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Mesure en temps réel du profil de densité dans le tokamak WEST par réflectométrie

Real time reflectometry measurement of density profiles in WEST tokamak

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Mots clés: plasma electronic density, reflectometry, micro-wave radar, real-time, densité électronique du plasma, réflectométrie, radar micro-ondes, temps-réel

Résumé/Abstract

En recherche sur la fusion nucléaire, les diagnostics sont les instruments mesurant les paramètres du plasma que ce soit pour son contrôle ou pour son étude, La réflectométrie est un diagnostic non-perturbatif basé sur le principe du radar : le diagnostic émet des micro-ondes (dizaines de gigahertz) qui se réfléchissent dans le plasma. La réception du signal réfléchi permet de calculer les profils radiaux de la densité électronique. Le traitement des mesures s'effectue pour l'instant après la décharge car l'algorithme est demandeur en temps de calcul. Une mesure temps-réel des profils de densité permettrait d'améliorer la détection et le contrôle des phénomènes et performances du plasma. Grâce au développement d'une carte d'acquisition innovante pour le diagnostic de diffusion Thomson, un calcul en temps réel du profil de densité est en cours de développement. Le traitement des données a été adapté pour être réalisé en temps réel, et deux nouvelles méthodes ont été développé pour réduire le temps de calcul. La reconstruction d'un profil de densité prend désormais 2 millisecondes. L'algorithme doit être implémenté dans le système de contrôle du réflectomètre pour obtenir les premières mesures en temps-réel pendant la campagne expérimentale actuelle qui finit en avril.

In nuclear fusion research, diagnostics are the instruments that measure the various plasma parameters serving for tokamak control or physics studies. Reflectometry is a non-intrusive diagnostic for the plasma density based on the radar principle: it emits microwaves (tens of gigahertz) that are reflected inside the plasma. The radial profile of the electronic density can be reconstructed from the phase or time delay of the return signal. The profiles are currently reconstructed with a post-discharge processing as the algorithm is computer and time-demanding. A real-time measurement of the density profile would improve the detection and control of plasma phenomena and performances. Thanks to the development of an innovative acquisition card for the Thomson Scattering diagnostic a real-time reflectometry measurement is being implemented. The data processing has been adapted to be performed in real-time and two new methods were developed to reduce the computer time. Single profile reconstruction in two milliseconds has been achieved. The algorithm will be implemented in the reflectometry control system to perform the first real-time measurement during the current winter experimental campaign.

1 Interest in real-time electronic density profile measurements

In magnetic nuclear fusion experiment, the electronic density n_e is a major parameter, both for real-time plasma control and physics studies. Interferometry is the standard diagnostic for real-time density measurement but provides only line-integrated quantities. Real-time measurement of the radial density profile $n_e(R)$ (R being the major radius) would enable control of the density profile at the plasma edge, a key parameter for plasma stability and performance optimization. Reflectometry is a radiofrequency diagnostic that probes the plasma with microwaves and returns the radial electronic density profiles with a centimeter precision. Currently, the data are processed after the plasma discharge and the reconstruction of 2000 profiles takes about 10 minutes. Real-time reflectometry measurements have been performed in the Ordinary polarization (in O-mode, the wave electric field E is parallel to the plasma magnetic field B_0) in AUG and Compass, and is planned for ITER and DEMO w [1]. In AUG, O-mode reflectometry was used for the real-time control of the plasma edge position. However, O-mode requires the knowledge of the very edge density profile to initialize the density reconstruction. The aim of this work is to develop real-time reflectometry measurement on the WEST tokamak using the eXtraordinary polarization ($E \perp B_0$) which enables plasma reconstruction without any assumption on the edge density profile but requires more computation. To do so, a new acquisition card will be used, with computation and storage abilities matching the real-time reflectometry challenge [2]. The first application of the real-time reflectometry measurement could be the Radiative X-Point (XPR) configuration control [3]. It is an efficient configuration to get an optimized confinement time in injecting neutral gas. Real-time reflectometry would measure the density and allow a control loop on the neutral injection, maintaining the equilibrium of the XPR regime.

The primary aim of this article is to introduce a new method that has been testing for reconstructing the electronic density profiles. The article explains the contribution of the method to real-time challenges and assess its level of accuracy.

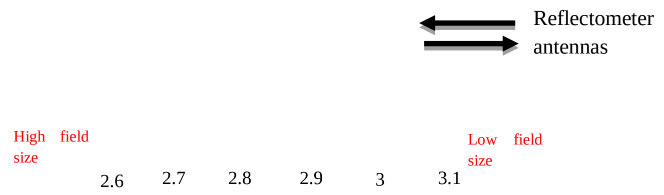
2 Reflectometry principle

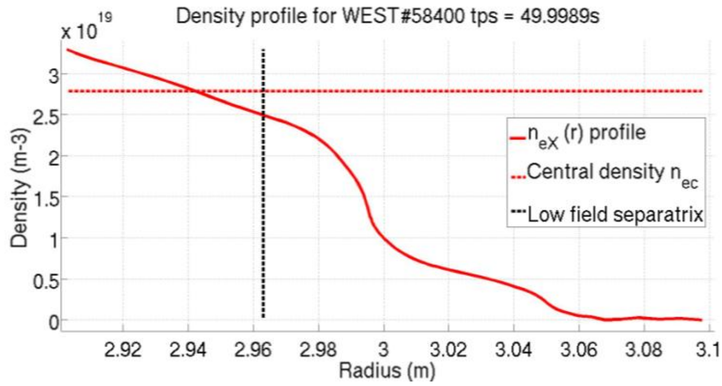
Reflectometry operates based on the radar principle, where a microwave is emitted into the plasma and subsequently received using the same antenna. The wave propagation follows the propagation equations within a one-dimensional field characterized by a certain refractive index N. The plasma refractive index N depends upon various plasma properties, including the plasma electric frequency and the cyclotronic electric frequency:

$$F_{pe} = \sqrt{\frac{n_e e^2}{4\pi^2 \varepsilon_0 m_e}} \qquad F_{ce} = \frac{eB_{plasma}}{2\pi m_e}$$

Additionally, it depends on the orientation of the wave electric field compared to the plasma magnetic field. In Ordinary polarization (O-mode), the wave electric field is parallel to the magnetic field: $E \,//\, B_0$, which leads to N_O, and in eXtraordinary polarization (X-mode), the fields are perpendicular: $E \perp B_0$ and gives the index N_X.

With a refractive index satisfying $N^2 > 0$, the wave propagates through the plasma. Conversely, when $N^2 = 0$, a cut-off point is reached, causing the wave to no longer propagates and be reflected by the plasma. The frequencies that verify this reflection conditions are defined as the cut-off frequencies: $F_0 = F_{pe}$ in O-mode and F_{Xh}, F_{Xb} in X-mode. Figure 1 illustrates these different frequencies useful for reflectometry comprehension. The





wave originates from the low field side at $r > 3.1m$ and moves toward the plasma center $r = 2.5m$.

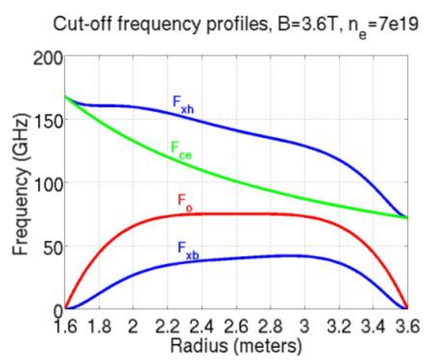


Figure 1: Cut-off, plasma electric and plasma cyclotronic frequencies in the frequency range of a reflectometer (1a). One radial electric density profile (1b).

In the one dimensional WKB approximation, the phase of the wave reflected on the plasma is depending on the refractive index along the propagating path:

$$\phi = 2k_0 \int_0^{r_c} N(r)dr - \frac{\pi}{2}$$

The phase of the return signal is collected and used in a calculation to determine the radial position of the reflection cut-off r_c. Then, with knowledge of the profiles of F_{pe}, F_{ce} and $B_{plasma}(r_c)$, the corresponding density n_e at the radial position r_c is deduced. The frequency source is swept linearly in time (75-110 GHz in 1 µs), enabling the probing signal to propagates progressively deeper into the plasma. In a single frequency sweep, the signal probes all along the radial direction, allowing to reconstruct one radial profile. To capture various profiles over time, the reflectometer emits multiple frequency sweeps. Figure 1a) illustrates a reconstructed density profile from one such frequency sweep.

3 Density profile reconstruction

The return signal is acquired and the phase is extracted for the whole frequency sweep. After several filtering and cleaning processes, the phase is used is a step-by-step algorithm to reconstruct the density profile $n_e(r)$.

i) Initialization :

The recurrence algorithm is initialized with the radial position of the edge of the plasma $n_e(r_0) = 0$. The existing method used in the post-discharge algorithm relies on an amplitude threshold, determined by the signal amplitude jump at the external position of the plasma. When the amplitude of the signal surpasses a predefined threshold, the signal is considered as reflecting on the edge of the plasma. In Figure 2, for frequencies below 65 GHz, the absence of a cut-off layer results in wave reflection on the inner side of the vacuum vessel. Conversely, above 65 GHz, the frequency is high enough for the wave to be reflected by the plasma. The plasma being located closer to the reflectometer antennas results in a sudden increase in amplitude. At this initial plasma position, the density is assumed to be zero: $n_e(r_0) = 0$. This initialization point serves as a starting reference for the profile reconstruction.

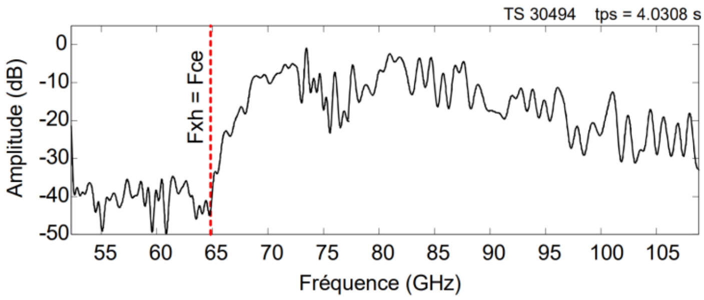


Figure 2: Amplitude jump for the initialization method

ii) Step by step reconstruction

Concerning the reconstruction, the current method uses the phase of the return signal: each point of the profile is computed using the phase of the corresponding cut-off layer in the Bottollier-Curtet algorithm [4].

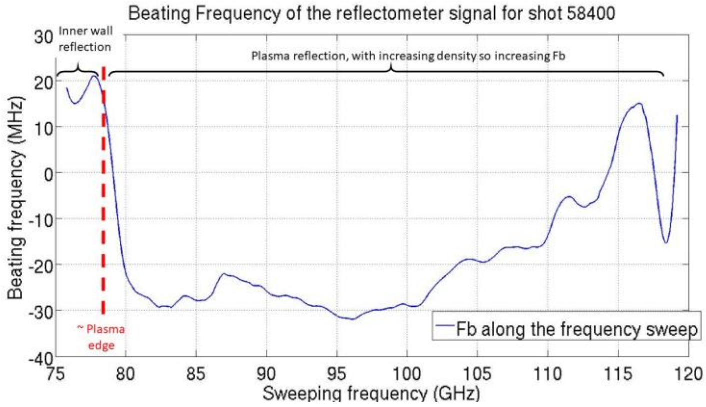
Starting at the initialized position r_0, each radial cut-off position r_{i+1} is computed by using the corresponding extracted phase ϕ_{i+1}, and the density profile previously computed until r_i. To do so, an approximation is made to deduce r_{i+1} from the formula of the phase ϕ_{i+1} through the refractive index N_X equal to zero at the cut-off. Then, $n_{e_{i+1}}$ is deduced from r_{i+1} and the magnetic field B_{i+1} through the formula of the cyclotronic electronic frequency F_{ce}.

4 Real-time adaptation

The current reconstruction program requires signal processing to obtain an exploitable phase. The filtering processes are time and computation demanding, and do not suit the challenges of real-time measurement. This article presents the development of a two new methods that enable to reconstruct the radial density profile without this large amount of data processing, but still extracting accurate data.

i. Initialization

First, a new initialization method was developed relying on the jump in the signal beating frequency. The beating frequency F_b is defined as the frequency of the reflected signal with respect to the reference signal frequency. This frequency jump is caused by the change of the reflection position between the inner wall and the outer plasma edge and is illustrated in Figure 3a. Figure 3a shows the beating frequency of the return signal for one frequency sweep: $F_b = \frac{1}{2\pi}\frac{d\phi}{dF}$ that varies depending on the position of the reflection in the plasma. The frequencies are different from Figure 2 because the studying plasma discharges where different but the principle stay the same. It illustrates the different interesting areas along the wave propagation during the frequency sweep. The new initialization method uses two filters to separate the signal, and the initialization point is determined when the amplitudes of the two filtered signals intersect, as shown in figure 3b.



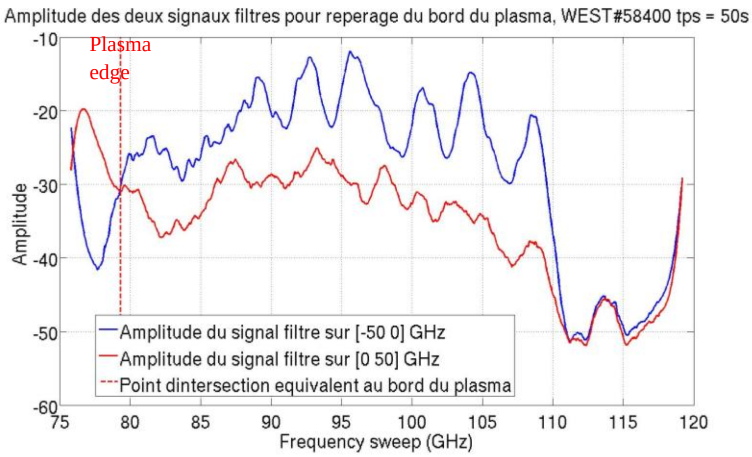


Figure 3: Beating frequency of the return signal in different plasmas areas (3a). Amplitudes of two filtered signals to detect the edge of the plasma (3b).

Amplitude (dB)

Figure 4 illustrates the initialization positions computed with the two different methods along time for an entire discharge, in addition to the low field side separatrix of the plasma R_{ext}. A shift is observed between the two initialization positions: it can be attribute to the low density plasma at the edge. The original computation collects the edge of this low density plasma, while the new calculation detects the frequency jump, marginally

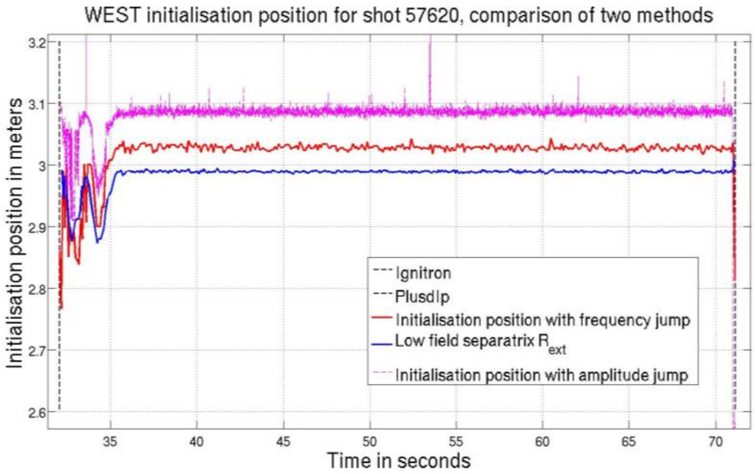


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Figure 4: Comparison of the initialization positions from two computation methods, along time for an entire plasma discharge of WEST.

The accuracy of this new initialization method has been evaluated through an analysis of its effects on the reconstructed profiles. It is observed that the slight deviation in the initialization point has minimal impact on the reconstruction, as depicted in Figure 5. Figure 5 visually presents the difference in radial positions of the density profile corresponding to the two initialization points. Consequently, introducing a small section a plasma with nearly zero density does not significantly affect the overall profile.

This new method enables a gain of time by minimizing the computational demands of signal processing, necessitating the application of two filters and two Savitzky-Golay cleaning procedures, as opposed to the comprehensive data processing methodology initially employed. In addition to the temporal efficiency gained, the signal can undergo real-time filtering during the reception of the return signal, avoiding the necessity to wait for the entire sweep for processing and utilization. Consequently, it is well suited for real-time signal processing.

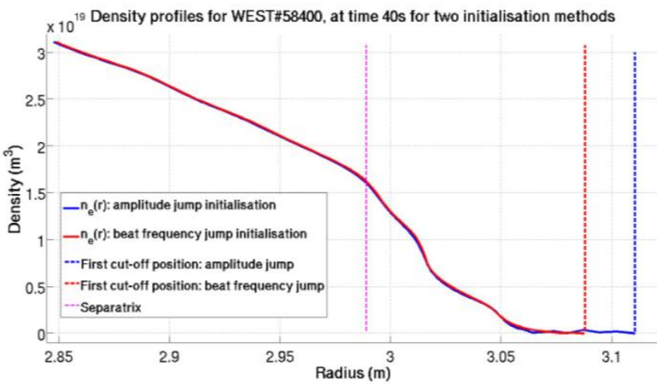


Figure 5: Electronic density profile for two initialization methods and illustration of the accuracy of the new one (5).

ii. Time of flight extraction

The newly tested real-time method uses time of flight rather than phase, making extraction more straightforward and less susceptible to noise and error. This facilitates the reconstruction with a reduced number of radial position. The phase is originally extracted from the signal, but requires an extensive cleaning process for usability. In contrast, the new method employs the time of flight, that can be directly extracted from the spectrogram of the return signal, as depicted in Figure 6a. The spectrogram is generated through the application of a Short Term Fourier Transform (STFT) along the frequency sweep. The intense line corresponds to the beating frequency F_b, and its extraction from the signal involves identifying the maximum of each windowed spectrum. The time of flight being the propagation time of the wave round-trip in plasma, it is directly obtained from this relation : $\tau = F_b \frac{\Delta t}{\Delta F}$. This approach enables the acquisition of a reasonable accurate time of flight without necessitating extensive signal processing. Figure 6b illustrates the time of flight extracted from a cleaned and processed signal, involving phase extracting with the unwrap function, in comparison to a time of flight extracted from the STFT method with a entirely unprocessed signal. It can be observed that the two time of flight are quite comparable, and the difference will not result in a significant impact on the profile reconstruction.

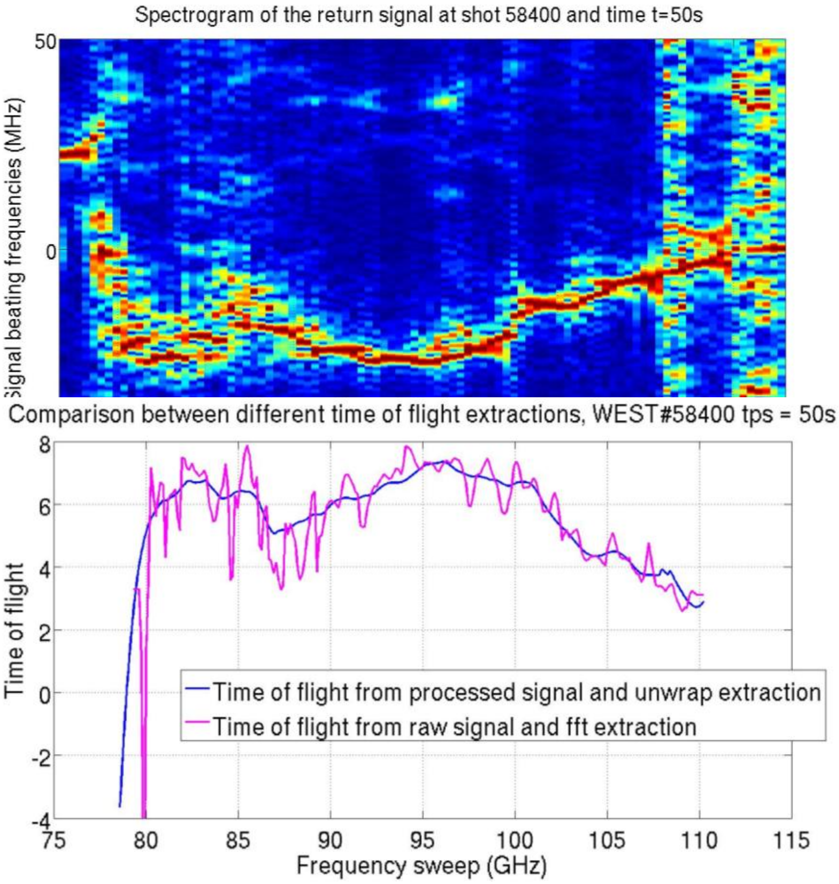


Figure 6: Spectrogram of the return signal, illustrating the extraction of Fb (6a). Time of flight from unwrap of processed signal versus time of flight from STFT on raw signal (6b).

iii. Reconstruction algorithm

Then, a new method was developed and examined for profile reconstruction, using the time of flight rather than the phase. This method is quite similar to the existing one, employing a step-by-step algorithm based on approximation of the refractive index. The development and testing of this new computation involved theoretical profiles, depicted in Figure 7a, as well as experimental data, presented in Figure 7b. Both investigation demonstrate a god level of accuracy in comparison to the original profiles. The experimental reconstruction reveals differences between the two reconstruction methods, likely attributed to the time of flight extraction that may need a slight processing for exact precision. Nevertheless, utilizing the raw data already gives satisfying profiles.

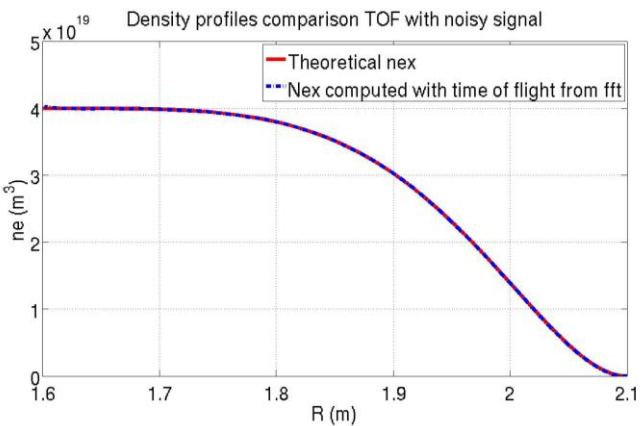
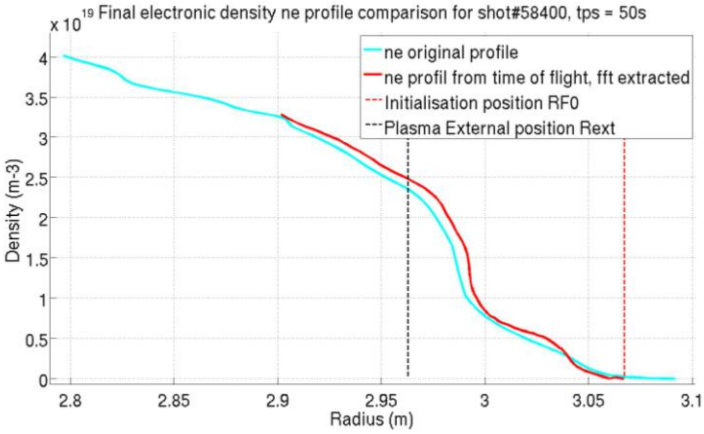


Figure 7: Density profile reconstructed with the new method from simulation (7a). Density profiles reconstructed with the new method from experimental data (7b)



5 Perspectives

After testing this new reconstruction program on matlab, the computation time was estimated. The initial profile reconstruction takes approximatively 307 milliseconds while the new method requires 143 milliseconds. Then, the newly developed reconstruction algorithm in matlab was transposed to the C language. The processing time for a single profile is reduced to 2.750 milliseconds, a time comparable to the WEST control cycle time.

The next step involves implementing the algorithm on the reflectometer PC to process data acquired by the innovative Nectarine card. Additionally, the algorithm must access real-time parameters like the plasma major and minor radius. The computation of the magnetic field is also necessary since real-time data for this parameter is not currently available. Following the programming of the card for a first prototype of profile reconstruction, the aim is to obtain real-time density measurement during the ongoing experimental campaign that will end in April 2024.

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