Simultaneous Power Deposition Detection of Two EC Beams with the BIS Analysis in Moving TCV Plasmas

L. Curchod*, A. Pochelon*, J. Decker†, F. Felici*, T.P. Goodman*, J.-M. Moret*, J.I. Paley* and the TCV Team*

*Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, CH-1015 Lausanne, Switzerland
†Association EURATOM-CEA Cadarache/DSM/IRFM, F-13108 Saint Paul lez Durance, France

Abstract. Modulation of power amplitude is a widespread to determine the radial absorption profile of externally launched power in fusion plasmas. There are many techniques to analyze the plasma response to such a modulation. The break-in-slope (BIS) analysis can draw an estimated power deposition profile for each power step up. In this paper, the BIS analysis is used to monitor the power deposition location of one or two EC power beams simultaneously in a non-stationary plasma being displaced vertically in the TCV tokamak vessel. Except from radial discrepancies, the results have high time resolution and compare well with simulations from the R2D2-C3PO-LUKE ray-tracing and Fokker-Planck code suite.

Keywords: Break in slope, EC power, profile, detection, simultaneous, plasma, TCV

INTRODUCTION

The highly local absorption of electron cyclotron (EC) waves in resonant heating (ECRH) and current drive (ECCD) makes them a perfect tool for the control of both the temperature and current profiles. In transport experiments via low frequency heating modulation as well as in sawtooth stabilization and thus neo-classical tearing mode (NTM) suppression via local current profile tailoring, a precise knowledge of the EC power deposition location is required for the understanding of the involved mechanisms. A widespread method to retrieve the profile of absorbed power is to analyze the plasma response to modulations of the externally launched power. Analysis techniques such as the singular value decomposition (SVD), the fast Fourier transform (FFT) and the correlation of the response signal with the modulation waveform give satisfactory results in heating and transport studies when the conditions are stationary and the MHD activity amplitude is moderate [1] [2] [3].

The break-in-slope (BIS) analysis provides a quasi-instantaneous estimation of the power deposition profile for each power step whereas SVD, FFT and correlation all need a finite number of power modulation cycles to lead to reasonable results spatially and frequency wise. The BIS analysis thus allows to retrieve a power deposition profile in presence of large sawteeth [4] like in the initial experiments of electron Bernstein wave deposition via O-X-B double mode conversion in the core of TCV H-mode plasmas [5]. The BIS analysis can also be used to track the power absorption profile in scenarios with a rapidly time-varying deposition location as presented in this paper.

BIS ANALYSIS MODEL AND EXPERIMENTAL SETUP

The BIS model for the auxiliary power absorbed by a given species α is based on the energy density conservation equation for that particular species. It is assumed that the auxiliary heating applied to the species α is modulated with a frequency much faster than the typical time evolution of the diffusion, viscosity and convection terms as well as the Ohmic power, the loss terms, and the other species temperature response. This yields a simplified energy density conservation equation [6]:

$$\frac{\partial \varepsilon_\alpha}{\partial t} \approx \frac{3}{2} n_{\alpha 0} \frac{\partial T_\alpha}{\partial t} \approx P_{\text{aux}} \quad \Rightarrow \quad \Delta P_{\text{aux}} \approx \frac{3}{2} n_{\alpha 0} \left(S_{t>t_0} - S_{t<t_0} \right) \tag{1}$$

where the density is also assumed to remain constant around the power step at time t_0, i.e. $n_\alpha(t,x) = n_\alpha(t_0,x) \equiv n_{\alpha 0}(x)$. In other words, the simplest form of the BIS analysis assumes that, if the heating power modulation is fast enough, the plasma temperature has a prompt linear response to the breaks in the auxiliary heating power. The variation ΔP_{aux} in the locally absorbed power at t_0 is then proportional to the jump in the slope S of linear fits of T_α around t_0. Applied to a diagnostic with multiple channels or lines-of-sight viewing at different flux surfaces, the BIS analysis thus provides an estimated heating profile for each power step i.e. at a frequency of the order of the power modulation frequency (typically a few 100 Hz).

The Tokamak à Configuration Variable (TCV) 2nd harmonic ECH system (82.7 GHz) is equipped with 6 gyrotrons of 0.5 MW power each. The power is injected in the plasma via 6 steerable launchers with 2 angles of freedom each. Four launchers are located in upper lateral ports of the TCV vacuum vessel (with their longitudinal axis at $Z_{\text{launcher}} \simeq 46\,\text{cm}$) and two in equatorial ports (with $Z_{\text{launcher}} = 0\,\text{cm}$). One of the injection angles can be programmed to change during the plasma discharge, as well as the toroidal magnetic field value, the position of the plasma column and the shape of its cross section, thus allowing variations of the normalized radius at which the EC wave-particule resonance takes place.

In this paper, the BIS analysis method is used to find the direct power deposition location in modulated ECH scenarios with one or two fixed EC power beams absorbed at different and varying normalized radius in plasmas moving in the vertical direction. The method is applied to the traces of a multiwire proportional soft X-ray detector (DMPX) viewing the plasma vertically from below with high time (200 kHz acquisition frequency) and space (64 lines-of-sight) resolutions [7]. When the electron density and plasma effective charge are constant, the soft X-ray flux is only a function of the electron temperature and a qualitative BIS profile can be calculated at each power step.

SINGLE AND DOUBLE EC POWER BEAM MONITORING

In a first experiment, one EC power beam is injected quasi-horizontally from the equatorial launcher L1. In a second experiment, an supplementary beam is injected obliquely from the upper lateral launcher L5. In both experiments, the value of the magnetic field is $B_\varphi = -1.45\,\text{T}$ such that the quasi-vertical locus of the second harmonic cyclotron resonance passes close to the plasma axis. Both plasmas vertical position is swept down

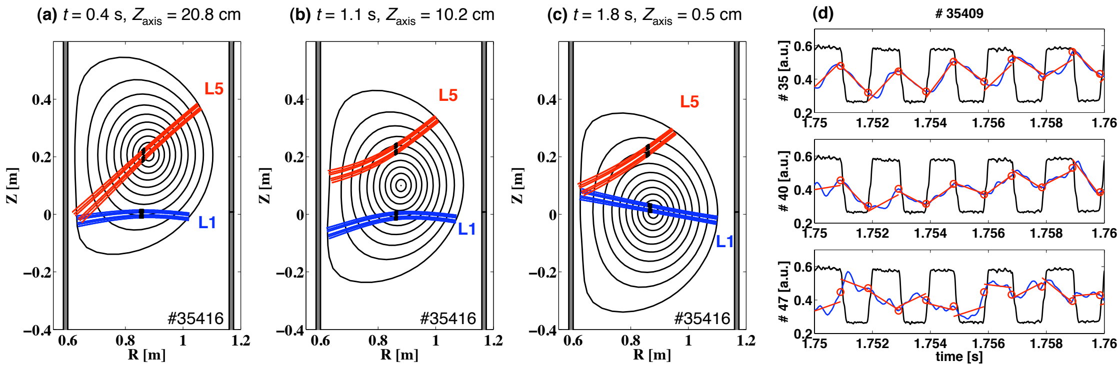

FIGURE 1. (a-c) Double beam ray-tracing simulations with the C3PO code. Poloidal trajectories of the X2 EC power beams from the equatorial launcher L1 (in blue) and the upper lateral launcher L5 (in red) at times $t = 0.4$ s (a), 1.1 s (b) and 1.8 s (c) when the plasma magnetic axis is at the vertical positions $Z_{\mathrm{axis}} \simeq 21$ cm, 10 cm and 0 cm respectively. The beam-plasma resonant interaction location thus moves from mid-radius to the plasma core for the L1 beam and in the opposite direction for the L5 beam. TCV #35416. **(d) The BIS analysis applied to soft X-ray channels (DMPX).** Linear fits (in red) are performed on the band-pass filtered signal (in blue) between the EC power (in black) step up and down times (red circles). The BIS amplitude is the highest at the most central viewing chord #35. TCV #35409.

from $Z_{\mathrm{axis}} = 21$ cm to $= 0$ cm in 1.4 s in front of the launcher(s) injecting the X2 EC beam(s) at fixed angles. The L1 beam absorption location is thus expected to move from off-axis to central normalized radius and in the opposite direction for the L5 beam. This evolution is confirmed by simulations from the R2D2-C3PO ray-tracing and the LUKE quasi-linear Fokker-Planck-equation solver codes [8] [9] at successive times, see Fig. 1 (a-c). Both beam power amplitudes are modulated at 60% with a $f_{\mathrm{mod}} = 500$ Hz square waveform, with a phase difference of $\pi/2$ to allow an independent but simultaneous BIS analysis of both beams deposition locations. The modulation period $\tau_{\mathrm{mod}} = 2$ ms is smaller than the typical electron energy confinement time $\tau_e^{\varepsilon} \approx 50$ ms and the plasma response is clearly linear, see Fig. 1 (d). Thus the BIS analysis based on linear fits can be applied to all the DMPX channels independently: the soft X-ray signal is first filtered (250 to 500 Hz band-pass) and normalized along time before linear fits are performed between all power step-up/down times. The break in slope of the linear fits is then calculated at each power step-up time for each DMPX chord, providing BIS amplitude profiles at a $f_{\mathrm{mod}} = 500$ Hz rate. For the single L1 beam injection, Fig. 2 (left middle) shows the successive BIS amplitude profiles versus time and the normalized radii ρ_ψ to which the DMPX lines-of-sight are tangential (i.e. integrated signal was used). A running median filter on 7 points tracks the maximum BIS amplitude and gives the time evolution of the estimated power deposition location. The latter clearly moves from off-axis to central radius when the plasma vertical position (Fig. 2, left top) is decreased. This evolution compares well with the R2D2-C3PO-LUKE simulations (Fig. 2, left bottom). The slight radial discrepancies may originate in the use of integrated soft X-ray signal. The inversion of the signal should improve the radial agreement. Similar results are obtained for the double L1 and L5 beams injection experiment, see Fig. 2 (center and right), though the discrepancies with the simulations are larger in this case, which may come from the EC power beams perturbing the detection of each other.

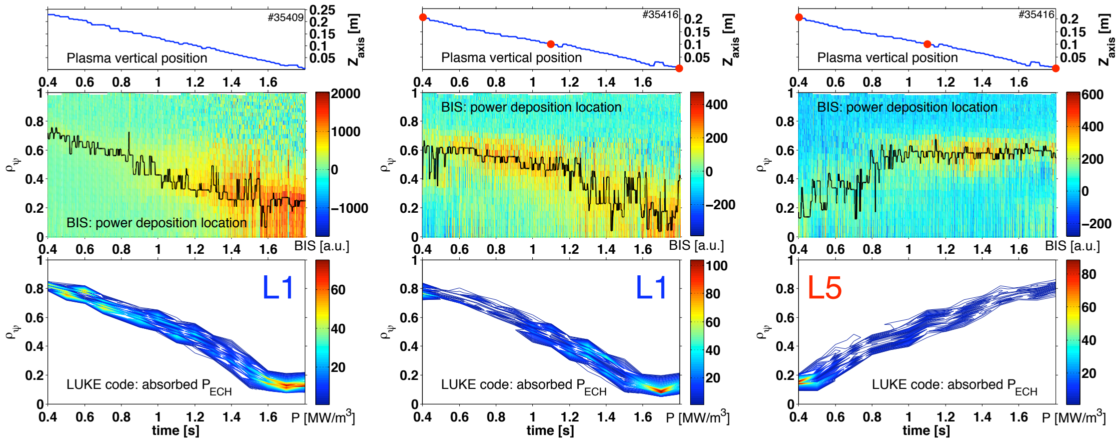

FIGURE 2. Left: Evolution of one beam power deposition location determined with the BIS analysis. Time evolution of the magnetic axis vertical position (top), the BIS amplitude profiles versus the normalized radius ρ_ψ to which the DMPX lines-of-sight are tangential (middle) and the local absorbed power density profiles versus the normalized radius ρ_ψ from C3PO-LUKE simulations (bottom). The running average of the maximum BIS amplitude position (black line) and the simulations show the power deposition moving from off-axis to central radius when the plasma is swept down. TCV shot #35409. **Center and right: Evolution of two simultaneous beams power deposition locations determined with the BIS analysis.** When the plasma position is swept down (top, the red dots indicating the times of simulations in Fig. 1), the maximum BIS amplitude position moves from off-axis to central radius for the beam from the equatorial launcher L1 and in opposite direction for the beam from the upper lateral launcher L5 (middle), to be compared to the C3PO-LUKE simulations (bottom). TCV shot #35416.

CONCLUSION

The BIS method is a simple though powerful analysis technique of the plasma response to modulated heating. It allows a high time rate monitoring of the power absorption profile of one or two EC beams in time-varying deposition location applications. In the double beam case, discrepancies with the simulations call for a method improvement.

ACKNOWLEDGMENTS

This work was supported in part by the Swiss National Science Foundation.

REFERENCES

1. A. Manini, et al., *CRPP internal report, LRP* **664/00** (2000).
2. A. Mueck, et al., *Phys. Rev. Lett.* **98**, 175004 (2007).
3. J. Berrino, et al., *IEEE Trans. Nucl. Sci.* **53**, 1009 (2006).
4. D. J. Gambier, et al., *Nucl. Fusion* **30**, 23 (1990).
5. L. Curchod, et al., *in Proc. 34th EPS Conf. CFPP, Warsaw, ECA Vol. 31F,* **P-5.52** (2007).
6. D. van Eester, *Plasma Phys. Controlled Fusion* **46**, 1675 (2004).
7. A. Sushkov, et al., *Rev. Sci. Instr.* **79**, 023506 (2008).
8. Y. Peysson, and J. Decker, *Report EUR-CEA-FC-1739, Euratom-CEA* (2008).
9. J. Decker, and Y. Peysson, *Report EUR-CEA-FC-1736, Euratom-CEA* (2004).