UKAEA-CCFE-CP(19)57

R. B. Morales, S. Heuraux, R. Sabot, S. Hacquin

The reconstruction of hollow areas in the density profiles from frequency swept reflectometry

The reconstruction of hollow areas in the density profiles from frequency swept reflectometry

R. B. Morales, S. Heuraux, R. Sabot, S. Hacquin

This paper has been submitted to
14th International Reflectometry Workshop, Swiss Plasma Center of the Ecole Polytechnique Fédérale de Lausanne, Switzerland, 22-24 May 2019

The reconstruction of hollow areas in density profiles from frequency swept reflectometry

R. B. Morales[*,1,2,3], S. Heuraux[2], R. Sabot[4], S. Hacquin[4,5], F. Clairet[4] and the Tore Supra team

[1]United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[2]IJL, UMR 7198 CNRS, University of Lorraine, 54011 Nancy, France
[3]Institute of Physics, University of Sao Paulo, Sao Paulo 05315-970, Brazil
[4]IRFM, CEA, Cadarache, Saint-Paul-lez-Durance, France
[5]EUROfusion Programme Management Unit, Culham Science Centre, Culham OX14 3DB, United Kingdom
[*] Corresponding author. E-mail: Rennan.Bianchetti-Morales@ukaea.uk

1. Introduction

The FM-CW (frequency-modulated continuous-wave) reflectometry diagnostic is a well established technique for density profile measurement with successful implementations on various medium and large size tokamaks, such as DIII-D [1], Tore Supra [2, 3], ASDEX Upgrade [4, 5] and JET [6]. Even though there has been significant improvements in the reflectometry hardware design [2, 7] and data extraction techniques [5, 8, 9] over the last two decades, the measured density profiles on fusion experiments still require further improvements in the data analysis front in order to improve the accuracy of the reconstructed profile. As an example of a demanding application, the LFS (Low Field Side) reflectometer being built for ITER has as its first operation priority to achieve a minimum radial accuracy of 5 mm [10]. Improving the accuracy on the reconstructed density profile also improves the accuracy of extracted parameters for physical studies such as transport, MHD instabilities and turbulence.

The data analysis for FM-CW profile reflectometry can be divided into three topics: the initialization technique as initially investigated in [11]; the recursive profile reconstruction algorithm as originally proposed by Bottollier-Curtet[12] with minor revisions in [13, 14] and a thorough review with some improvements in [15]; and the description of blind areas, as focused in this contribution.

Both O-mode and X-mode density profile reconstruction techniques rely on the assumption of a monotonic cut-off frequency profile. However, there are many plasma perturbations that introduce hollow areas in the cut-off frequency profile, breaking the aforementioned assumption. Inside these hollow areas, the probing microwaves exhibit no specular reflections and thus they are refereed to as blind areas. Even though no reflections occur inside the blind areas, the higher probing frequencies that propagate through these areas carry information about them. For isolated perturbations, the perturbation signature in the reflectometer signal is related to the size of the perturbation. In this contribution, large perturbations are considered, which are out of the Born approximation validity and the probing electric field over the perturbation is no more similar in magnitude to the unperturbed case. This situation can occur during massive gas and pellet injections [17], MHD activity [18] and in hollow profiles that emerge during the initiation of heating systems [19] or even due to relativistic effects [20].

If the reconstruction method does not incorporate identification and reconstruction tools for the blind regions, big discrepancies can appear in the reconstructed profile. An example is shown in figure 1 using a simulated phase under the WKB approximation as the input signal and profiles typical of Tore Supra with a low magnetic field strength of 2 T at the plasma center.

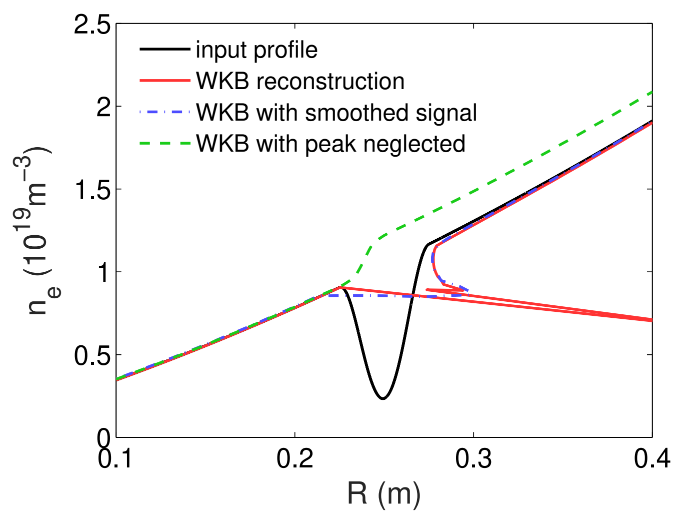

Figure 1. Synthetic example of input versus reconstructed density profiles with a blind area. The profile was reconstructed with the standard Bottollier-Curtet algorithm and a constant correction, as in [13–15], using three different treatments in the phase signal. The radial axis is defined from zero at the plasma edge and increasing towards the plasma center.

It is clear from figure 1 that the unmodified standard reconstruction algorithm is unable to reconstruct the density perturbation. Furthermore, if the oscillations are smoothed, the perturbation can be neglected entirely, or even worse, a shift can be introduced in the reconstructed profile after the perturbation if the time-of-flight jump is filtered out.

2. Reconstruction of blind areas using database of perturbation signatures

The profiles of the blind areas can be reconstructed by inverting a database of perturbation signatures in the time-of-flight signal. Various perturbations were investigated with 1D full-wave simulations in reference [21], and the conclusion was that the full-wave effects simulated in 1D (tunneling, wave-trapping, scattering and interference) were restricted to a probing frequency band of about 1 GHz around the time of flight jump over the blind area. As long as a corresponding experimental signal is treated outside of the bandwidth affected by full-wave effects, the experimental time-of-flight can be assumed well described by the WKB simulated signal, which significantly simplifies the construction of a database.

An initial database was constructed for a simple sine shaped valley and a broad range of all parameters (f_{prob},f_{ce},∇f_{cut},width,depth) including coverage for O-mode since the f_{ce} domain starts at zero. The database inversion procedure was successfully tested in a noise-free synthetic example. As covered in detail in [21], it also demonstrated how a single database can accommodate a broad range of plasma conditions and it was also used to infer the dependencies of the reconstruction accuracy across the full database domain. As expected, the reconstruction accuracy decreases when the perturbation signal is smaller, as is the case for the highest cutoff gradients and widths. In practice, the biggest contribution for the inversion accuracy is the precision on the estimations of the perturbation width, gradient, the unperturbed profile and the experimental noise level.

To demonstrate the potential of this method to reconstruct blind areas, figure 2 shows the first experimental application of a database inversion for the Tore Supra discharge 32029, where magnetic islands have been identified.

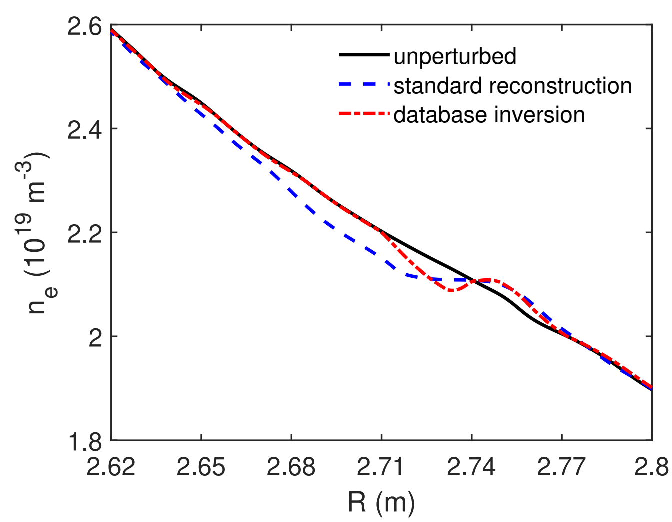

Figure 2. The reconstructed density profiles using the standard reconstruction method on the perturbed and unperturbed measurements versus the new method to reconstruct blind areas introduced in this paper.

The perturbation being investigated builds up from previous observations of MHD activity with reflectometry [22, 23]. In this circumstance, the focus is on the reconstruction of the magnetic island on the $q = 2/1$ rational surface, as calculated from the equilibrium code [23]. The magnetic islands are formed by a positive perturbation followed by a negative perturbation along the probing path. The unperturbed signal is well determined since the island is intermittent with an directly observable frequency. In this case, a reduced database is constructed based only on the current plasma conditions, with the profile already including the positive perturbation, and the valley shape assumed symmetrical from the positive probed section. This is an advantage of this application since the shape assumption agrees well with simulations [24, 25]. Next, the simulated signals with different valleys are compared to the experimental signal to find a best match.

It is clear from observing figure 2 that the new reconstruction scheme for the blind area describes much better the magnetic island and eliminates a reminiscent tail of lower density.

3. Final remarks and future prospects

As it was demonstrated, the standard reconstruction process adds a significant error in the density profile if no special technique is applied around the perturbed region. This contribution showed a brief summary of the work started in [21] that aimed at laying the foundations for this novel technique to describe the blind areas. More detailed explanations of the reconstruction steps will also be found in the coming extended version of this proceeding in a special issue of the Plasma Science and Technology journal.

This technique was verified to be very accurate in the absence of noise and with precise input of parameters when tested on synthetic data. Thus, the final reconstruction accuracy is expected to be related to available signal-to-noise ratio and the accuracy in which the perturbation width, shape and the local parameters of ∇f_{cut} and f_{ce} have been determined, which will vary significantly according to each application. Based exclusively on the comparison of the database signal to the noise level of the experimental signal, the experimental application shown in figure 2 had an error bar of 30% of the estimated valley depth. A detailed consideration of the resulting error-bars propagating from the assumptions of the valley shape and estimations of the width and cut-off gradient will be the focus of future publications where the use of an ultra-fast sweeping rate [26] with the technique to stack multiple sweeps [5] is expected to improve the extracted perturbation signal.

Even though the main physical characteristics of the blind regions have been well described by the 1D simulations present in this contribution, future 3D simulations [27] will be necessary to verify any additional geometrical aspects. After all, the probing beam area and shape, plus the shape of the perturbations, make in conjunction a system too complex to be completely described in one dimension. These geometrical aspects influence the amplitude signal across the perturbation bandwidth and the appearance and dynamics of scattering and resonances. Understanding these effects will help to better extract the signals from the blind area, apply any correction due to the 3D structures and ultimately will lead to a more accurate employment of the database inversion technique. This research on the geometrical aspects will also intersect with the application on improved initialization techniques that observe the time-of-flight and amplitude evolution in the presence of perturbations.

Acknowledgments

This work has been carried out with the support of the Brazilian National Council for Scientific and Technological Development (CNPq) under the Science Without Borders programme, within the framework of the French Federation for Magnetic Fusion Studies (FR-FCM) and of the EUROfusion consortium with funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053, and also been part-funded by the RCUK Energy Programme [grant number EP/P012450/1]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Wang G, Zeng L, Doyle E J, Rhodes T L and Peebles W A 2003 *Review of Scientific Instruments* **74** 1525–1529

[2] Moreau P, Clairet F, M Chareau J, Paume M and Laviron C 2000 *Review of Scientific Instruments* **71** 74–81

[3] Clairet F, Sabot R, Bottereau C, Chareau J M, Paume M, Heuraux S, Colin M, Hacquin S and Leclert G 2001 *Review of Scientific Instruments* **72** 340–343

[4] Silva A, Manso M E, Cupido L, Albrecht M, Serra F, Varela P, Santos J, Vergamota S, Eusébio F, Fernandes J, Grossmann T, Kallenbach A, Kurzan B, Loureiro C, Meneses L, Nunes I, Silva F and Suttrop W 1996 *Review of Scientific Instruments* **67** 4138–4145

[5] Varela P, Manso M, Silva A, the CFN Team and the ASDEX Upgrade Team 2006 *Nuclear Fusion* **46** S693

[6] Sirinelli A, Alper B, Bottereau C, Clairet F, Cupido L, Fessey J, Hogben C, Meneses L, Sandford G, Walsh M J and JET-EFDA Contributors 2010 *Review of Scientific Instruments* **81** 10D939

[7] Clairet F, Bottereau C, Chareau J M and Sabot R 2003 *Review of Scientific Instruments* **74** 1481–1484

[8] Clairet F, Ricaud B, Briolle F, Heuraux S and Bottereau C 2011 *Review of Scientific Instruments* **82** 083502

[9] Briolle F, Lima R and Mendes R V 2009 *Measurement Science and Technology* **20** 105502

[10] Doyle E J 2015 Status of the system design and component testing for the ITER low-field side reflectometer system. 12th International Reflectometry Workshop, Jülich, Germany

[11] Heuraux S, Clairet F and da Silva F 2009 An X-mode reflectometry study on the reflection point for the density profile reconstruction Talk and proceeding at the 9th International Reflectometry Workshop, Lisbon, Portugal
www.ipfn.tecnico.ulisboa.pt/irw9

[12] Bottollier-Curtet H and Ichtchenko G 1987 *Review of Scientific Instruments* **58** 539–546

[13] Shelukhin D A, Vershkov V A, Sarychev D V, Petrov A A, Petrov V G and Subbotin G F 2011 X-mode lower cutoff high field side reflectometer for electron density profile measurements in T-10 tokamak 11th International Reflectometry Workshop, Palaiseau, France
www.lptp.polytechnique.fr/news/11/Workshop/index.html

[14] Bottollier-Curtet H 1986 *Réflectométrie hyperfréquence pour la détermination de la densité électronique et de ses fluctuations sur le Tokamak Petula-B* Ph.D. thesis Université de Paris XI

[15] B Morales R, Hacquin S, Heuraux S and Sabot R 2017 *Review of Scientific Instruments* **88** 043503

[16] Fanack C, Boucher I, Clairet F, Heuraux S, Leclert G and Zou X L 1996 *Plasma Physics and Controlled Fusion* **38** 1915

[17] Sakamoto R, Pégourié B, Clairet F, Géraud A, Gil C, Hacquin S and Köchl F 2013 *Nuclear Fusion* **53** 063007

[18] Donné A J H, van Gorkom J C, Udintsev V S, Domier C W, Krämer-Flecken A, Luhmann N C and Schüller F C (TEXTOR team) 2005 *Phys. Rev. Lett.* **94**(8) 085001

[19] Baiocchi B, Bourdelle C, Angioni C, Imbeaux F, Loarte A, Maslov M and JET Contributors 2015 *Nuclear Fusion* **55** 123001

[20] Vayakis G, Walker C, Clairet F, Sabot R, Tribaldos V, Estrada T, Blanco E, Sánchez J, Denisov G, Belousov V, Silva F D, Varela P, Manso M, Cupido L, Dias J, Valverde N, Vershkov V, Shelukhin D, Soldatov S, Urazbaev A, Frolov E Y and Heuraux S 2006 *Nuclear Fusion* **46** S836–S845

[21] B Morales R 2018 *Density profile reconstruction methods for X-mode reflectometry* Ph.D. thesis Université de Lorraine URL `http://docnum.univ-lorraine.fr/public/DDOC_T_2018_0031_BIANCHETTI_MORALES.pdf`

[22] Clairet F, Heuraux S, Leclert G and Vermare L 2005 FM-CW reflectometry for MHD activity measurements on Tore Supra Proc. 7th Intl. Reflectometry Workshop for fusion plasma diagnostics - IRW7 Garching, IPP Report II/9, p104

[23] Vermare L, Clairet F, Heuraux S and Leclert G 2005 *Plasma Physics and Controlled Fusion* **47** 1895–1909

[24] Bergmann A, Poli E and Peeters A G 2009 *Physics of Plasmas* **16** 092507

[25] Poli E, Bottino A, Hornsby W A, Peeters A G, Ribeiro T, Scott B D and Siccinio M 2010 *Plasma Physics and Controlled Fusion* **52** 124021

[26] Clairet F, Bottereau C, Medvedeva A, Molina D, Conway G D, Silva A and Stroth U 2017 *Review of Scientific Instruments* **88** 113506

[27] da Silva F, Heuraux S and Ribeiro T 2017 Introducing REFMULF, a 2D full polarization code and REFMUL3, a 3D parallel full wave Maxwell code. 13th International Reflectometry Workshop (IRW13), Daejeon, South Korea.