

# DESIGN OF A MICROWAVE FREQUENCY SWEEP INTERFEROMETER FOR PLASMA DENSITY MEASUREMENTS IN ECR ION SOURCES\*

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## Abstract

Electron Cyclotron Resonance Ion Sources (ECRIS) are among the candidates to support the growing request of intense beams of multicharged ions. Their further development is related to the availability of new diagnostic tools, nowadays consisting of few types only of devices designed on purpose for such compact machines. Microwave Interferometry is a non-invasive method for plasma diagnostics and represents the best candidate for the whole plasma density measurements. Interferometry in ECR Ion Sources is a challenging task due to their compact size. The typical density range of ECR plasmas ranging from  $10^{11}$  to about  $10^{12}$   $\text{cm}^{-3}$ , causes the probing beam wavelength to be in the order of few centimetres which is comparable to the chamber radius. The paper describes the design of a new microwave interferometer based on the so-called “frequency sweep” method: the density is here derived by the frequency shift of a beating signal obtained during the fast sweep of both probing and reference microwave signals; inner cavity multipaths contributions can thereby be suppressed by cleaning the spurious frequencies from the beating signal spectrum.

## INTRODUCTION AND MOTIVATION

The development of microwave diagnostics is a fruitful strategy because microwaves crossing the plasma are sensitive to the entire energetic spectrum of the plasma, allowing global evaluation of the average density. In the classical scheme of a microwave Mach-Zender type interferometry, a microwave signal at frequency larger than any cutoff/resonance frequency of the plasma under investigation is splitted into two different branches: the first one is launched into the plasma, the second one is used as reference signal, propagating into a waveguide of calibrated length, as shown in Fig. 1.

The basic idea [1] is that the density can be determined from phase shift which explicitly depends on the natural plasma oscillation  $\omega_p$ , 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,  $\omega$  the probing microwave pulsation,  $\omega_p^2 = \frac{n_e e^2}{m_e \epsilon_0}$  the plasma oscillation, and the other quantities are the standard fundamental physical constants. In ECRIS the measurement is greatly complicated by the mechanical constraints, which limit considerably the ratio  $L/\lambda$ , where  $L$  is the characteristic length of the plasma chamber, and  $\lambda$  is the wavelength.

In our experimental setup, 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 dispersion relation of the magnetized plasma has two solutions: right-hand (R) and left-hand (L) circularly polarized waves, with the following propagation constants:

$$k_R = \frac{\omega}{c} \sqrt{1 - \frac{\omega_p^2}{\omega(\omega - \omega_g)}} \quad (2)$$

$$k_L = \frac{\omega}{c} \sqrt{1 - \frac{\omega_p^2}{\omega(\omega + \omega_g)}} \quad (3)$$

where  $\omega_g = eB_0/m_e$  is the electron cyclotron frequency and we can assume that the collision frequency is much smaller than the microwave frequency. Without loss of generality we choose a cartesian reference system so that the  $z$  axis is parallel to  $\vec{B}_0$  and to the  $yz$  plane containing the propagation constant vector  $\vec{k}$  directed along  $\vec{B}_0$ . In this configuration the electric field vectors associated to R and L waves can be written as:

$$\vec{E}_R = (\hat{x} - i\hat{y})e^{ik_R z} \quad (4a)$$

$$\vec{E}_L = (\hat{x} + i\hat{y})e^{ik_L z} \quad (4b)$$

The sum of the two waves provides the composed wave  $\vec{E}_t = \vec{E}_R + \vec{E}_L$  having the following effective constant of propagation:

$$k_{eff} = (k_R + k_L)/2$$

So, the phase shift due to the presence of the plasma is:

$$\Delta\phi = \int_0^L (k_0 - k_{eff})dL \quad (5)$$

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

Figure 1 highlights the conceptual layout of an interferometer setup applied to small-size plasma chambers like in case

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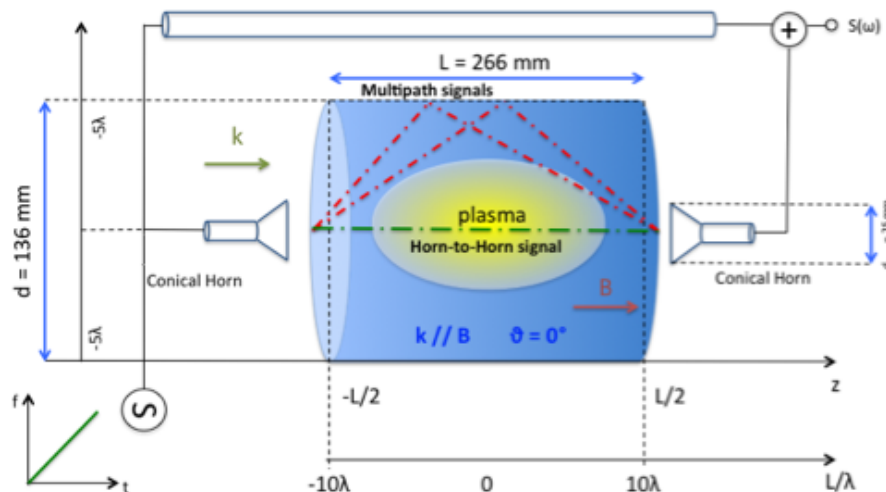


Figure 1: Sketch of the microwave interferometer design, with particular emphasis on the dimensions of the plasma chamber and their relationship with the wavelength.

of ECR ion sources. The main problem consists in the multipath given by probing signal reflections at the chamber walls (reflecting surfaces). To be significant, the measurement must be deperated by these spurious components, and this can be done only applying a more sophisticated experimental strategy.

### EXPERIMENTAL STRATEGY

The proposed methodology moves from the one described in [3, 4] but it needs to be specifically developed for ECR ion source devices. In order to suppress multipath signal we have to follow two main directions: first we need to use a frequency swept method, where the density is derived by the frequency shift of a beating signal obtained during the fast swept of both probing and reference microwave signals:

$$M(t) = A \sin(\omega_{int}t + \phi_2 + \phi_p) + B \sin(\omega_{int}t + \phi_1) \quad (6)$$

where A and B are the amplitudes of the plasma and reference leg signals respectively,  $\omega_{int}$  is the microwave source frequency,  $\phi_1$  is the phase shift due to dispersion in waveguide in the reference leg,  $\phi_2$  is the phase shift due to dispersion in waveguide in the plasma leg, and  $\phi_p$  is the phase shift due to dispersion in the plasma; the inner cavity multipaths contributions (the lower amplitude spectral components of figure 2) can thereby be suppressed by cleaning the spurious frequencies from the beating signal spectrum component (the fundamental first frequency component of figure 2).

This deperation of the spectrum (a sort of “instrument calibration” to be carried out without the plasma) is possible because we are able to perform spectral analysis of the beating signal: Fast Fourier Transform (FFT) of the receiving horn collecting signal has been done, displaying

the quasi-monochromatic beating that it is evident in case of “in-vacuum” propagation (see Fig. 3).

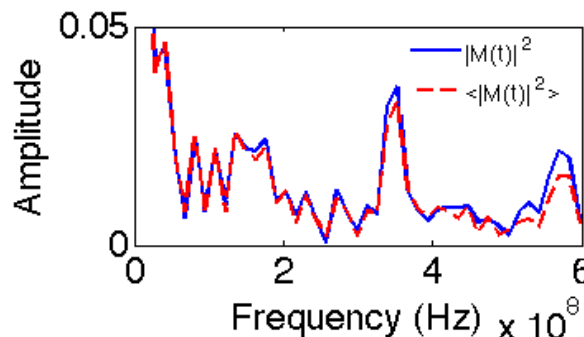


Figure 2: Spectrum of the beating signal in case of “in-vacuum” horn-to-horn propagation.

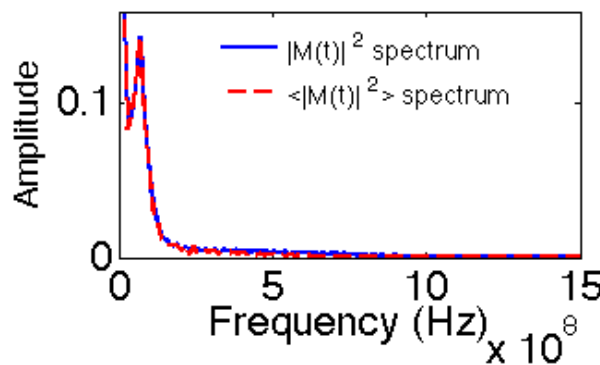


Figure 3: Spectrum of the beating signal in case of “in-vacuum” horn-to-horn propagation.

Concerning the antenna design, since the characteristic densities of our plasmas, the frequencies suitable for

high sensitivity “beating shift” detection lie in the range 20-25 GHz. This second (not mandatory but very useful) part of the interferometer design concerned the optimization of an high-directivity horn antenna carried out through CST EM and RF COMSOL simulations at high frequency (see Fig. 4).

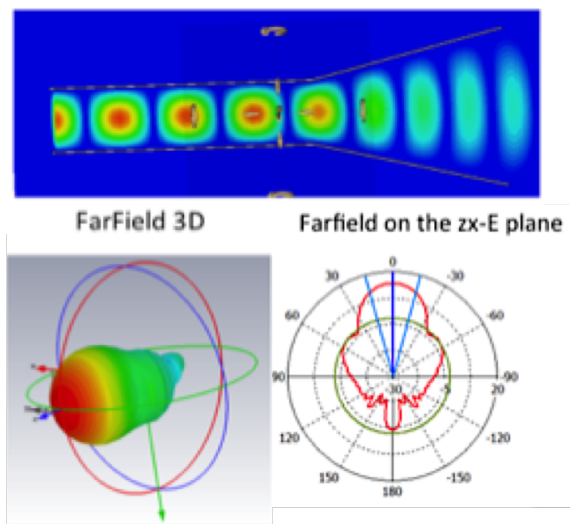


Figure 4: Preliminary design of the launching/receiving antennas for the proposed interferometry setup (simulations performed in COMSOL Multiphysics).

Further optimization of the antennas should additionally improve the aspect ratio between the main spectral component and the multipath peaks. In a practical way, the measurement consists in the evaluation of the beating signal shift, as depicted in figure 5 (simulation).

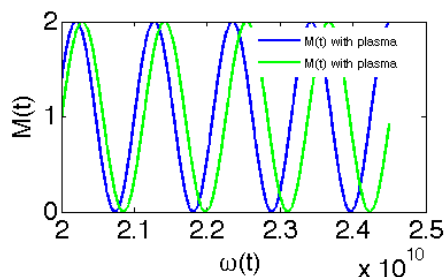


Figure 5: Simulation of the beating signal frequency shift due to the plasma. The simulation has been done for a plasma of density:  $n_e = 5 \cdot 10^{17} m^{-3}$ .

We want to remark that the density measurement in our interferometric method is based on the evaluation of the beat frequency between two signals: one which crosses the plasma and the other which travels along a so-called reference arm. The key concept of the principle of measurement

is that the signals that are sent along two paths, are "up-chirped" signals (signals whose frequency increases over time): because of the plasma, there is a shift of the measured beat frequency, compared to the case of the vacuum chamber. The design aim is to detect this shift and to filtrate the multipath components in order to measure only the beat frequency due to the plasma presence.

Although some details have still to be fixed by improving the modelling and the numerical simulations, the overall layout of the experimental setup is already defined: the most important components are listed in the table 1.

Table 1: Microwave Components

Component
WR42 to Coax SMA adapter
3 dB Short Slot Hybrid Divider
0-360° WR42 Phase Shifter
10dB Dir. Coupler in place of 2
0-30 dB WR42 Variable Attenuator
WR42 90° E or H Bend
WR42 Straights Sections
YIG Signal oscillator in place of NA
RF Bench Test Cable SMA-SMA
20-25 GHz Conical Horn Antennas
WR42 Rect. to Circ. Transitions

## NEXT STEPS

The microwave interferometer setup will be installed on the "plasma reactor", a testbench used at LNS for plasma physics studies; these test are preliminary for the installation of the apparatus on a 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 an other feedback on the cutoff density overcoming together with the measurements of the other diagnostics.

## REFERENCES

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