Electron density profiles measurements by micro-wave reflectometry in front of a lower hybrid plasma heating system

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Abstract. This work aims to carry out the challenging measurement of electron density in the vicinity of a tokamak heating system: the Lower Hybrid Current Drive (LHCD) launcher. Coupling efficiency of heating waves with the plasma requires a precise knowledge of edge electron density which can be provided by a frequency swept reflectometer embedded into the launcher. This micro-wave diagnostic operates in a manner analogous to radar, sending an electromagnetic wave into the plasma and receiving the same signal with a phase shift. An iterative method is used to retrieve electronic density from the acquired phase shifts. Special efforts are devoted to signal processing to minimize phase noise and the influence of various parasites on radial density profiles. The automation of this process allows for the reconstruction of profiles for an entire plasma discharge. A first attempt of heating wave coupling efficiency study is presented.

Résumé. Ce travail à pour but de mesurer la densité électronique à proximité d'un système de chauffage de tokamak: le chauffage à fréquence hybride basse générateur de courant (LHCD). L'efficacité du couplage des ondes de chauffage avec le plasma nécessite une connaissance précise de la densité électronique de bord, qui peut être fournie par un réflectomètre à balayage en fréquence. Ce diagnostic micro-onde fonctionne de manière analogue à un radar, émettant une onde électromagnétique dans le plasma et recevant le même signal avec un décalage de phase. Une méthode itérative est utilisée pour calculer la densité électronique à partir des décalages de phase acquis. Des efforts particuliers sont consacrés au traitement du signal afin de minimiser le bruit de phase et l'influence de divers parasites sur les profils de densité radiale. L'automatisation du traitement permet la reonstruction des profils de densité pour l'entièreté d'une décharge plasma. Une première analyse de l'efficacité du couplage des ondes de chauffage avec le plasma est proposée.

1 Introduction

A tokamak is a magnetic confinement fusion device which aims to generate electricity from fusion reactions. To achieve this goal, the plasma contained inside the tokamak must be heated to extremely high temperatures. The ITER project aims to demonstrate that a tokamak can produce more energy than it consumes. While awaiting the completion of its construction, the french tokamak WEST (tungsten (W) Environment in Steady-state Tokamak) supports its successor notably by testing plasma facing components. Thanks to its superconducting coils and special radio frequency heating systems, 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. Section 2 gives an overview of its operation principle and its setup. In a nutshell, 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. This active diagnostic is based on plasma-wave interaction and operates in the micro-wave range quite similarly to a radar. Section 3 provides further explanations about the reflectometry principle. It also describes the characteristics of the reflectometer.

The measurements are quite challenging due to low S/n ratio and require specific signal processing techniques. This is highlighted in section 4 accompanied with experimental results. Finally, the automation of the process allows first LH coupling efficiency studies which are presented in section 5.

2 Lower Hybrid Heating and Current Drive

In a tokamak, external heating systems are used to counterbalance energy losses. The most commonly used heating systems relies on electromagnetic waves created outside the reactor and directed toward the plasma. With well chosen frequencies and polarizations, the energy from the waves can be transferred to the charged particles of the plasma.

The LH launcher is one of the wave heating system technologies. Initially, its purpose was to send "slow waves" of few GHz frequencies to the plasma in order to heat ions. The advantage is that a $\sim 3.7\ GHz$ frequency corresponds to centimeter wavelength so energy can be launched by means of waveguides operating in their fundamental mode. To achieve this goal, the wave has to encounter the so-called lower hybrid resonance during its path through the plasma. However, as it is very challenging for this resonance to occur in the plasma and to control its location, this first idea of the LH waves function has been discarded. LH launchers actually found more success in coupling to electrons at low density via Landau damping. A Landau-damped wave does not affect all electrons, but only those within a certain velocity range around the phase velocity of the wave were electrons get trapped. Since, in a Maxwellian distribution (MHD approximation), there are more slow electrons than fast electrons, the wave accelerates more electrons than it decelerates. As a result, the wave transfers energy to the electrons, leading to its damping. If the launcher is designed to send more power to one side than the other, it becomes possible to generate a non-inductive current. Thus, the LH current is due to an asymmetric deformation of the electron velocity distribution function [1].

In summary, generating a non-inductive current in this manner involves transmitting a high-power directional wave into the plasma. The wave is absorbed, accelerating electrons parallel to the field lines. It will generate the required current for confinement. However, collisions will gradually remove the distortion of the distribution function, leading to the attenuation of the current. Therefore, due to collisions, it is necessary to continuously sustain this distribution function distortion by continually injecting waves into the plasma.

The lower hybrid wave becomes evanescent as it reaches the plasma's outer edge, necessitating the positioning of the lower hybrid launcher in close proximity to the plasma. After that the slow wave successfully tunnels through the evanescent layer at the plasma edge, it must propagate freely toward the plasma center. Nevertheless, under some specific conditions (referred to as the *Stix-Golant accessibility condition*) an interaction occurs between the slow wave and the fast wave between the plasma's cut-off point and its center. This interaction leads to a conversion from the slow wave to the fast wave, resulting in the reflection of energy [2]. Consequently, an important parameter for assessing coupling efficiency is the fraction of reflected power. This fraction can also be expressed as a percentage of the injected power and is sometimes referred to as coupling resistivity or simply as the reflection coefficient (RC). Several historical lower hybrid coupling efficiency studies have been conducted showing its high dependence on the edge electron density and density gradient [3], [4]. It has been proven that only the first few millimeters of the edge plasma matters for coupling efficiency.

On WEST, the LHCD system stands as an indispensable tool, vital for the realization of long pulse operation objectives. It is composed of distinct launchers which provides in total a maximum power of 7 MW [5]. These launchers are actively cooled and equipped with carbon protection limiters, fortified with tungsten coating. Moreover, both launcher offer radial mobility within a few centimeters. The LH launcher studied in this work is known to has optimal coupling conditions when the edge electron density is about $n_c = 2 - 3 \times 1.7 \times 10^{17}\ m^{-3}$ [6]. To optimize wave coupling, both launchers are outfitted with localized gas injection systems and various diagnostic tools including our reflectometer.

3 Reflectometry principle and experimental setup

A reflectometer consists in sending an electromagnetic wave towards the plasma. The interaction between the wave and the plasma occurs based on their respective characteristics, ultimately resulting in the reflection of the wave. Specifically, a certain plasma behaves as a mirror for a wave with a frequency corresponding to particular threshold value called the cut-off frequency.

The mathematical framework capable of describing this behavior combines electromagnetic wave equations (Maxwell's equations) with plasma equations (electron equation of motion). The outcome of this combination is known as "the wave equation" which writes,

$$\frac{\partial \vec{J}}{\partial t} = \varepsilon_0 \, \omega_{pe}^2 \, \vec{E} - \vec{J} \times \vec{\omega_{ce}} \tag{1}$$

with the electron plasma frequency $\omega_{pe} = (e^2 n_e / \varepsilon_0 m_e)^{1/2}$ and the electron cyclotron frequency $\vec{\omega_{ce}} = e\vec{B_0}/m_e$.

The reflectometry framework consists in several assumptions: stationary plasma, ions considered at rest, non-relativistic electrons and monochromatic probing wave.

From equation (1) one can easily distinguish two cases, if the current induced by the wave is parallel to the local external magnetic field $\vec{B_0}$, electrons are not influenced by the Laplace force $\vec{j} \times \vec{B_0}$; on the contrary, if the current is perpendicular to the external magnetic field, electrons are influenced by the Laplace force and the magnetic field matters. As a result, two polarization modes exist, the O-mode where $\vec{E} \parallel \vec{B_0}$ and the X-mode with $\vec{E} \perp \vec{B_0}$. X-mode polarization offers the possibility to measure the very edge electronic density [7]. In this context, the frequency at which the wave gets reflected by the plasma equals,

$$F_{cut-off} = \frac{\omega_{ce} + \sqrt{\omega_{ce}^2 + 4\omega_{pe}^2}}{4\pi} \tag{2}$$

In consequence, one cut-off frequency corresponds to one electronic density. Moreover, the longer is the wave path through the plasma, the larger its phase shift. Thus, sweeping the wave's frequency is equivalent to probe deeper into the plasma. Finally, the electronic density is computed from the phase of the reflected signal using the Bottollier-Curtet algorithm [8].

This section presents the currently LH reflectometer installed on WEST. For reasons discussed in the above, we use X-mode polarized waves ranging from 75 GHz to 110 GHz (W-band). The reflectometer's waveguides are embedded between the two rows of the LHCD launcher and are left opened on the plasma side, so they are used as reception and emission antennas (see figure 1). Thus, electron density is measured radially in the azimutal plane of the low field side of the tokamak. An heterodyne detection system provides good S/n and discriminates phase from amplitude of the reflected signal [9].

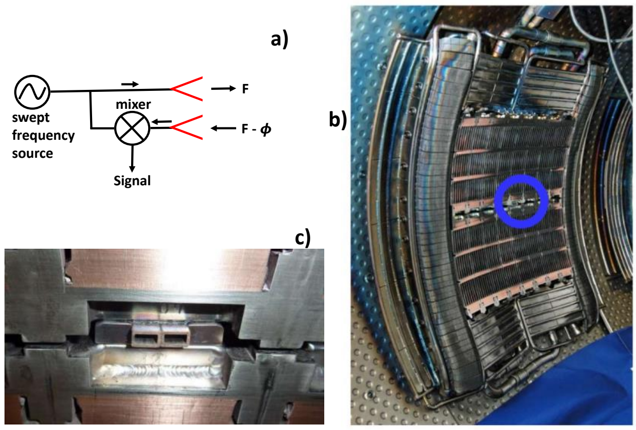

Figure 1: a) simplified reflectometer system. b) LH launcher with a blue circle indicating the reflectometer open waveguides. c) open waveguides embedded between two LH launcher rows.

4 Signal processing technique

Several reasons are responsible for the degradation of the S/n ratio of the LH reflectometer signal, making it particularly difficult to process. Among these reasons are the fact that LH reflectometer antennas are extremely close to the plasma and are located in a metallic environment. These factors combined tend to enhance signal parasites generation. Consequently, a special signal processing technique has been developed to deal with very noisy signals.

Once the reflected signal $s(t) = A(t)\ e^{i\phi(t)}$ is acquired, there are two ways of extracting the phase evolution in function of the probing frequency. The first consists in simply computing the phase as $\phi(t) = arg[s(t)]$, and then the "instantaneous" beating frequencies $F_b = d\phi(t)/2\pi dt$. The second is done by applying sliding Fast Fourier Transforms (FFTs) on the signal. The advantage of this method is that it provides a full picture of every signal component by averaging on a moving window. The signal evolution is thus represented by a spectrogram, useful to discard signal components corresponding to parasites. From the spectrogram, it is possible to extract beating frequencies taking the amplitude maxima.

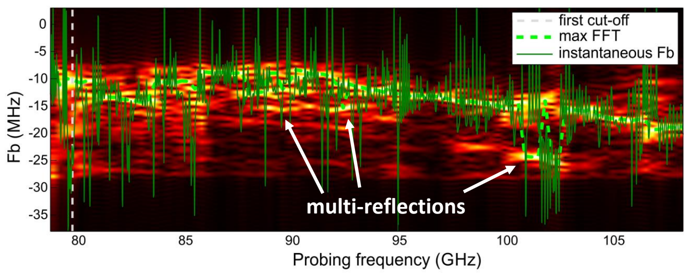

Figure 2: Spectrogram obtained from sliding FFTs. It presents the signal evolution with all frequency components including parasites.

Figure 2 is an example of a spectrogram which exhibits parasitic frequencies of significant amplitudes. When these parasites have beating frequencies quite distant from the useful signal, they can be easily eliminated by employing a pass-band filter. However, when parasites are very close; since the useful signal's beating frequencies often vary a lot in function of probing frequency, the use of pass-band filters could result in cutting out the useful signal. These parasites, occurring at frequencies close to the useful signal, are frequently induced by multi-reflections. Indeed, it is common for a part of the probing wave to not be reflected only once by the plasma, but rather to bounce multiple times between the cut-off layer and the LH launcher/walls before reaching the reception waveguide [10]. As a result, for a given probing frequency, F_b values will be too high (in absolute value), as it corresponds to a wave that has traveled for a longer time into the plasma.

The special processing technique uses both F_b from FFT's maxima and instantaneous F_b and is able to remove most of the anomalous points corresponding to multi-reflections. Then, it employs a sliding filter which allows for the removal of remaining parasites and a slight reduction in noise. The corrected phase of the reflected signal can finally be extracted and fed into the Bottollier-Curtet algorithm to retrieve electronic density. Figure 3 shows density profiles obtained at one time of an ohmic discharge. The profile resulting from the complete signal processing technique (blue) is in good agreement with the standard edge reflectometer [11] which is used as a reference. In fact, this reflectometer is away by 1.5 m from the plasma and do not suffer from multi-reflection echoes. On the contrary, the non-treated density profile (green) exhibits erroneously low densities. As discussed previously, this is due to the influence of multi-reflections on F_b.

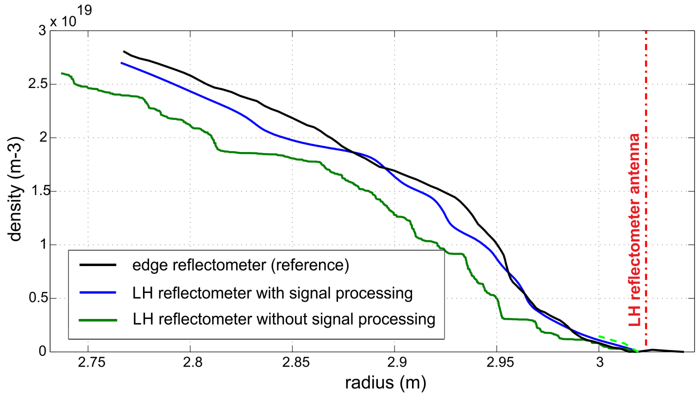

Figure 3: One electronic density profile obtained during an ohmic discharge. The black curve corresponds to edge reflectometer used as a density profile reference. The green curve results from the LH reflectometer data without specific signal processing while the blue one is obtained with the complete treatment.

5 Preliminary results and study of the LH coupling efficiency

Special endeavors have been dedicated to the automation of the full signal treatment and reconstruction process. Density profiles can now be routinely computed for complete plasma discharges which should allow to start LH coupling efficiency studies. First results show clearly the increase of electronic density due to the injection of LH power (see figure 4).

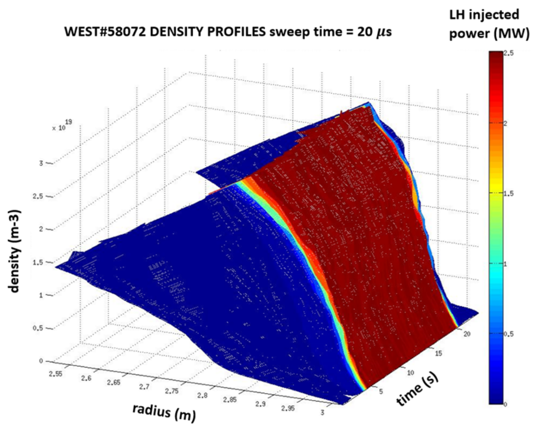

Figure 4: Electronic density profiles in function of time and radius reconstructed for a complete discharge. Time resolution equals 64ms.

However, it has also been observed that phase noise is increased when LH power is injected. On figure 5, it is clear that the density measured by the LH reflectometer fluctuates much more during LH phase than during ohmic phase. Moreover, fluctuations are much more important just in front of the LH launcher than at higher distance. For this shot, LH launcher is located at $r = 3.015\ m$. Density at 1.5 cm from the antenna (green curve) is very noisy when LH injected power reaches 1 MW. From 20 cm away from the antenna (purple curve) the noise is considerably reduced. This phenomena is likely due to the increase of the density fluctuations towards the plasma edge.

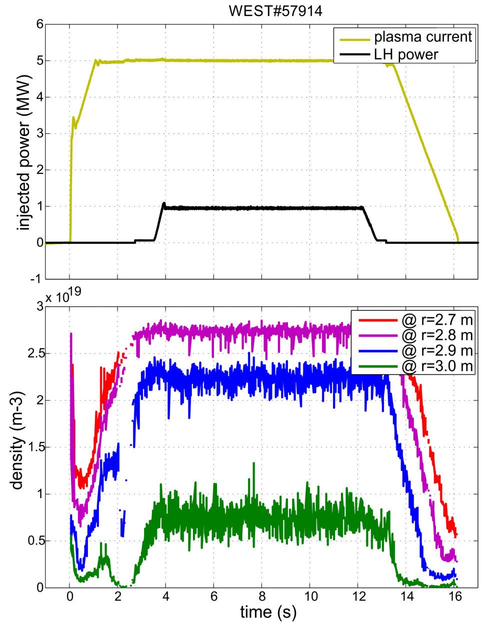

Figure 5: Fluctuating measured electronic density during LH power injection.

The following study presents a rather poor shot conducted with difficulty to couple LH injected power to the plasma. As illustrated in the first graph of figure 6, the reflection coefficients RCs are excessively high during the LH heating phase, averaging 13.3% which indicates a poor coupling efficiency. Therefore, the objective of this study is to investigate the factors influencing the RCs.

During the slow and anomalous LH power ramp-up, RCs are unsatisfactory yet remain stable at approximately 20%. Such elevated RCs are elucidated by M. Preynas [6] to stem from a density in front of the launcher that is lower than $n_c \sim 1 \times 10^{17}\ m^{-3}$. This is consistent with our measurements: the second graph in figure 6 depicts an iso-density curve of $n_e = 10^{17}\ m^{-3}$ positioned a few millimeters away from the launcher. When this iso-density curve eventually reaches the launcher (3.4s), RCs decrease to acceptable values $\leq 4\%$. This moment also coincides with the peak of injected power which is actually the parameter that governs the dynamic of this study. Shortly after 3.5 s, the opposite phenomenon occurs: LH power decreases, and RCs rise to a plateau of approximately 40%. Additionally, the plasma experiences a minor detachment, resulting in a decrease in edge density. Notably, the iso-density curve for $n_e = 5 \times 10^{17}\ m^{-3}$ shifts by 1.5 cm from its previous location, creating a separation of 2 cm from the antenna.

So when injected power is increased, density increases, leading to a reduction of reflected power and reflected power fraction. Nonetheless, let us remind that $RC = P_{reflected}/P_{injected}$. The injected power appears in the RC formula such that, if it increases, it will directly leads to a decrease of RC. Thus this double influence on RCs makes the density variation contribution to RCs difficult to quantify.

Determining the specific contribution of each factor is challenging, necessitating the need for statistical studies to delve deeper into the matter. Additionally, the temporal resolution of our measurements is relatively low for the phenomena under study. This should be improved in upcoming experimental campaigns.

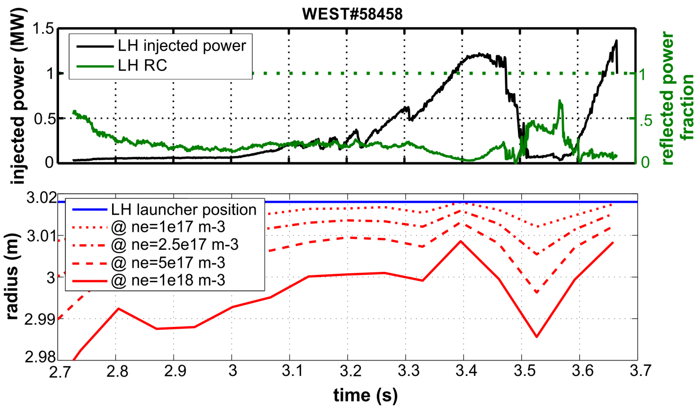

Figure 6: LH summary, LH reflectometer iso-density curves. LH launcher is located at $r = 3.018\ m$.

6 Discussion and perspectives

This work presented a plasma diagnostic based on electromagnetic wave which aims to study the efficiency of an other wave for plasma device, the LH heating system.

A reflectometer sends a wave at a given frequency, it propagates into the plasma until it gets reflected by a cut-off layer with a specific electron density. A higher frequency leads to the wave being reflected by a higher density (i.e, deeper in the plasma). Considering that its phase varies along its path through the plasma, frequency sweeping allows access to different cut-off layers and thus enables probing deeper into the plasma.

Most of the efforts were allocated to the development of a signal processing code allowing to compute radial density profiles from acquired phases. Particularly, the most significant challenge was to find a process capable of handling a low S/n ratio and extract the relevant phase. Several factors contribute to this diminished signal quality, such as the injected wave power, the complex environment surrounding the LH launcher, supra-thermal electron generation [12], and multi-reflections. The latter is the biggest issue on this reflectometer, it greatly influences density profiles by lowering density.

Nonetheless, the accuracy of the finally reconstructed density profiles was verified through comparison with profiles from another reflectometer. Furthermore, the processing has been automated, enabling the generation of profiles for complete plasma discharges. Further progress are required to allow proper studies of the LH plasma-wave coupling efficiency, namely the reflectometer time resolution has to be improved. Additionally, ongoing modelling efforts are devoted to better understand the cut-off layer physics in order to improve reflectometry measurements precision [10].

For future works it would be interesting to compare the LH reflectometer profiles with simulations. Specifically, the density as function of reflection coefficients could be benchmarked using the linear coupling code [13] or the full-wave modeling of the non-linear coupling [6].

References

[1] C. F. F. Karney and N. J. Fisch, "Numerical studies of current generation by radio-frequency traveling waves," *The Physics of Fluids*, vol. 22, pp. 1817–1824, 09 1979.

[2] T. Stix, *Waves in Plasmas.* Waves in Plasmas, American Institute of Physics, 1992.

[3] M. Brambilla, "Waveguide launching of lower hybrid waves," *Nuclear Fusion*, vol. 19, p. 1343, oct 1979.

[4] J. Stevens, M. Ono, R. Horton, and J. Wilson, "Edge density profile effects for lower hybrid waveguide coupling," *Nuclear Fusion*, vol. 21, p. 1259, oct 1981.

[5] L. Delpech, J. Achard, A. Armitano, G. Berger-By, A. Ekedahl, L. Gargiulo, M. Goniche, D. Guilhem, P. Hertout, J. Hillairet, R. Magne, P. Mollard, P. Piluso, S. Poli, M. Prou, A. Saille, and F. Samaille,

"Evolution of the tore supra lower hybrid current drive system for west," *Fusion Engineering and Design*, vol. 96-97, pp. 452–457, 2015. Proceedings of the 28th Symposium On Fusion Technology (SOFT-28).

[6] M. Preynas, M. Goniche, J. Hillairet, X. Litaudon, A. Ekedahl, and L. Colas, "Experimental characterization and modelling of non-linear coupling of the lower hybrid current drive power on tore supra," *Nuclear Fusion*, vol. 53, p. 013012, jan 2013.

[7] F. Clairet, C. Bottereau, J. M. Chareau, M. Paume, and R. Sabot, "Edge density profile measurements by x-mode reflectometry on tore supra," *Plasma Physics and Controlled Fusion*, vol. 43, p. 429, apr 2001.

[8] H. Bottollier-Curtet, *Réflectométrie hyperfréquence pour la détermination de la densité électronique du tokamak Pétula.* PhD thesis, Université de Paris XI, 1986.

[9] R. Sabot, C. Bottereau, J.-M. Chareau, F. Clairet, and M. Paume, "Single sideband modulator, a key component of Tore-Supra heterodyne reflectometers," *Review of Scientific Instruments*, vol. 75, pp. 2656–2659, 07 2004.

[10] F. da Silva, S. Heuraux, E. Ricardo, P. Quental, and J. Ferreira, "Assessment of the measurement performance of the in-vessel system of gap 6 of the ITER plasma position reflectometer using a finite-difference time-domain Maxwell full-wave code," *Review of Scientific Instruments*, vol. 87, p. 11E727, 09 2016.

[11] F. Clairet, C. Bottereau, A. Medvedeva, D. Molina, G. D. Conway, A. Silva, U. Stroth, A. U. Team, T. S. Team, and E. M. Team, "1 µs broadband frequency sweeping reflectometry for plasma density and fluctuation profile measurements," *Review of Scientific Instruments*, vol. 88, p. 113506, 11 2017.

[12] L. Valade, *Modélisation de l'accélération d'électrons au voisinage des antennes lower-hybrid.* PhD thesis, Université d'Aix-Marseille, 2023.

[13] J. Hillairet, D. Voyer, A. Ekedahl, M. Goniche, M. Kazda, O. Meneghini, D. Milanesio, and M. Preynas, "Aloha: an advanced lower hybrid antenna coupling code," *Nuclear Fusion*, vol. 50, p. 125010, nov 2010.