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Electrondensity profiles measurements by micro wave reflectometry in front of a lower hybrid plasma heating system

Antoine Jamann, Christine Bottereau, Frédéric Clairet, Christian Jammes

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A. Jamann, C. Bottereau, F. Clairet, C. Jammes and the WEST team^{a)}

CEA, IRFM, 13108 St Paul-lez-Durance cedex, France

a) <http://west.cea.fr/WESTteam>

Introduction

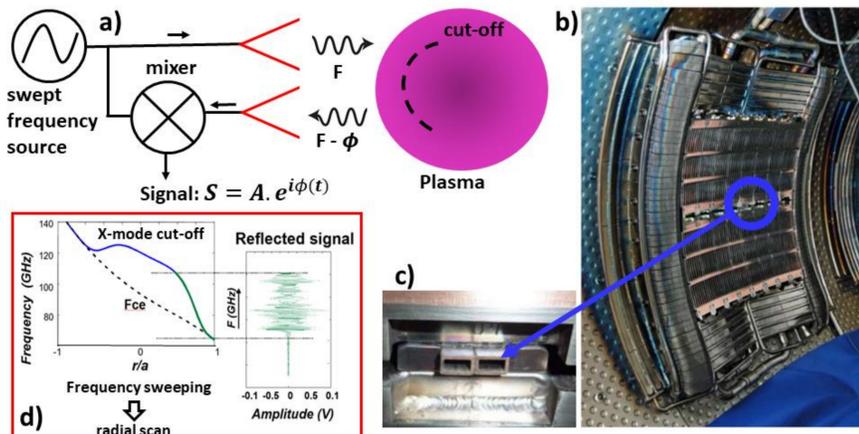
A tokamak is a magnetic confinement fusion device which aims to generate electricity from fusion reactions. To achieve its goal, the plasma contained inside the tokamak must be heated to extremely high temperatures. Thanks to its superconducting coils and special radio frequency heating systems, the French tokamak WEST has the capability of conducting long plasma discharges, allowing to reach constraints on material comparable to what is expected for ITER. Indeed, electromagnetic waves can be employed both to heat the plasma up to fusion temperatures, and to drive current allowing plasma sustainment. On WEST, this is done by the Lower Hybrid Current Drive (LHCD or simply LH) heating system. The power coupling efficiency of the LH launcher is highly dependent on the electron density in its vicinity, accurate measurements of this quantity are thus required.

On the other hand, frequency swept reflectometry is well known for its capability of providing electronic density profile measurements with both high spatial and temporal resolution [1]. Thus, reflectometry measurements in the vicinity of a LH launcher would allow in detail studies of the LH wave-plasma coupling efficiency.

Reflectometry principle and experimental setup

- Reflectometry is a radar technique. A wave with a frequency F is sent towards the plasma and gets reflected if $F = F_{cut-off}$
- For X-mode polarized waves ($\vec{E} \perp \vec{B}_0$):

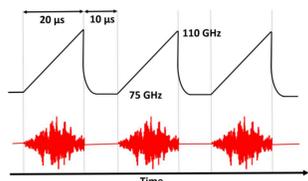
$$F_{cut-off} = \frac{\omega_{ce} + \sqrt{\omega_{ce}^2 + 4\omega_{pe}^2}}{4\pi} \quad \text{with} \quad \begin{cases} \omega_{pe} \propto n_e^{1/2} \\ \omega_{ce} \propto B_0 \end{cases}$$



a) Simplified reflectometer system. b) LHCD launcher. c) Open reflectometer waveguides. d) signal acquisition along frequency sweeping.

- The reflectometer's waveguides are left opened on the plasma side, so they are used as reception and emission antennas.

- probing wave frequency range: 75 -110 GHz (W-band).
- sweep time: 20 μ s, rest time: 10 μ s



Multiple sweeps \Rightarrow multiple density profiles

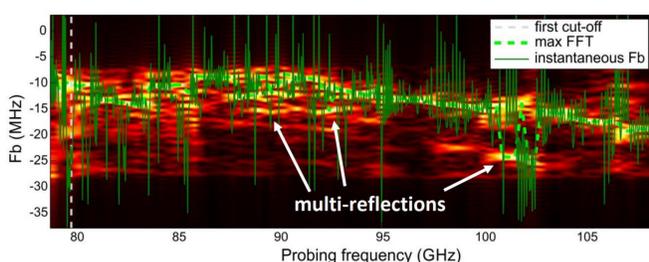
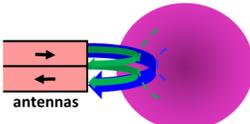
- 10 bits resolution, 100MSamples/s, 10 000 profiles per shot max

The reflectometer antennas are located very close to the plasma and in a metallic environment. These factors combined tend to enhance signal parasite generation such as multi-reflections. Consequently, a special signal processing technique has been developed to deal with very noisy signals.

Signal processing technique

- Signal: $s(t) = A(t) e^{i\phi(t)}$, phase: $\phi(t) = \arg[s(t)]$, beating frequency: $F_b(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt}$
- Signal evolution is described by beating frequencies $F_b(t)$. We use sliding Fast Fourier Transforms (FFTs) to discriminate parasites from the useful signal.
- Parasites caused by turbulence and multi-reflections.
- Use of sliding filters to remove parasites.

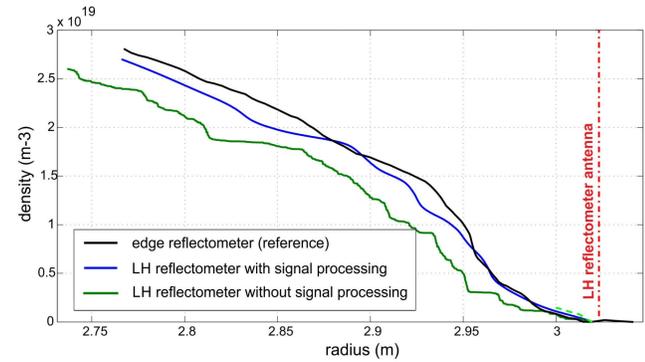
Multi-reflections issue



Spectrogram obtained from sliding FFTs. It presents the signal evolution with all frequency components including parasites.

- Electron density from phase? \Rightarrow Bottollier-Curtet recursive algorithm [2]:

$$\phi_{i+1} = \frac{4\pi F_{i+1}}{c} \int_{r_i}^{r_{i+1}} N_X(r_i, F_{i+1}) dr + \frac{4\pi F_{i+1}}{c} \left[\frac{4}{3} [N_X(r_{i+1}, F_{i+1}) - N_X(r_i, F_{i+1})] \left(\frac{r_{i+1} - r_i}{2} \right) \right] - \frac{\pi}{2}$$

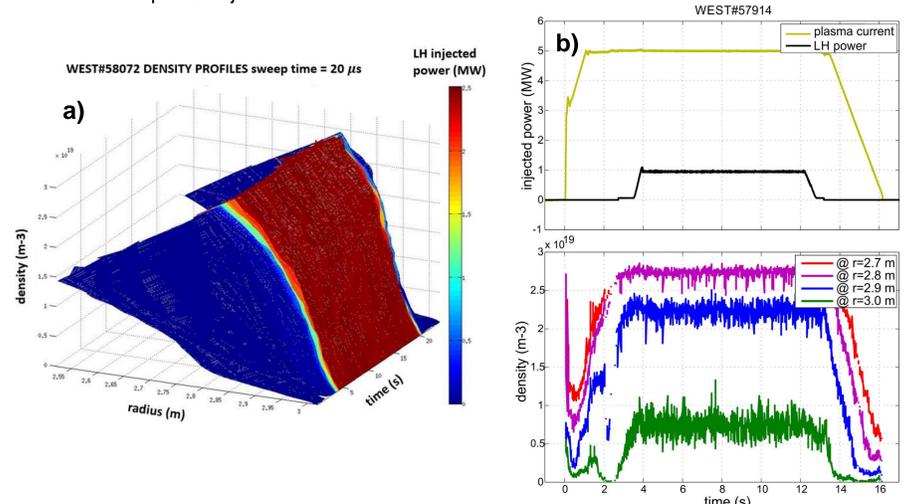


One electronic density profile obtained during an ohmic discharge. The black curve corresponds to edge reflectometer used as a density profile reference. This reflectometer does not suffer from multi-reflections.

- Multi-reflections tend to lower density profiles.
- Density profiles computed with the complete signal processing technique are in good agreement with the standard edge reflectometer [1] which is used as a reference.

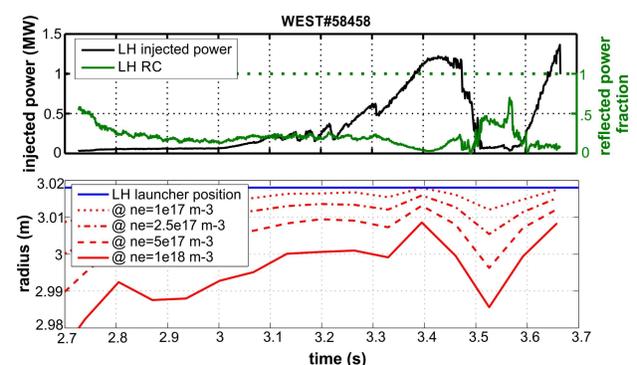
Results and study of the LH coupling efficiency

- Automation of the full signal processing technique \Rightarrow density profiles can now be routinely computed for complete plasma discharges.
- Results clearly show the increase of both electronic density and density fluctuations due to LH power injection.



a) Electronic density profiles in function of time and radius reconstructed for a complete discharge. Time resolution equals 64ms. b) Fluctuating measured electronic density during LH power injection.

- Reflection coefficient RC is a key indicator of the LH wave-plasma efficiency.
- High RCs represent a bad wave-plasma coupling and stem from a density in front of the launcher lower than $10^{17} m^{-3}$ [3]. This is consistent with our measurements.
- The coupling is correct for RCs $\leq 4\%$ i.e. when the $10^{17} m^{-3}$ iso-density curve reaches the launcher's position.
- LH wave-plasma coupling efficiency is multifactorial (LH injected power, plasma position and density) \Rightarrow need further statistical study.
- Need to improve the temporal resolution of the measurements.



LH summary, LH reflectometer iso-density curves. LH launcher is located at $r=3.018$ m.

References

- [1] H. Bottollier-Curtet, « Réflectométrie hyperfréquence pour la détermination de la densité électronique du tokamak Pétula ». PhD thesis, Université de Paris XI, (1986).
- [2] F. Clairet et al. "1 μ s broadband frequency sweeping reflectometry for plasma density and fluctuation profile measurements," Review of Scientific Instruments, vol. 88, p. 113506, 11 (2017).
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