EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

EFDA–JET–PR(05)48

E.A. Lerche, D. Van Eester and JET EFDA contributors

Extending the Break-in-Slope Analysis to Indirect Heating Regimes in Tokamaks

Extending the Break-in-Slope Analysis to Indirect Heating Regimes in Tokamaks

E.A. Lerche, D. Van Eester and JET EFDA contributors*

[1]Plasma Physics Laboratory, LPP-ERM/KMS, EURATOM Association,
Trilateral Euregio Cluster, B-1000 Brussels, Belgium
* See annex of J. Pamela et al, “Overview of JET Results ”,
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

1. INTRODUCTION

The so called Break-In-Slope analysis (BIS) [2] is a very simple, although powerful, data analysis technique that is widely used to determine the power absorption profiles of the plasma particles during auxiliary heating experiments in tokamaks, such as Radio-Frequency (RF) or Neutral Beam Injection (NBI) heating experiments. It is based on the study of the energy response of the particles to sudden changes in the external power supplied to the plasma. If convection effects are neglected, the radial component of the energy conservation equation for a given plasma species ! can, to a first approximation, be written as

$$\frac{¶\varepsilon_\alpha}{¶t} = \nabla ¥ [\kappa \nabla \varepsilon_\alpha] + p_{aux} + \sum_j p_j \quad (1)$$

where $\varepsilon_a \equiv \varepsilon_a(\rho, t) = 3/2\, n_\alpha k_B T_\alpha$ is the local energy density of the particles in a certain magnetic surface labeled by ρ, n_α and T_α being the local species density and temperature, respectively, κ is the local diffusion coefficient, p_{aux} is the local auxiliary heating power density absorbed by the particles in the infinitesimal shell around the considered magnetic surface, and the sum $\Sigma\, p_j$ represents all the other local sources and sinks in the linearized power balance equation, such as the ohmic power input, radiation and collisional losses, etc. Here aux p will just be the local RF power density, p_{RF}.

In most cases, a periodic square wave modulation is imposed on the RF power supplied to the antenna and the change in the slope of the energy density time evolution $\partial\varepsilon_\alpha/\partial t$ due to the RF 'power steps' is used to infer the local RF power density absorbed by the plasma. Assuming that the diffusion processes occur on a much longer time scale than the modulation period, $\tau_{mod} >> \tau_E$ mod , where τ_E) is the energy confinement time, and discarding rapid variations of the other power sources and sinks, such as variations of the ohmic power density p_{OH} caused by fluctuations of the plasma resistivity due to the temperature perturbations, $\Delta\Sigma p_j \to 0$, the change in the slope of the local temperature time evolution $\partial T_\alpha/\partial t$ due to a variation Δp_{RF} in the locally dissipated RF power density can be approximated as [3]

$$\frac{3}{2} n_\alpha k_B \Delta \frac{¶T_\alpha}{¶t} \approx \Delta p_{Rf}, \quad (2)$$

where k_B is the Boltzmann constant and the local density n_α is assumed not to vary significantly during the power step. Here it is important to mention that in many practical applications $\tau_{mod} < \tau_E$, rather than the stricter condition $\tau_{mod} << \tau_E$. As a consequence, the heat wave propagation somewhat distorts the constant t T $ $! response, such that the absorption profiles determined with the BIS method do not fully mimic the shape of the actual RF power deposition (see, e.g. [3]).

In this letter, we will focus on the BIS analysis of the electron temperature response in Ion-Cyclotron Resonance Heating (ICRH) experiments in tokamaks, usually measured with a fast Electron-Cyclotron Emission (ECE) radiometer. The BIS method is routinely adopted to estimate the electron power deposition profiles in direct electron heating scenarios, such as Mode-Conversion (MC) and Fast Wave Landau Damping (FWLD) experiments [4-6]. However, for experiments with dominant ioncyclotron heating, commonly referred as Minority Heating (MH) scenarios, the traditional BIS analysis is not straight forwardly applicable, because in this regime, the electrons are indirectly heated by collisions with the resonant ions near the IC layer(s) and the electron temperature response is delayed with respect to the RF power change. This time delay is usually not taken into account in the standard BIS analysis and, as will be shown further on, can lead to considerably underestimated values of the power absorption. Since this collisional time delay is different for each region of the plasma, even a given 'time-offset' used in the standard BIS analysis to perform the temperature fit in a more appropriate time window would not be enough to correctly determine the electron power deposition profile over the entire plasma column.

To illustrate the characteristic time signals used in the BIS analysis and their differences according to the main heating process taking place in the plasma, Fig.1 depicts examples of a 20Hz square-wave power modulation (gray curves) together with the corresponding electron temperature responses (black) measured with a fast heterodyne ECE radiometer [7] for typical MC (a) and MH (b) heating regimes in the JET tokamak. Both temperature signals correspond to the same ECE channel (R, 3.15m) registered in two different time intervals in an inverted (^{3}He)H minority heating experiment (Pulse No: 63322), where a ramp-up of the ^{3}He concentration was performed to study the transition between the MH regime, for low [^{3}He], and the MC regime, for [^{3}He] > 2-3% [8, 9]. Note that the minority ion concentration corresponding to the MH to MC transition in the case of inverted heating scenarios is appreciably lower than in the standard MH case (with lighter minority), where typical values are around 15-20% [4]. The temperature traces shown in Fig.1 correspond to $T_e^* = T_{ECE} - \langle T_{ECE} \rangle_t$, i.e. the original ECE signal from which a smooth time-averaged temperature signal was subtracted. This operation is commonly done in the BIS analysis to remove the undesired slower variations of the temperature response. The amplitude of the RF power modulation was approximately the same in both time intervals, namely $\Delta P_{RF} \approx 2.2$MW. The solid vertical lines indicate the time instants of the power modulation steps whilst the dashed ones indicate the approximate instants of the change in the temperature response (break-in-slope instants) registered by the ECE radiometer.

One clearly sees an almost instantaneous temperature response to the RF modulation in the MC regime (Fig.1a), whereas a time delay $\Delta t \approx 10$ms is needed for observing the change in the electron temperature slope in the MH case (Fig.1b), evidencing the nature of the indirect electron heating mechanism dominant in this regime. As mentioned, in this case the standard BIS method, which is based on the linear fitting of the experimental temperature signals in each half-period of the modulation (within solid lines), would include a sample of undesired data points in each time interval and therefore lead to wrong values of the temperature slopes.

Also note the nearly linear $\partial T_e^*/\partial t$ slopes observed in the two temperature signals during each phase of the RF power modulation, indicating that the assumption $\tau_{mod} >> \tau^*$, where $1/\tau^* = 1/\tau_E + 1/\tau_{OH} + ...$ represents the effective characteristic time of all non-RF processes in eq.(1), is satisfied.

The modulation frequency in these experiments was indeed intentionally chosen such that the non-linear 'saturation' phase of the temperature response is absent.

2. THE IMPROVED BREAK-IN-SLOPE PROCEDURE (BIS*)

In this letter we propose an improved data analysis procedure to extend the breakin-slope technique to indirect heating scenarios, such as minority heating experiments. The method is based on the evaluation of the actual break-in-slope instants observed in each experimental ECE signal (at each radial position) to determine the appropriate time intervals for computing the temperature response slopes (e.g. within the dashed lines in Fig.1). The performance of the new method has been assessed through benchmarking with the results obtained with FFT analyses on both direct and indirect electron heating ICRH experiments. The FFT method includes the time delays of the temperature response automatically, but has the drawback of needing a periodic power modulation to accurately determine the power deposition profiles [3]. For the BIS analysis, a single step in the RF power applied to the plasma is, in principle, sufficient to allow the evaluation of the instantaneous power deposition. Besides producing realistic power absorption profiles in the MH regime, the new method has the advantage of providing, by definition, an estimative of the time delays needed to observe the change in the temperature response with respect to the RF power step, referred here as the local heating time delays +tH. Since these time delays are evaluated at all ECE measuring positions, the new method offers a very convenient way to help diagnose different heating processes occurring, sometimes simultaneously, in the various regions of the plasma.

In Fig.2 we show the time delays Δt_H observed between the RF power modulation and the local electron temperature responses as function of the major radius of the plasma for the MC (a) and the MH (b) regimes discussed in Fig.1 (JET Pulse No: 63322). Each time delay value corresponds to the average of the time delays determined in a 0.2s time window (4 modulation periods) starting at t = 8.6s (a) and t = 6.1s (b), respectively. The minority ion concentrations, estimated through charge exchange spectroscopy measurements [10], were respectively [^{3}He] , 2.6% (a) and [^{3}He] , 0.8% (b) [8, 9]. The gray box in Fig.2a indicates the region of dominant ^{3}He-H mode conversion heating (MC), as obtained from full-wave simulations using the CYRANO code [11], whilst the vertical dashed lines represent the cold ^{3}He Ion-Cyclotron resonance layer (IC) for this discharge. A fourth-order Butterworth filter was applied to the ECE signals in order to increase the accuracy in the determination of the breakin-slope instants. The absence of data near the plasma center is due to the fact that the JET fast ECE diagnostic system has a horizontal line-of-sight located ~15cm below the equatorial plane of the plasma [7], and the abscissa of Fig.2 correspond to the measuring positions of the several ECE channels projected against the equatorial midplane.

First note the higher values of the heating time delays Δt_H observed near the plasma center in the MH regime (Fig.2b), gradually increasing towards the IC resonance layer (R ≈ 2.98m). This feature indicates a region of predominant indirect electron heating, where the wave energy is first absorbed by the resonant ions and afterwards transferred to the electrons by collisions. In the MC regime

(Fig.2a), on the other hand, the electron temperature response is practically instantaneous over the central plasma, confirming the fact that direct electron heating via the mode-converted wave is the dominant heating mechanism in the bulk plasma.

The fact that the electron temperature response is not absolutely in phase with the RF power modulation in the MC regime (Fig.2a) has several causes. First, it is related to the somewhat distorted shape of the RF power modulation in this discharge (see Fig.1), what compromises the accurate determination of the power step instants ($\Delta t_H = 0$ levels in Fig.2), given by the average of the up- and down- power transition instants found in each analyzed time window. Another contribution to this slight 'time-offset' observed in the MC case can be associated with the rather small 3He concentration in this experiment, a condition in which significant indirect electron heating can not be avoided and thus inevitably contributes to the energy response measured in the plasma. Finally, first order corrections to the temperature response due to diffusion processes could also lead to slightly shifted time delay values [3,6]. Backed up by wave equation studies, we can only state at this point that the time delays obtained with the new BIS* method are qualified indicators for distinguishing between different heating regimes in the plasma. More detailed studies, including their relationship with the physical processes that cause them, require sophisticated transport modeling and therefore fall outside the scope of this letter.

The minimum observed near $R \approx 3.3-3.4$m in Fig.2b, indicating a region of direct electron heating in the MH regime, deserves a few additional words. A detailed analysis of this inverted scenario experiment [8, 9] has shown that the presence of small traces of Carbon and Deuterium in the discharge gave rise to a complementary mode conversion layer at the high-field side of the plasma, near , $R \approx 2.6$m. Recalling that the plasma magnetic axis is around $R \approx 2.96$m, we see that the reduced values of the heating time delays detected at the low-field side of the plasma ($R \approx 3.3-3.4$m) are consistent with direct electron heating on the magnetic surfaces associated to this new MC layer.

Let us now discuss the main subject of the present letter and demonstrate a major weakness of the standard BIS technique, which can be overcome by the here presented upgraded BIS procedure. In Fig.3 we show the electron power absorption profiles obtained in the MC (a) and in the MH (b) phases of Pulse No: 63322 with three different methods: FFT analysis (□), standard BIS analysis (○) and improved BIS* analysis (▲). As mentioned, the improved BIS* method takes into account the time delays observed in the ECE signals (as shown in Fig.2) to determine the correct time intervals to perform the linear fit of the temperature responses related to each half-period of the RF power modulation. Similar to Fig.2, the power density values p_{RF} (shown per MW of the power modulation amplitude) correspond to the average of the individual values obtained in a time window of 0.2s starting at t = 8.6s (a) and t = 6.1s (b), respectively. Again, the gray box in Fig.3a represents the predominant mode conversion region and the dashed line indicates the cold IC resonance layer. Due to the rather low spatial resolution of the Thomson scattering diagnostic system (LIDAR) [12] used to measure the electron density in JET, a high-order polynomial fit was applied to its radial data in order to obtain smooth electron density profiles for the calculation of the power absorption densities.

First note the very good agreement between the power absorption profiles obtained with the three different methods in the MC case (Fig.3a), where the time delays between the temperature response and the RF power modulation are virtually negligible throughout the bulk plasma (Fig.2a). In the MH regime (Fig.3b), on the other hand, the standard break-in-slope method (which uses fixed time intervals and assumes that the $\partial T_e/\partial T$ slope breaks promptly when the RF power changes abruptly) leads to totally inconsistent power density values in the indirect electron heating region of the plasma ($R < 3.3$m), whereas the power deposition profile obtained with the improved BIS* method tends to agree with the FFT result.

A more careful examination of Fig.3 shows that the FFT power densities are slightly higher than those obtained with the improved BIS* analysis in the central region of the plasma, both in the MC (a) and in the MH (b) regimes. This is connected to the fact that only the first harmonic (N=1) deposition profile of the FFT analysis is shown in Fig.3, which represents the temperature response to a (single frequency) sinusoidal variation of the launched power at the modulation frequency. The BIS* result, on the contrary, contains information of the complete response spectrum, since it is based on the linear fit of the 'triangular' temperature response signals to the actual square wave modulation (with infinite spectrum) imposed in the RF power.

CONCLUSION

An improved procedure to extend the break-in-slope analysis to indirect heating scenarios in tokamaks was presented. It takes into account the time delays observed between the experimental temperature responses in the various regions of the plasma and the RF power modulation to determine the correct break-in-slope instants and therefore consider only the proper data points to evaluate the temperature slopes in each half-period of the modulation. Filtering of the ECE signals was used to increase the accuracy in the determination of the experimental break-in-slope instants. Benchmarking against FFT analysis results has shown that the improved BIS* method can be trustfully used to estimate the electron power deposition profiles in both experiments with direct and indirect electron heating for sufficiently rapid power modulations.

Because of the inherent experimental determination of the heating time delays at all ECE measuring positions, the upgraded BIS* is a very useful data analysis tool to identify distinct heating processes occurring simultaneously in different regions of the plasma, a very common situation in multi-ion tokamak plasmas. Since the break-inslope method (unlike the FFT technique) does not require a periodic variation of the power input, the heating time delays can be determined at each individual power step. Hence, a detailed visualization of the changes in the electron power absorption profile during the transitions between heating regimes in ICRH experiments is possible.

REFERENCES

[1]. Pamela J. et al 2003 Nucl. Fusion **43** p.1540

[2]. Gambier D.J. et al. 1990 Nucl. Fusion **30** p.23

[3]. Van Eester D. 2004 Plasma Phys. Control. Fusion **46** p.1675

[4]. Mantsinen M. et al. 2004 Nucl. Fusion **44** p.33

[5]. Lin Y. et al 2003 Plasma Phys. Control. Fusion **45** p.1013

[6]. Mantica P. et al 2002 Proc. of 19th IAEA Fusion Energy Conference (Lyon)

[7]. de la Luna E. et al 2004 Rev. Sci. Instrum. **75**(10) p.3831

[8]. Mayoral M-L. 2005 Proc. of 16th Topical Meeting on RF Power in Plasmas (Park City, Utah)

[9]. Mayoral M-L. et al, Hydrogen plasmas heating with ICRF inverted minority and mode conversion regimes in the JET tokamak, to be submitted to Nucl.Fusion

[10]. von Hellermann M.G. et al 1990 Rev. Sci. Instrum. **61**(11) p.3479

[11]. Lamalle P. U. 1994 LPP-ERM/KMS Lab. Report 101 (Brussels)

[12]. Saltzmann H. et al 1988 Rev. Sci. Instrum. **59** p.1451

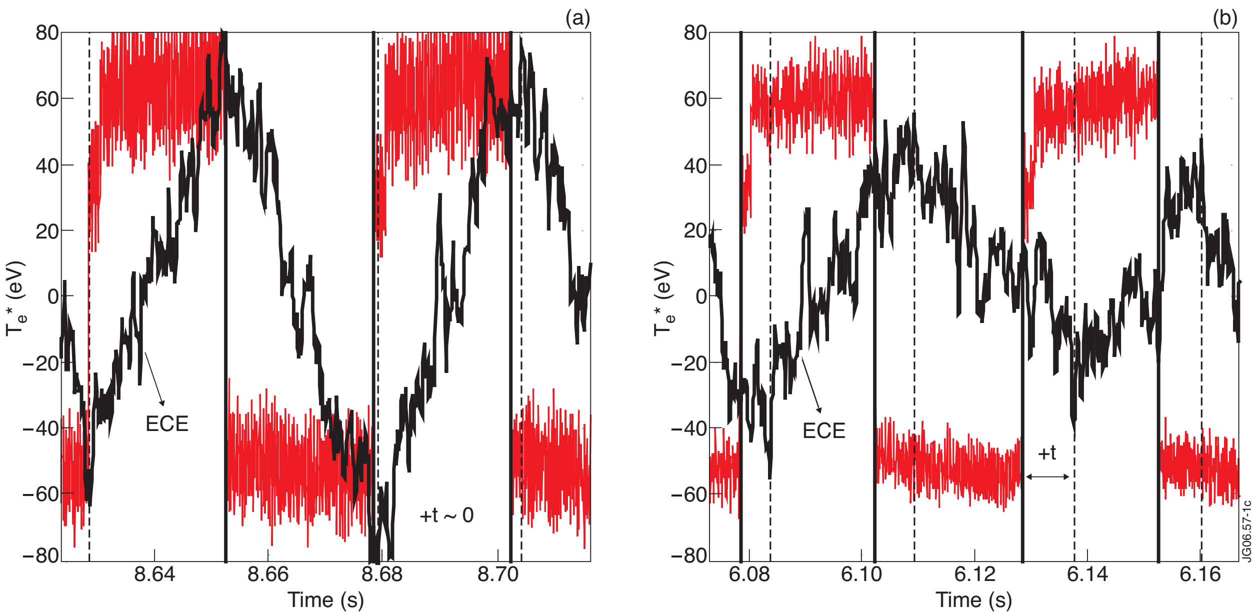

Figure 1: Examples of the electron temperature responses (ECE) used for the break-in-slope analysis in typical MC (a) and MH (b) heating scenarios in JET. Note the clear time delay Δt observed in the temperature response with respect to the RF power modulation (gray curve) in the MH regime (b), a typical signature of the indirect heating of the electrons.

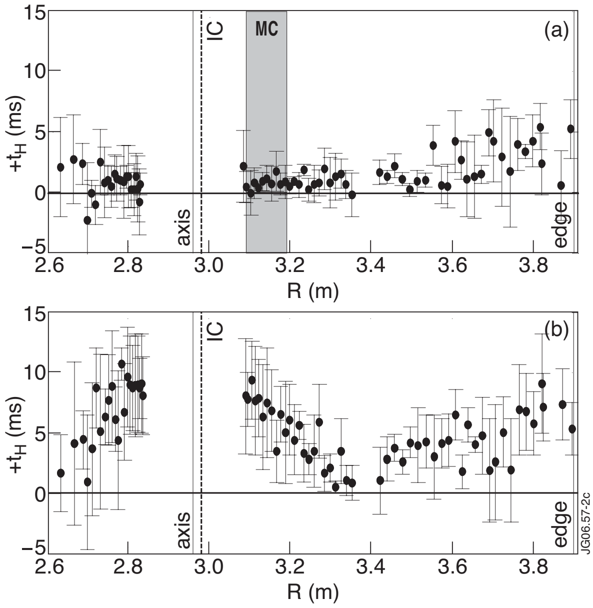

Figure 2: Electron heating time delays +tH as function of the plasma major radius R ($Z=Z_0$) obtained for the MC (a) and the MH (b) heating regimes discussed in Fig.1. Note the almost instantaneous electron response observed in the MC case (a) in contrast to the gradually increasing time delays detected in the MH regime (b) in the bulk plasma region.

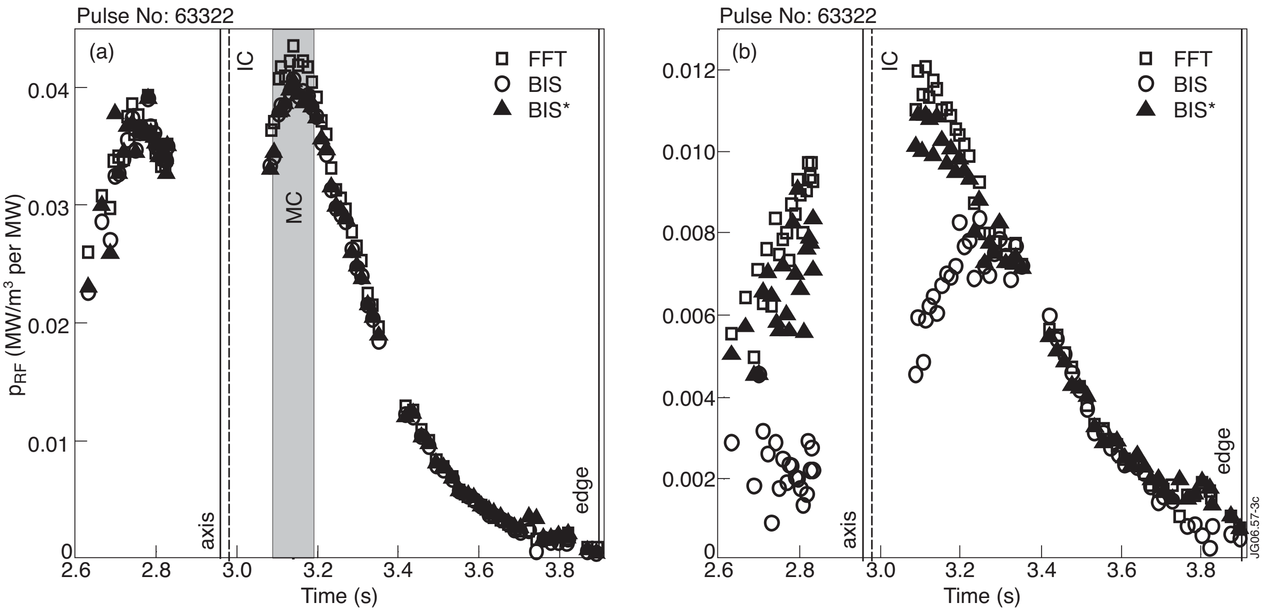

Figure 3: Electron power absorption profiles obtained in the MC (a) and MH (b) regimes with three different methods: (N=1) FFT analysis (□), standard BIS analysis (○) and improved BIS analysis (▲). Note that the standard BIS method yields erroneous power density values in the indirect electron heating region in the MH case (b), while the improved BIS* method fairly reproduces the absorption profile obtained with the FFT.*