constants. In ECRIS, the interferometric measurement is greatly complicated by the low ratio l/λ , between the plasma chamber length and probing wavelength, and by the mechanical constraints, which limit considerably the position of probing ports.

II. EXPERIMENTAL STRATEGY

In our experimental setup, shown in Fig. 1, typical of all ECRIS setup, the direction of the electromagnetic wave vector $\vec{k}$ is along the magnetostatic confinement field $\vec{B}_0$, then the probing wave³ has the following effective constant of propagation:

$$k_{\text{eff}} = \frac{1}{2} \frac{\omega}{c} \left(\sqrt{1 - \frac{\omega_p^2}{\omega(\omega - \omega_g)}} + \sqrt{1 - \frac{\omega_p^2}{\omega(\omega + \omega_g)}} \right),$$

and the phase shift due to the presence of the plasma is

$$\Delta\phi = \int_0^L (k_0 - k_{\text{eff}}) dl, \quad (2)$$

where $k_0 = \frac{\omega}{c}$ is the free space propagation constant.

In small-size plasma chambers like the ones of ECR ion sources, the probing signal is subject to multipath due to the signal reflections at the chamber walls (reflecting surfaces). In order to have a reliable measurement, the useful direct-path component must be depurated by spurious components due to these multiple reflections, and this can be done only applying a more sophisticated experimental strategy. The density measurement in our interferometric method is based

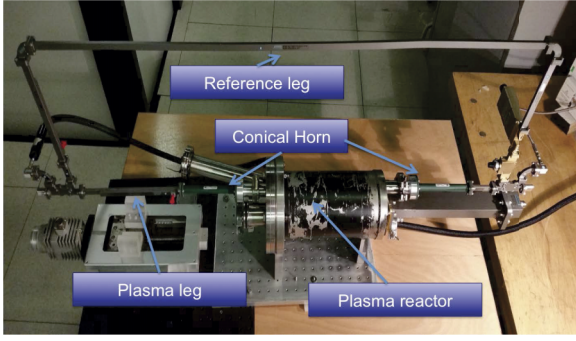


FIG. 1. K-band (18–26.5 GHz) microwave interferometer mounted on a plasma reactor operating at 2.45 GHz.

on the evaluation of the beat signal between the signal which crosses the plasma and the reference one which travels along the reference arm.⁴ The key concept of the measurement is that the signals launched along two paths are “up-chirped” signals (signals whose frequency increases over time): the presence/absence of plasma causes a down/up shift of the measured beat frequency.⁵ In order to measure only the contribution to the beat frequency due to the plasma along the direct-path, the design aims to filter out the multipath components.

The above mentioned beat signal “cleaning” is a sort of “instrument calibration” to be carried out without the plasma and is possible because we are able to perform spectral analysis of the beating signal: Fast Fourier Transform (FFT) of the receiving horn collecting signal could be done, displaying the quasi-monochromatic beating that it is evident in case of “in-vacuum” propagation as discussed in the numerical simulation.³

III. ANTENNA MEASUREMENT RESULTS

For the typical densities of our plasmas, a suitable probing signal lies in the range 18–26.5 GHz because at these frequencies we can achieve high sensitivity in the “beating shift” detection. In order to couple the probing signal into the plasma chamber, two circular horn antennas have been designed in the above band, and realized in copper: vacuum tightness is provided by an 8 μm layer of Kapton and proper adaption flanges have been realized to be installed on the standard DN25 flange of the plasma reactor (Fig. 2). This choice considerably increases the versatility of the experimental interferometric setup since it can be easily installed on other plasma experiments. Our setup is operated with a uniform

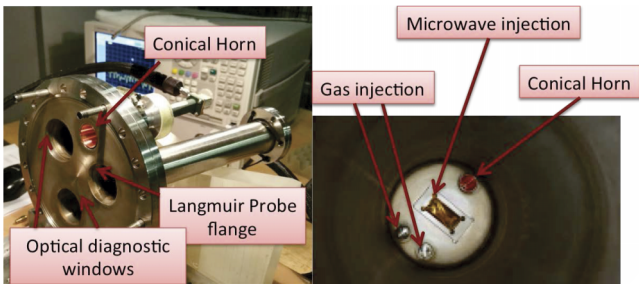


FIG. 2. Conical Horn mounted on injection flange.

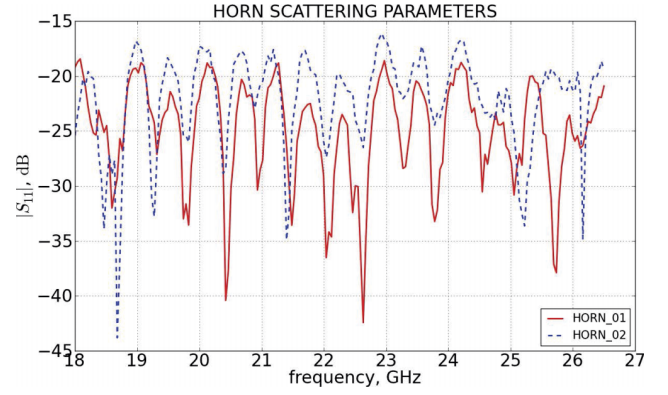


FIG. 3. Measured S_{11} for the two the proposed antennas.

axial magnetic field and the shape of the produced plasma is approximately cylindric. There is some evidence⁶ that the plasma cylinder has an annular cross section that can be investigated by means of the off-axis positioning of the horn.

The conical horn antennas are coupled with a rectangular WR42 to circular WG20 waveguide transition that provides also a right-hand circular polarisation. The use of circularly polarized antennas is desirable since, in this case, the horn to horn transmission does not suffer signal loss due to polarization mismatch that should be considered for two linearly polarized antennas where the Polarization Loss Factor (PLF) is $\cos^2\alpha$ (with α the angle between the two horn-linearly polarized electric fields).

The horn antennas have been characterized in terms of impedance matching and they are well matched in the band of interest since the coupling horn reflection coefficient $|S_{11}|$, shown in Fig. 3, is lower than -17 dB. A larger aperture would improve the antenna directivity and reduce the multipath in cavity but we are limited by mechanical constraints. In Fig. 3, we show the free-space $|S_{11}|$ but the antennas remain well matched also when mounted on cavity.

The horn radiation pattern has been measured experimentally (see Figure 4) on a laboratory apparatus in which the transmitting horn was mounted on a stationary pole located 266 mm (length of the plasma chamber) from the receiving antenna that was rotated at steps of 3.2° in the horizontal plane.

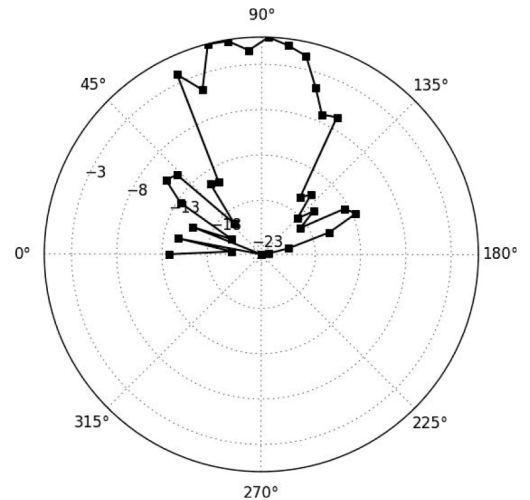


FIG. 4. Measured radiation diagram at 22.5 GHz.

The measured radiation diagram of Fig. 4 is in agreement with the numerical calculations³ in terms of shape of the main lobe.

However, measured radiation pattern shows a worsening of the level of sidelobe with respect to the simulation (−11 dB vs −19 dB). This lack of agreement is partly due to the ideal farfield approximation of the simulated radiation patterns, conversely to the closer distance at which the two antennas were experimentally tested.

IV. CALIBRATION OF MEASUREMENT DEVICES: FREE SPACE CHARACTERIZATION ON A SIMPLIFIED SETUP

In the present section, we describe the use of the above described setup and horns in material characterization that represents a useful testbench for the subsequent, more challenging, plasma density measurement.

The many similarity with the plasma density measurement suggested us to use a network analyzer and the horn to characterize flat materials in free space. In this case, the reference arm is internal to the network analyzer. We use the Agilent 2-Port PNA-L Microwave N5230A 10 MHz–50 GHz network analyzer to measure the dielectric constant of materials based on free-space method that uses the horn antennas to focus microwave energy through a sheet of material (Fig. 5). The precise knowledge of the material slab thickness provides the information to characterize the frequency dependence of the permittivity because the vector network analyzer makes swept high frequency measurements from 18 GHz to 26.5 GHz and the measured transmission produces the phase data at that frequency. The material under test is assumed large, flat, and homogeneous. It is easily demonstrated that the plane wave solutions associated with an electromagnetic wave propagating through a uniform dielectric medium with thickness d and dielectric constant ϵ_r satisfy the following relation for the phase shift $\Delta\phi$:

$$\Delta\phi = \frac{2\pi}{\lambda_0} \sqrt{\epsilon_r} d = \beta d, \quad (3)$$

where β is the phase constant. First of all, the phase-measuring bridge was adjusted to a null, by a waveguide phase shifter. After phase shift in vacuum was measured varying the horn to horn distance ΔL . As expected, starting from the minimum horn to horn distance of 266 mm, where $\Delta L = 0$, we find a linear relationship between the displacement with respect to

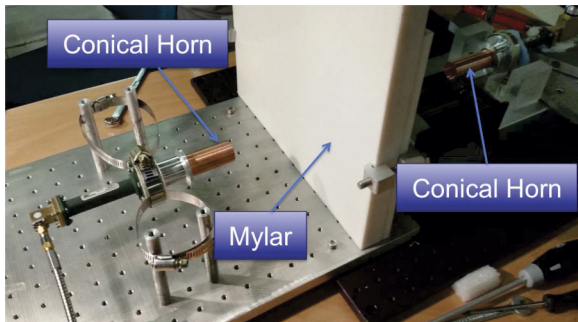


FIG. 5. Dielectric constant measurement.

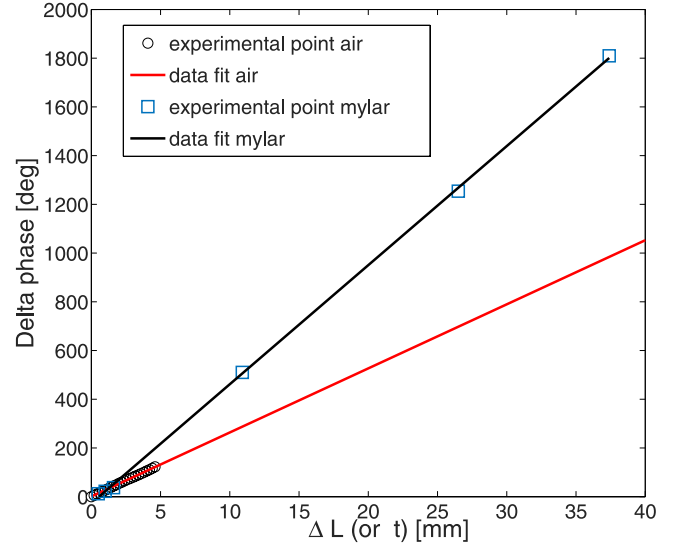


FIG. 6. Phase shift as a function of distance between the horn antennas ΔL in the presence of vacuum and of various thicknesses t of PETP (Mylar).

the starting position (zeroing it through the phase shifter) and phase shift (red curve and black circle marker in Fig. 6).

After the free space “calibration,” the phase shift was measured also in presence of Polyethylene terephthalate (PETP) to compute its dielectric constant. We used sheets of various thicknesses t . The measured phase shifts (black curve and square marker in Fig. 6) very well agree with the expected linear fit, providing a very low error in the derivation of the electrical permittivities ϵ_r , as shown in Table I, that are in very good agreement with the literature data.^{7,8}

The interpretation of such microwave phase-shift measurements is crucial for a correct and valid interpretation of the observed phase shift for our small cylindrical plasma columns that may be seriously subject to difficulties. The study of dielectric materials at 18 GHz–26.5 GHz has revealed a necessary requirement for the plasma’s index of refraction measurement.

V. FREE SPACE INTERFEROMETRIC SETUP: BEAT SIGNAL MEASUREMENT

In order to calibrate the instrument and validate the experimental strategy in an easy scenario of known index of refraction n , we performed an “in air” measurement consisting in the evaluation of the beating signal obtained with the setup described in Fig. 1 without the plasma chamber. The vacuum index of refraction of the air can be determined from a nonlinear fit of the frequency dependent measured phase shift pattern with the following equation of the time averaged power of the superposition signal of each of the signals from the two legs of the interferometer:

TABLE I. Measured and expected index of refraction.

Material	Measured index of refraction	Error (%)	Expected value
Air	0.98	0.9	1
Mylar	1.82	2.18	1.6–1.8

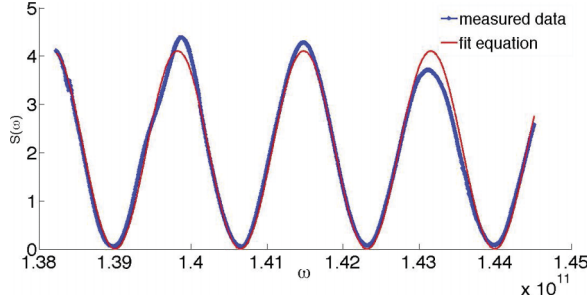


FIG. 7. Measured beat pattern obtained without plasma and fit equation.

$$S(\omega) = A \cos^2 \left\{ \frac{1}{2c} \left[\Delta L \sqrt{(\omega^2 - \omega_c^2)} - \omega n L \right] \right\}, \quad (4)$$

where ΔL is the waveguide length difference, ω is the source frequency, that in this test it is swept over a frequency range of 22–23 GHz, ω_c is the cut-off frequency in the waveguide, L is the vacuum length, and c is the speed of light. In Fig. 7, we show that the measured beat pattern for the case without plasma is very well fit by Eq. (4).

VI. NEXT STEPS

The next step will be the test in presence of the plasma chamber which it will give the need to filter out the multipath

and noise contribution. These tests are preliminary for the installation of the apparatus on an innovative ion source, the flexible plasma trap (FPT), designed for the investigation of alternative heating mechanisms on overdense plasmas; in this scenario, the interferometer could give another feedback on the cut-off density overcoming together with the measurements of the other diagnostics.

ACKNOWLEDGMENTS

Work supported by the 5th National Commission of INFN (VESPRI Experiment).

- ¹H. J. Hartfuss and T. Geist, *Fusion Plasma Diagnostics with mm-Waves: An Introduction* (Wiley, 2013).
- ²I. H. Hutchinson, *Principles of Plasma Diagnostics* (Cambridge University Press, 2002).
- ³G. Torrì, R. Agnello, G. Castro, L. Celona, V. Finocchiaro, S. Gammino, D. Mascali, L. Neri, S. Passarello, G. Sorbello, and T. Isernia, in *IPAC15 Conference Proceedings at the JACoW*, 2015, <http://www.jacow.org>, p. 2512.
- ⁴J. Howard and D. Oliver, *Appl. Opt.* **45**(34), 8613-8620 (2006).
- ⁵E. E. Scime, R. F. Boivin, J. L. Kline, and M. M. Balkey, *Rev. Sci. Instrum.* **72**, 1672 (2000).
- ⁶D. Mascali, L. Celona, S. Gammino, R. Miracoli, G. Castro, N. Gambino, and G. Ciavola, *Nucl. Instrum. Methods Phys. Res., Sect. A* **653**, 11 (2011).
- ⁷A. Elhawil, L. Zhan, J. Stiens, C. D. Tandt, N. A. Gotzen, G. V. Assche, and R. Vounckx, in *Proceedings Symposium IEEE/LEOS Benelux Chapter, 2007, Brussels* (IEEE, 2007).
- ⁸S. Hamilton, *An Analog Electronics Companion: Basic Circuit Design for Engineers and Scientists* (Cambridge University Press, 2003).