Plasma diagnostics by microwaves interferometry

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Ions sources

Two of the ions sources installed at LNS

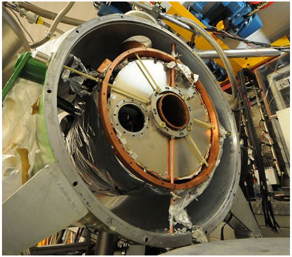


Figure: *SERSE* was the most performant ion source until the beginning of 2000s

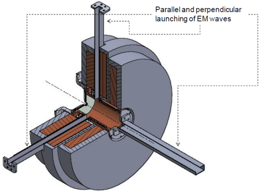


Figure: *FPT* is an ion source designed for cutting edge studies of plasma physics

Applications of Ion Sources:

- Injectors for particle accelerators
- Studies on plasma physics

The Electron Cyclotron Resonance Ion Sources (ECRIS)

The ECRISs are based on the resonance between the external injected electromagnetic wave and the gyration motion, at a frequency ω_g, of electrons in a magnetized plasma:

$$\omega_g = \frac{|e|B}{m}$$

The extracted current I and the mean charge state $\langle q \rangle$ are proportional to electron density n_e:

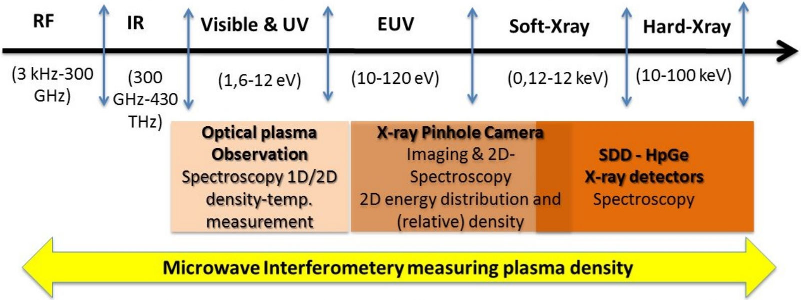
$$I \propto \frac{n_e}{\tau} \qquad \langle q \rangle \propto n_e \tau$$

- electron density n_e has to be maximized.
- the confinement time τ has to be carefully set in order to have the best compromise between I and $\langle q \rangle$

The knowledge of plasma parameters in then essential to maximize to performances, this can be done by means of **Plasma Diagnostics**

Plasma diagnostics techniques

Plasma Diagnostics: sophisticated tools for covering the entire electromagnetic spectrum



We need a tool able to measure density of electrons with an externally injected "probing" radiation (no perturbation since $P_{probing}/P_{exciting}<1\%$)

→ Density measurement technique no-longer based on plasma emission but on "response-on-transmission" of microwaves through the plasma

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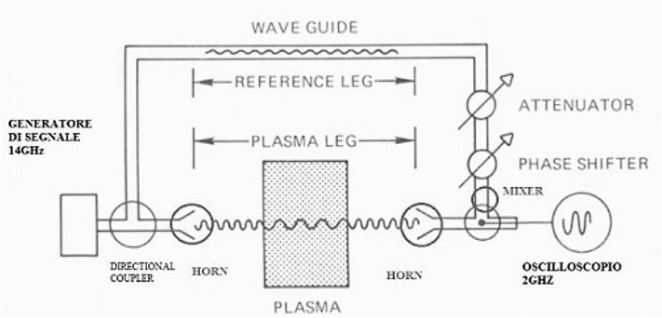
MICROWAVE INTERFEROMETRY

Interferometry for plasmas

- A classical scheme of an interferometer

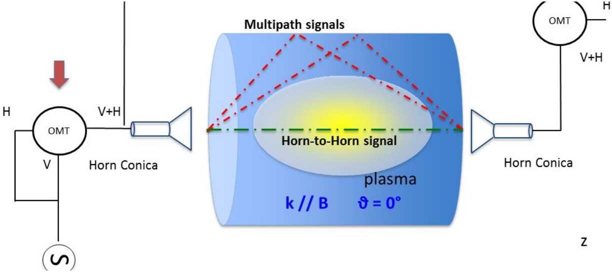


How to calculate the density n of the plasma

$$\Delta\phi = \frac{\omega}{c}\left[1-\left(1-\frac{\omega_p^2}{\omega^2}\right)^{1/2}\right]L \quad \rightarrow \quad \boxed{\omega_p^2 = \frac{4\pi n e^2}{m\epsilon_0}}$$

Experimental difficulties

- The reflections on the internal walls generate "multi-paths", introducing spurious signals.
- Few access areas available on ECRIS (extraction system, magnets...).



Multipaths suppression, two approaches:

1. *Study and design of High Directivity antennas*
2. *"Frequency sweep" method with post-filtering procedure of the beating signal $S(\omega)$*

The "frequency sweep" interferometer

The method is based on the frequency shift of the **beating signal** given by the superposition of the waves coming from the reference leg and the plasma leg. Frequency ω_{beat} of the beating signal:

$$\omega_{beat} = \frac{\partial \omega}{\partial t}\left(\Delta L \frac{\partial k_g}{\partial \omega} + \int_{plasma} \frac{\partial k_{plasma}}{\partial \omega} dl\right)$$

- $\frac{\partial \omega}{\partial t}$ *depends on the kind of sweep*
- ΔL *is the difference between the reference leg and the plasma leg*
- k_g *and* k_{plasma} *are the dispersion coefficients for waveguide and plasma*

The signal measured by the detector is the **power averaged signal**

Analytical beat signal

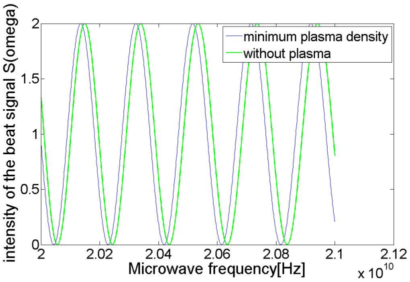
$$S(\omega) \propto 2A^2 \cos^2\left\{\left[\Delta L\sqrt{\omega^2 - \omega_c^2} + \int_0^L \sqrt{\omega^2 - \omega_p^2(l)}dl\right]/2c\right\}$$

Frequency domain

The frequency range of the sweep depends on the plasma density we expect to measure. $\rightarrow f_{probing} > f_{plasma}$

f= 20 - 24.5 GHz

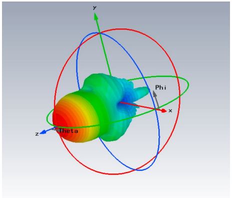
Mininum density	$n_{e(min)} = 5 \times 10^{17} e/m^3$
Maximum density	$n_{e(max)} = 4 \times 10^{18} e/m^3$



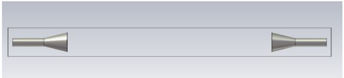
When the plasma is injected in the chamber, the beating signal is shifted: plasma density is related to this shift.

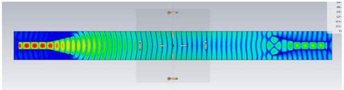
Numerical simulations of the electromagnetic fields

Antenna directivity

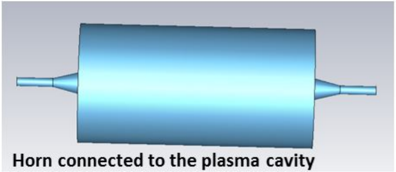


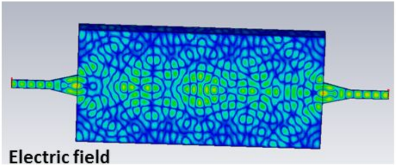
Simulations in free space

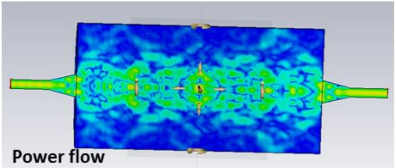




Simulations in cavity







Simulated spectrum of the beating signal in free space

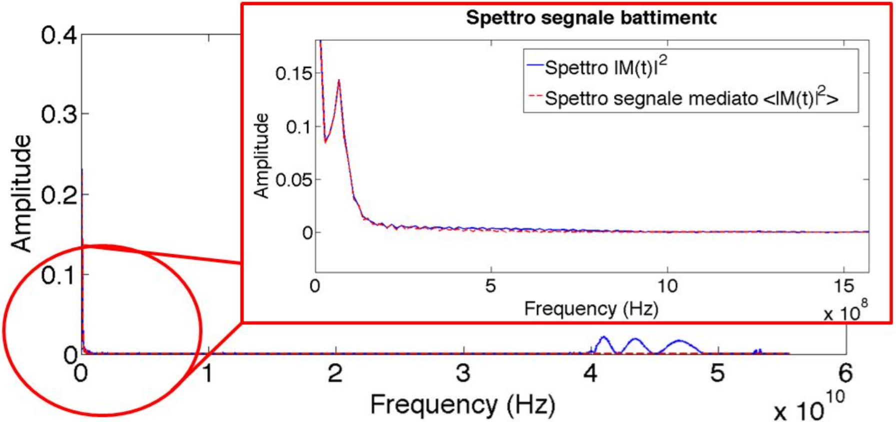


Figure: *Only one frequency is visible, corresponding to the beating signal.*

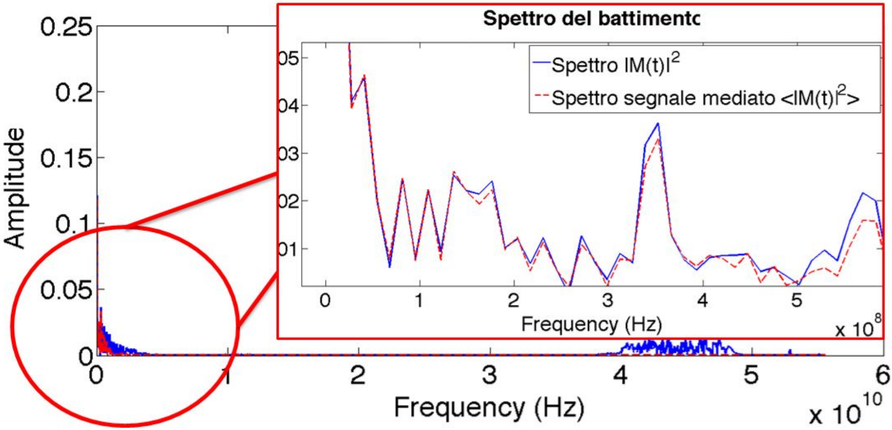
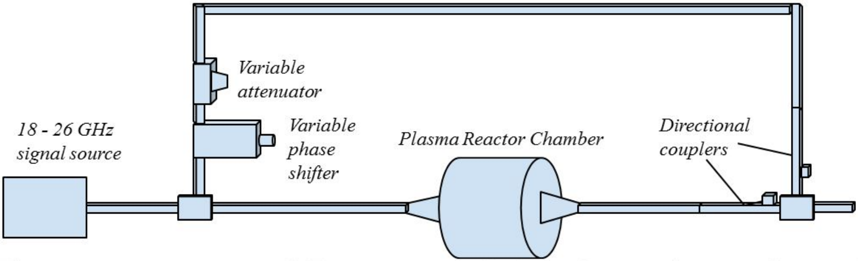


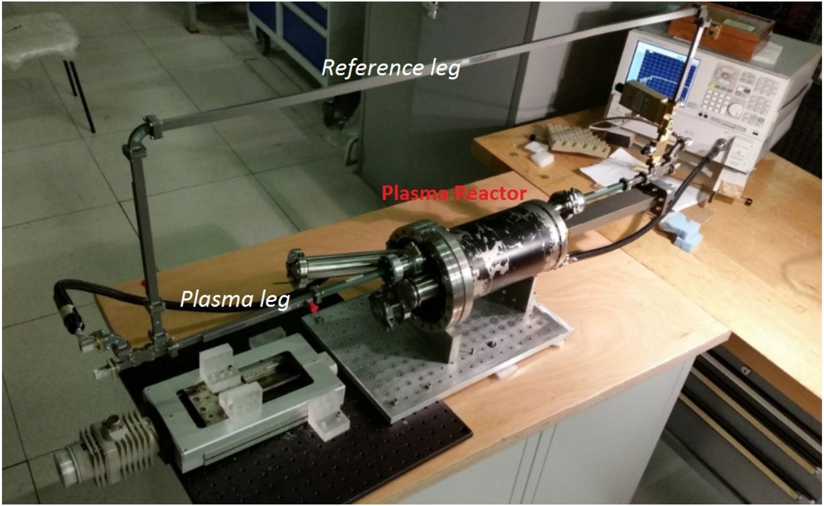
Figure: *Many peaks emerge due to the multipaths.*

Block diagram of the experimental setup



- The "**Plasma Reactor**" ion source is the scenario where the interferometer will be tested, it emulates the operation of an ECR ion source
- *Signal source*: a radio-frequency which gives a linear chirp signal in output.
- *Variable phase shifter*: varies the phase of the signal, useful for the calibration
- *Variable attenuator*: Attenuates the intensity of the signal
- *Directional couplers*: Probes the signal intensity

The experimental setup



Horns assembly

Horns characteristics:

- Diameter: 2.5 cm
- Standard DN25
- Vacuum: kapton layer of 8μm thickness

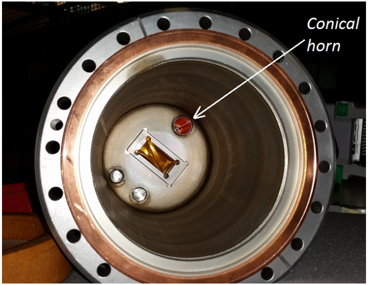


Figure: *a view inside the plasma chamber.*

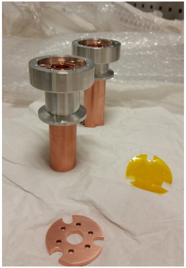


Figure: *Components of horns.*

Figure: *the two horns assembled.*

Horn characterization: impedance matching

Measurement of the impedance matching of the horns

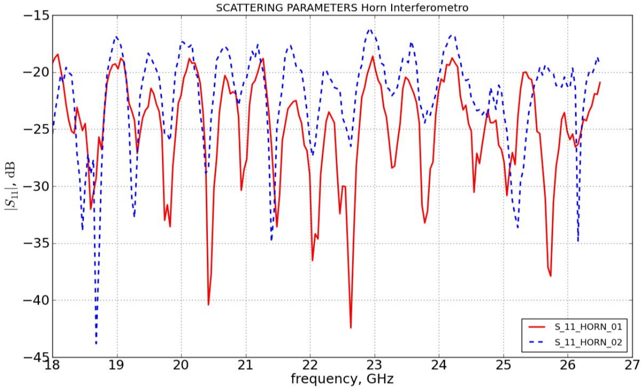


Figure: *The two horns are well matched in the band of interest (18-26 GHz).*

Experimental set up for the measurement of the radiation diagram: we want to measure the antenna transmissivity

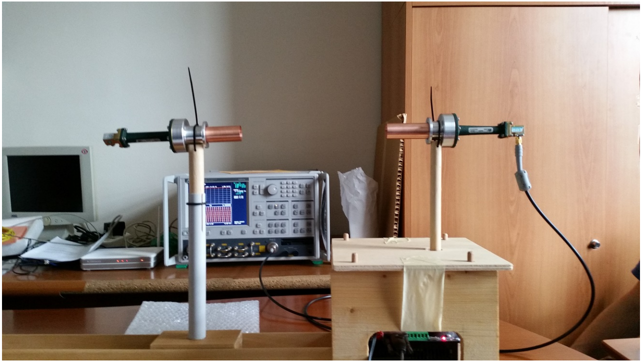


Figure: *One horn is fixed and the other one is placed on a plywood rod, rotating at 3.2 deg steps, for each angle was measured the intensity of the transmitted signal*

Horn characterization: The radiation diagram

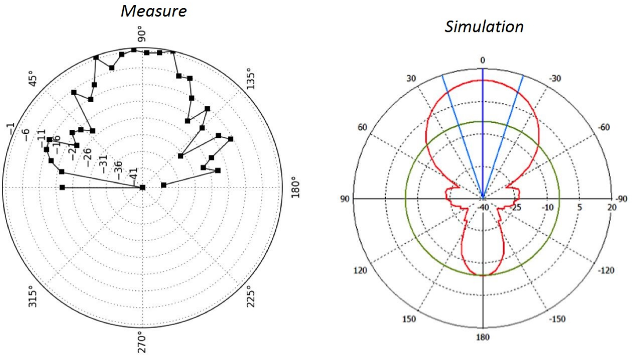


Figure: *The experimental radiation diagram agrees well with the theoretical one, especially for the forward direction. Some noise is present at the sidelobes.*

Preliminary tests: calibration in free space

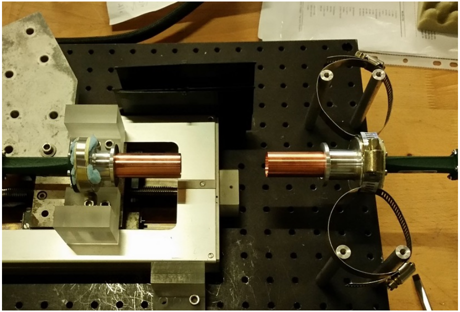


Figure: *One horn was fixed and the other one was moved on a sliding rail at steps of 0.2 mm*

Measure of the wave's phase

$$\Delta\phi = \frac{\omega}{c} n \Delta L$$

Preliminary tests: calibration in free space

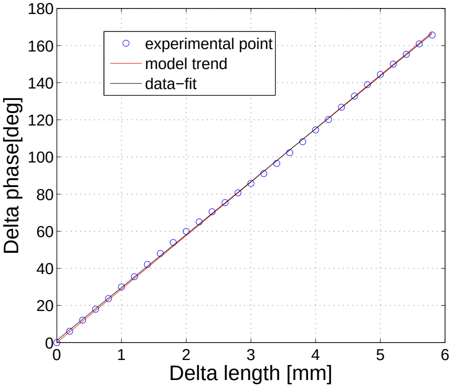


Figure: *Plot of $\Delta\phi$ vs. ΔL, from the slop of the curve we can deduce the refractive index of the medium*

Excellent agreement of the experimental data $\rightarrow n_{meas} = 0.98$ (0.9% error)

Preliminary tests: calibration with dielectric material

- Measure of the wave's phase with layers of mylar of various thickness

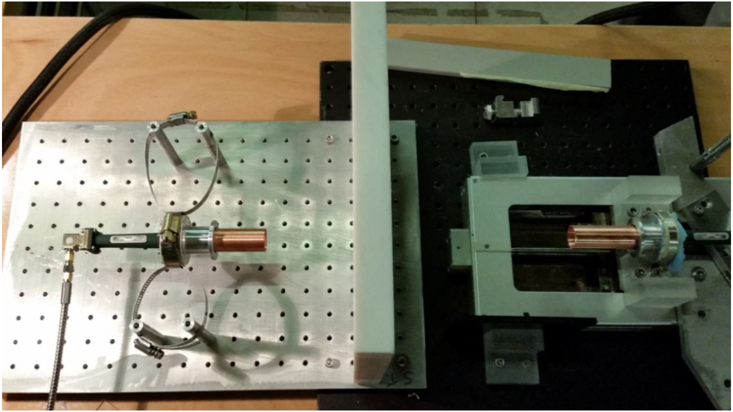


Figure: *Measurement of the wave's phase after the insertion of a mylar layer.*

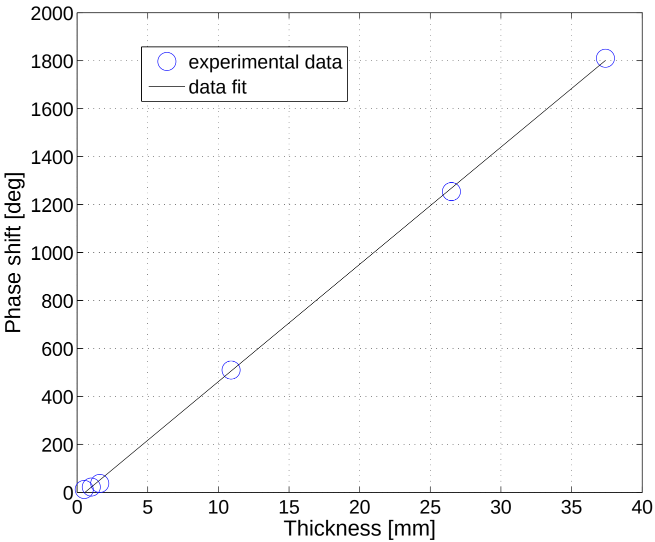


Figure: *Phase vs. mylar thickness*

Preliminary tests: calibration with dielectric material

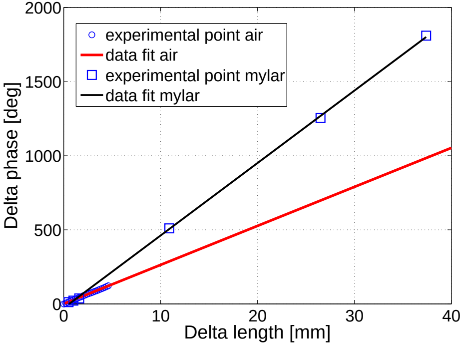


Figure: *Comparison of phase shift air - mylar*

Material	Measured index of refraction	Error	Expected Value
Air	0.98	0.9%	1
Mylar	1.82	2.18%	1.6÷1.8

Beating signal in free space: set up

Figure: *Experimental set up*

Analytical beating signal in free space

$$S(\omega) \propto 2A^2 cos^2 \left\{ \left[\Delta L \sqrt{\omega^2 - \omega_c^2} - \omega L \right] /2c \right\}$$

FFT spectrum of the beat signal in free space

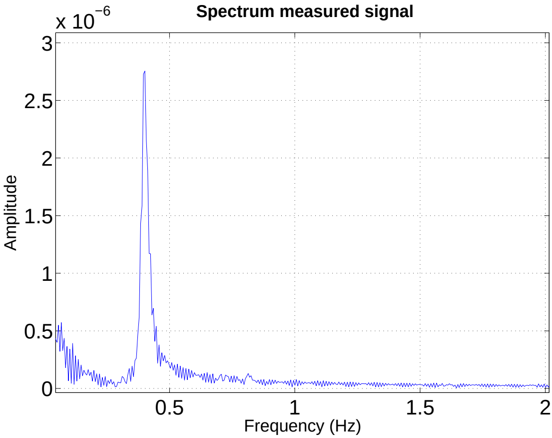


Figure: *FFT spectrum of the beat signal in free space for a frequency sweep varying in the range 20.5-24.5 GHz, a clear peak is visible.*

Beating signal in free space: measured signal

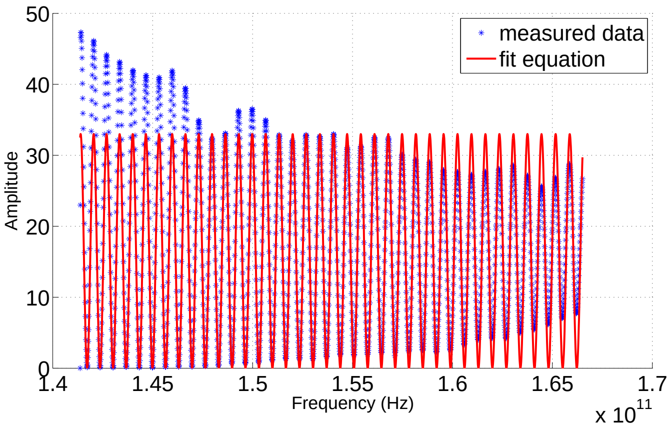


Figure: *curve fitting (red) of the measured beat signal in free space(blue), the frequency of the fitting curve is found from the FFT of the measured signal, the amplitude of the signal decreases because of frequency dependence response of apparatus, anyway we are interested in frequency of the fitting.*

Beating signal with paraffin wax

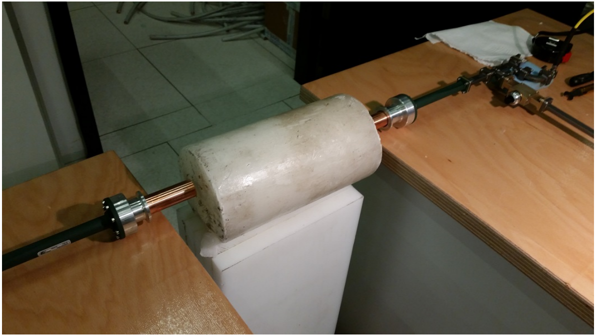


Figure: *A cylindrical block of paraffin was placed between the horns*

Analytical beating signal with paraffin wax

$$S(\omega) \propto 2A^2 cos^2 \left\{ \left[\Delta L \sqrt{\omega^2 - \omega_c^2} - N\omega L \right] /2c \right\}$$

FFT spectrum of the beat signal with paraffin wax

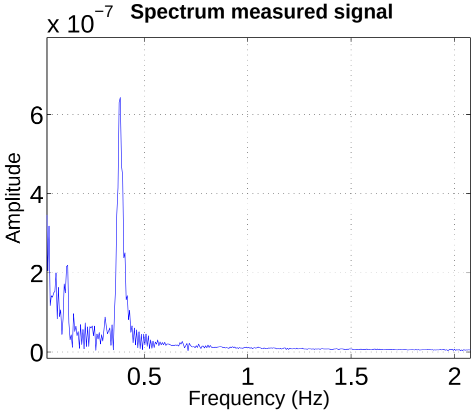


Figure: *FFT spectrum of the beat signal for paraffin wax for a frequency, a clear peak is visible.*

Measured beat signal with paraffin wax

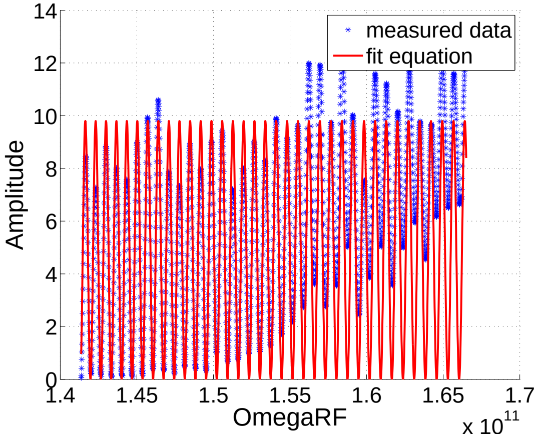


Figure: *curve fitting (red) of the measured signal (blue)*

Installation on Plasma Reactor

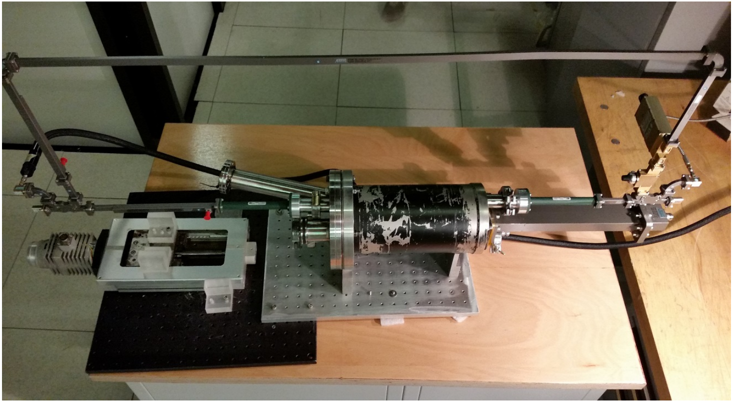


Figure: *The full set up installed on the Plasma Reactor ion source*

Installation on Plasma Reactor

In cavity interferometric setup:
evaluation of the beat signal obtained with the plasma chamber

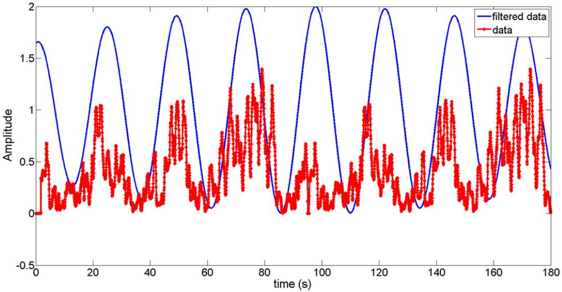


Figure: *The measure signal (red) is very noisy due to the multipaths.*

- The measured signal has a high frequency ripple due to multipaths and is attenuated

Future steps

1. Measurement with plasma in the Plasma Reactor ion source and evaluation of the integrated plasma density.
2. Installation of the interferometer on the new Flexible Plasma Reactor (FPT) ion source for advanced studies on plasma physics.

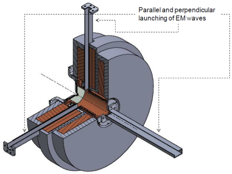


Figure: *Scheme of the "Flexible Plasma Trap"*

Grazie per l'attenzione