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# Improved break-in-slope analysis for the estimation of power deposition profiles in JET

# LH Wave Coupling over ITER-Like Distances at JET

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## ABSTRACT

Most of today's tokamak experiments rely on auxiliary heating of the plasma for achieving reactor-relevant temperatures. On top of the theoretical efforts to estimate the power deposition profiles of the various adopted heating schemes (NBI, ICRH or ECRH) by numerical modelling, there are various techniques used to infer the power profiles experimentally, usually based on electron/ion temperature data. Amongst these methods, the break-in-slope (BIS) and the Fast Fourier Transform (FFT) analyses of the experimental temperature signals responding to a discontinuity (or modulation) on the applied power have been systematically used in JET in the last years. The FFT method requires a periodic modulation of the auxiliary power and provides information on both the power deposition profile and the diffusive heat transport. The standard BIS (linear fit), a priori, does not distinguish between local power deposition and heat transport, but has the advantage of needing only a single discontinuity on the auxiliary power level. In this work we present an improved BIS procedure that not only considers the time delays between the RF power change and the respective temperature responses at the several plasma radii, but also extends the original linear fit of the experimental signals to an exponential one, in a tentative to capture part of the transport phenomena. The results of the improved BIS analysis are compared with the FFT results and the main advantages/restrictions of the two methods are discussed.

## INTRODUCTION

One of the most popular techniques adopted to infer the experimental RF power absorption profiles in tokamak plasmas is the 'break-in-slope' (BIS) method [1]. It is based on the analysis of the energy density response of the plasma to a sudden change $\Delta P_{RF}$ in the externally applied RF power. In many practical applications, the RF power is modulated and it is assumed that all processes in the plasma (including heat diffusion and variations of other power sources/sinks) occur on a much slower time scale than the changes in the plasma temperature, so that the local energy conservation law can be exploited in its most simple form

$$\frac{3}{2} n_a k_B \Delta \frac{\partial T_a}{\partial t} \approx \Delta p_{RF} \tag{1}$$

where $k_B$ is Boltzman's constant and $(n_\alpha, T_\alpha)$ are the species density and temperature, respectively (the density was assumed to also vary much slower than the temperature). Hence, the temperature signals measured in several regions of the plasma are simply linearly fit during each semi-period of the modulation and the break in the temperature slopes $\partial T_\alpha/\partial t$ at each power step gives an estimative of the local RF power density $\Delta p_{RF}$. It is clear that the rather strong assumptions made above are only valid in certain conditions. For example, if the RF modulation applied is not fast enough, transport processes become important and the linearization of the energy equation breaks down. Furthermore, because of their different dynamics, electron and ion responses are quite different and thus require different modulation frequencies for a successful BIS analysis. Other important parameters are the density and the radiated power, which may change during the RF power steps and in some cases should be taken into account. These corrections can become particularly important in low absorption efficiency scenarios or when the RF power step is large compared to the total external power applied to the plasma. The main drawback of the traditional BIS analysis is the fact that one assumes that the temperature response of the plasma species is prompt to the RF power change, what is not always true, as in the case of the electron response in ion-cyclotron minority heating regimes, where a significant part of the RF power is first absorbed by the ions and afterwards transferred by collisions to the electrons.

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

We propose an improved data analysis procedure to extend the break-in-slope technique to indirect heating scenarios, by taking into account the time delays between the temperature response of the plasma species and the RF power change. In this method, the maxima and minima of the temperature signals are statistically determined near all power 'breaks' in the various diagnostic (radial) channels, involving a careful processing of the experimental data.

As an illustration of the improved BIS* method, we show in Fig.1 comparisons of the experimental electron power deposition profiles obtained during a ($^3$He)H ICRH experiment at JET (#63322) with three different methods: FFT(□) [2], standard BIS(○) and improved BIS*(▲). In this discharge the minority concentration was systematically increased to change the nature of the ICRF power absorption from a minority heating regime MH (b) to a mode-conversion heating regime MC (a). An RF power modulation of 20Hz was applied throughout the pulse [3]. Note that although the standard BIS results nicely agree with the FFT results in the MC regime, the RF power densities obtained in the MH regime are completely underestimated in the central region of the plasma, where the ECE response is delayed with respect to the RF power modulation (see inset of Fig.1b). The improved BIS*, that takes into account this effect, satisfactorily reproduces the FFT results in both cases. As a matter of fact, the time delays determined in the MH regime by the BIS* procedure show a clear correlation with the phases obtained by the FFT analysis, as illustrated in Fig.2.

Note that the time delays obtained near the plasma center in this case reach values of $\Delta t \sim 12$ms, roughly 1/4 of the RF modulation period (50ms). The minimum observed around R=3.4m is believed to be related to a parasitic mode conversion layer associated to Carbon impurities present in the experiment [3]. The main advantage of the BIS* technique with respect to the FFT is the fact that it provides 'instantaneous' information of the power density profiles and time delays at each power step, which is particularly interesting when studying discharges with RF heating regime transitions.

A further improvement to the BIS* procedure was the inclusion of a simplified loss term ($\propto T_\alpha$) in eq.(1), in a tentative to capture some of the transport phenomena. This has shown to be particularly important for slow RF power modulations and for the analysis of single power 'breaks' (e.g. RF switch-on/off). In Fig.3a we show an example of the exponential fit applied to the ion temperature response (measured by charge-exchange) to a single step in the RF power applied to the plasma (see inset) in a fundamental D majority ICRH experiment performed at JET [4]. In Fig.3b we show the respective RF power absorption profiles obtained when including (▲) or not (●) the simplified loss term correction in eq.(1). Although the linear and exponential fits lead to similar temperature slopes before the power step (where the plasma is in thermal equilibrium), the linear fit is not capable to capture the temperature evolution that follows the RF switch-off, leading to considerably underestimated power density values. One could claim that by taking a sufficiently small interval after the power step to perform the linear fit, the two methods would converge, but with the low time resolution of the CX signals this would lead to large statistical errors in the determination of the temperature slopes. The broad absorption profile obtained with the exponential BIS* analysis (Fig.3b) is characteristic of the D fundamental ICRH scenario, which is dominated by Doppler-shifted IC absorption of the NBI ions [5]. Additionally, even with the inclusion of the loss term mentioned above, the transport effects can never be completely 'filtered out' of the ion temperature responses.

The analysis of recent experimental results have shown that only 50-60% of the nominal RF power applied is recovered when integrating the power absorption profiles obtained in the BIS* analysis of single power steps. Besides the fact that a substantial fraction of the RF power may be absorbed outside the line-of-sight of the diagnostics (SOL coupling, central absorption, etc.) we believe that radiation and density changes may also introduce important corrections to the power density values in such cases.

## CONCLUSIONS

An improved break-in-slope procedure that takes into account the time delays between the experimental temperature responses and the RF power modulation in the various regions of the plasma was presented. This method has been benchmarked against FFT and standard BIS results in various experimental conditions at JET. Its performance in most cases is comparable to the FFT analysis, with the advantage of capturing the 'instantaneous' power densities and time delays (FFT phases) at each RF power step. Recent developments, as the inclusion of an exponential fit to the temperature signals to partially account for transport effects allowed to extend the applicability of the BIS* procedure to one single power step (e.g. RF switch-off). Further enhancement of the BIS* analysis procedure for these cases is under way.

## REFERENCES

[1]. D.J. Gambier et al., Nucl. Fusion **30**, p.23 (1990).
[2]. D. Van Eester, Plasma Phys. Control. Fusion **46**, p.1675 (2004).
[3]. M.-L. Mayoral, P. Lamalle, D. Van Eester et al., Nucl. Fusion **46**, p.550-563 (2006).
[4]. A. Krasilnikov, et al., "ICRH of JET D plasmas at the fundamental frequency", this conference.
[5]. E. Lerche, D. Van Eester et al., "D majority heating in JET plasmas: ICRH modelling and experimental RF deposition", this conference.

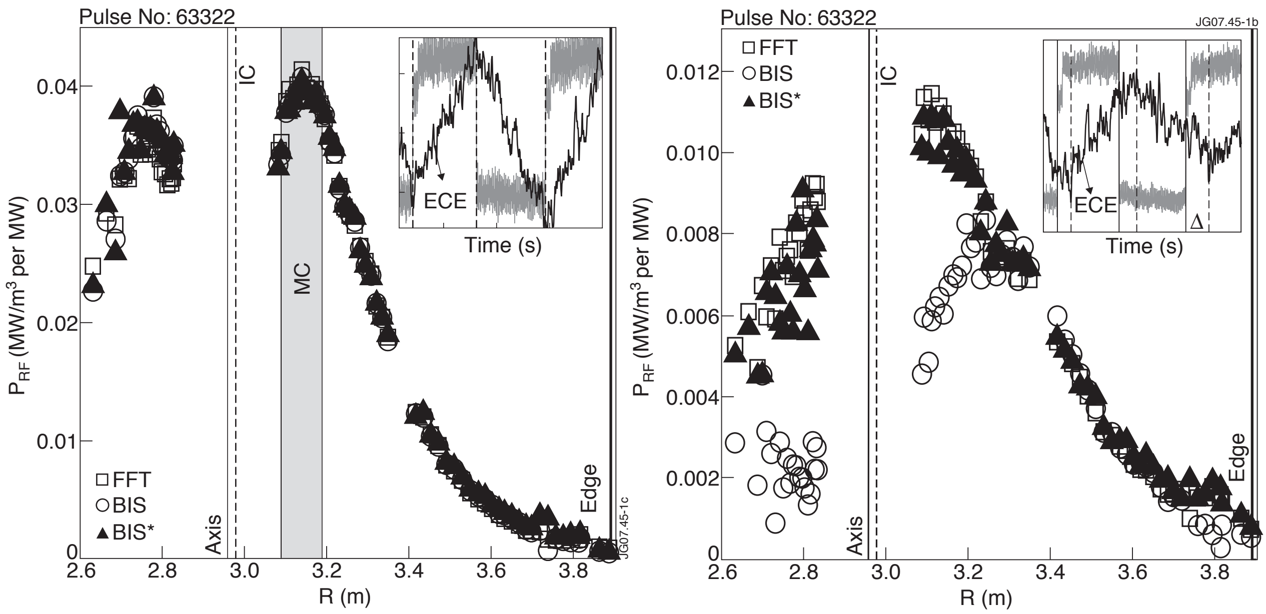


*FIGURE 1: Electron power absorption profiles obtained from ECE measurements in mode conversion MC (**a**) and minority heating MH (**b**) regimes in an inverted ($^3He$)H ICRH experiment at JET with three different methods: (N=1) FFT analysis (□), standard BIS analysis (○) and improved BIS* analysis (▲).*

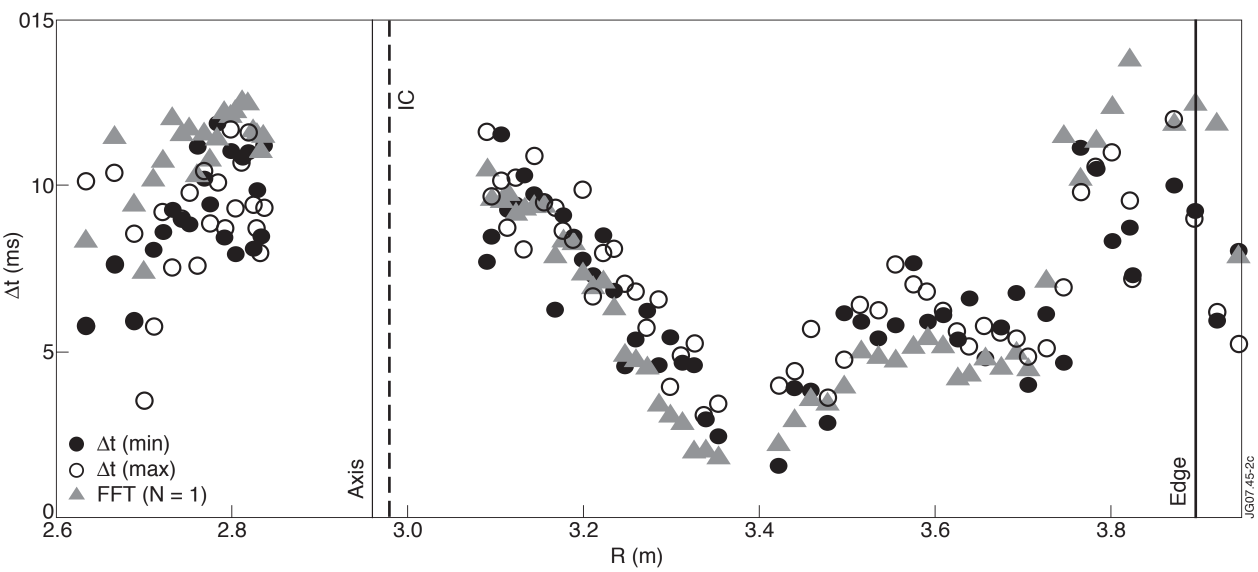


*FIGURE 2: Time delays between the electron temperature response of the various ECE channels and the RF power modulation compared with the phases (ϕ/ω) obtained in the FFT analysis (▲) for the MH regime shown in Fig.1b. An interval of 0.2s was used for the FFT and the represented BIS* time delays are the averaged values of the single time delays at the minima (●) and maxima (○) of the ECE signals.*

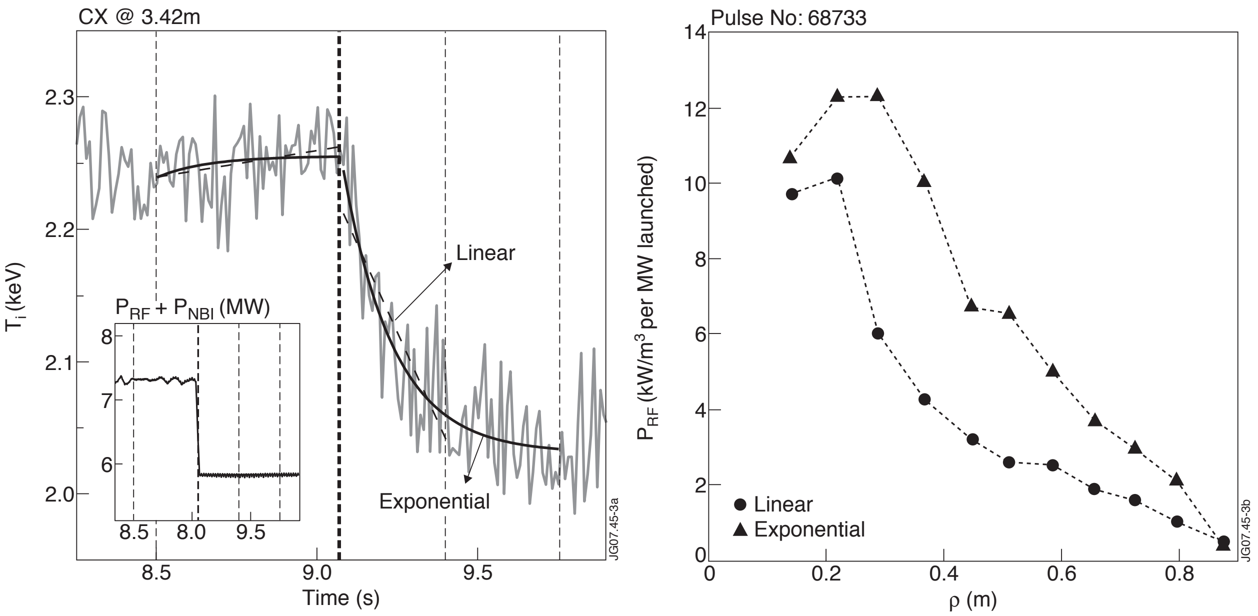


*FIGURE 3: (a) Example of the exponential fit applied to the CX ion temperature signals during the RF-switch-off in pulse #68733 and (b) respective power absorption profiles obtained with the BIS* analysis with (▲) and without (●) the loss term corrections.*