Experimental Determination of the ECH Power Deposition Profile in TCV

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Introduction

Good knowledge of the ECH power deposition profile is essential for the experimental study of heated plasmas (energy and particle transport, magnetic confinement stability), for profile tailoring, current drive, as well as for the verification ECH ray tracing codes. In TCV this is complicated by the combination of a large variety of plasma shapes (elongation < 2.56, -0.7 < triangularity <+0.5, to date) and a versatile ECH launching system (ultimately 9 beams, 6 at the second harmonic with independent poloidal and toroidal launching angles and 3 at the third harmonic with independent poloidal launching angles). The dynamic response to ECH power perturbations of the electron temperature inferred from soft X-ray emissivity and diamagnetic measurements is used in this paper to examine the ECH deposition. The deposition can be examined with different modulation waveforms: sinusoidal at high frequencies (70Hz to 500Hz) to diminish the effect of transport; random binary signal (RBS) to diminish the effect of coupling with the sawteeth; the response at power turn on and off. The pollution of the X-ray response from the component due to the sawtooth instability, which usually makes analysis difficult, has been treated using a Generalized Singular Value Decomposition (GSVD) technique. This study is thus not restricted to non sawtoothing discharges but covers the whole plasma current capability of TCV.

Experimental set up

The dynamic response of the plasma to ECH power perturbations has been performed in a relatively simple experimental scenario. A "typical" TCV plasma has been chosen with an elongation of 1.6, a triangularity of 0.3 and a density of $\sim 1.5 \times 10^{19}$ m^{-3} and a single gyrotron was used (P_{max} = 500 kW). The following steps were performed:
- the effectiveness of the sawteeth suppression with the GSVD was tested using discharges with low (Ip = 260 kA, q ~ 4.5) and high plasma current (I_p = 400 kA, q ~ 2.5).
- the dependence of the dynamic response at different ECH deposition locations was examined; the vertical position of the magnetic axis was modified instead of the ECH launching angle to reduce the refraction effects resulting from a small incident angle between the EC waves and the plasma flux surfaces.
- the frequency dependence of the plasma response was investigated using square wave power modulation at 5 frequencies during each plasma discharge.

Description of the analysis procedure

Figure 1 shows an outline schematic of the analysis procedure. The soft X-ray emissivities, integrated along their lines of sight, are analysed with the GSVD to separate the sawteeth and the power modulation contributions (MECH). The GSVD decomposes the

signals providing a set of topos (spatial eigenvectors) and their corresponding chronos (temporal eigenvectors). This method 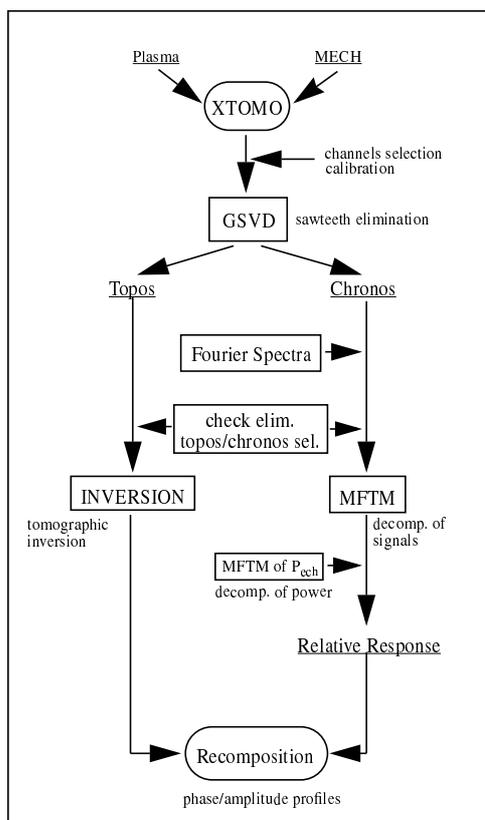involves filtering in phase space, as opposed to regular linear filtering, which only works if the noise and the dynamics of interest have sufficiently different power spectral densities [1]. Discharge periods are chosen in which there are only sawteeth contributions and others with sawtooth and MECH contributions. The GSVD, which has been simultaneously applied to both periods, gives base function common to both which optimises the representation of the MECH whilst diminishing the sawtooth contribution. A frequency analysis of the chronos is used to verify the sawteeth component elimination and the selection of the topos and chronos relevant to the MECH. The selected topos are submitted to a tomographic inversion [2], and the chronos are analysed with a Modified Fourier Transform Method (MFTM). The electron temperature is composed of a modulation contribution superimposed on signals caused by changes in the main plasma parameters. The goal is to simultaneously eliminate the base signal and to extract the complex amplitudes of the harmonics of the modulation frequency through Fourier analysis [3]. A decomposition, using the same procedure, of the reference power signal is used to determine the relative response of each harmonic. The relative responses and the inverted topos are then recombined to obtain the amplitude and phase profiles. Maxima in the amplitude profiles and minima in the phase profile indicate the power deposition location.

Figure 1: procedure scheme.

Results

The effectiveness of the GSVD was studied using a range of plasma and ECH parameters and different input signal normalisation procedures. A discharge window with 6 to 8 sawteeth periods during the ECH, but before ECH modulation, was chosen as the reference. The best decoupling between the sawteeth and MECH components was obtained with a normalisation where the raw signals were divided by their mean values.

Figures 2 and 3 show an example of the separation that was obtained. Figure 2a shows the Fourier spectrum of a raw signal. The peaks at 71Hz and 214Hz are the 1st and 3rd harmonic of the MECH, at 330Hz the sawteeth, at 400Hz the 1st harmonic coupling between sawteeth and MECH, at 1350Hz the electrical pickup, at 1020Hz the coupling between electrical pickup and sawteeth. Figure 2b shows the spectrum of reconstruction of the same signal using the first 5 topos and chronos of the GSVD. Not only has the sawteeth dependent component been strongly reduced, but the coupling between sawtooth frequency and MECH was also reduced. The first three odd harmonics of the modulation are now evident.

Figure 3 shows signals corresponding to lines of sight passing through three different plasma regions. Figure 3a and 3b show respectively reconstructions using 1 3 5 and 7 topos/chronos for discharges with a square 71.4Hz and 166.7Hz ECH power modulation. At 166.7Hz the

number of topos/chronos that can be used in the reconstruction is reduced by the proximity of the sawtooth frequency whereas modulation at lower frequencies has the disadvantage of being more strongly influenced by energy transport. A compromise is required which must be verified for a range of experimental conditions. The GSVD has the advantage of reducing the computation required for tomographic inversion of the reconstructed signals since only a few topos are inverted which cover the whole analysis period.

Figure 2: Fourier spectrum before (a) and after (b) GSVD (selected 5 components).

The selected chronos and the reference power signal are then decomposed with a MFTM. The complex relative response is calculated for the first n odd harmonics of the Fourier decomposition of the modulation
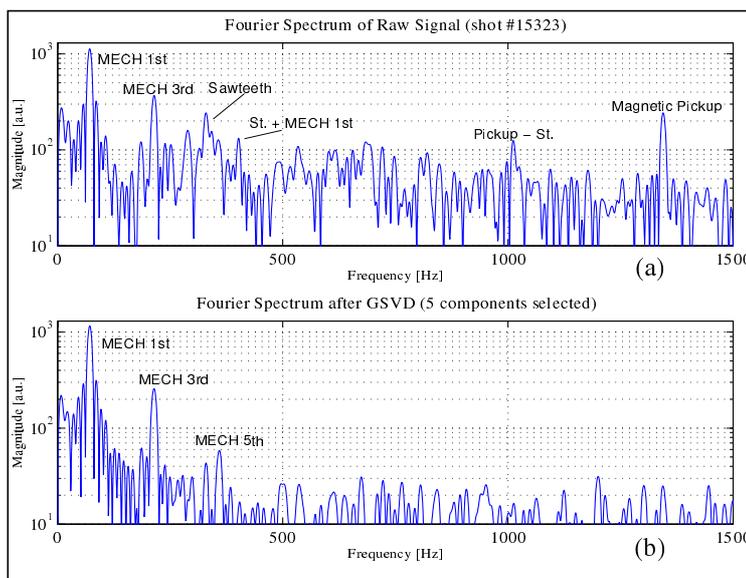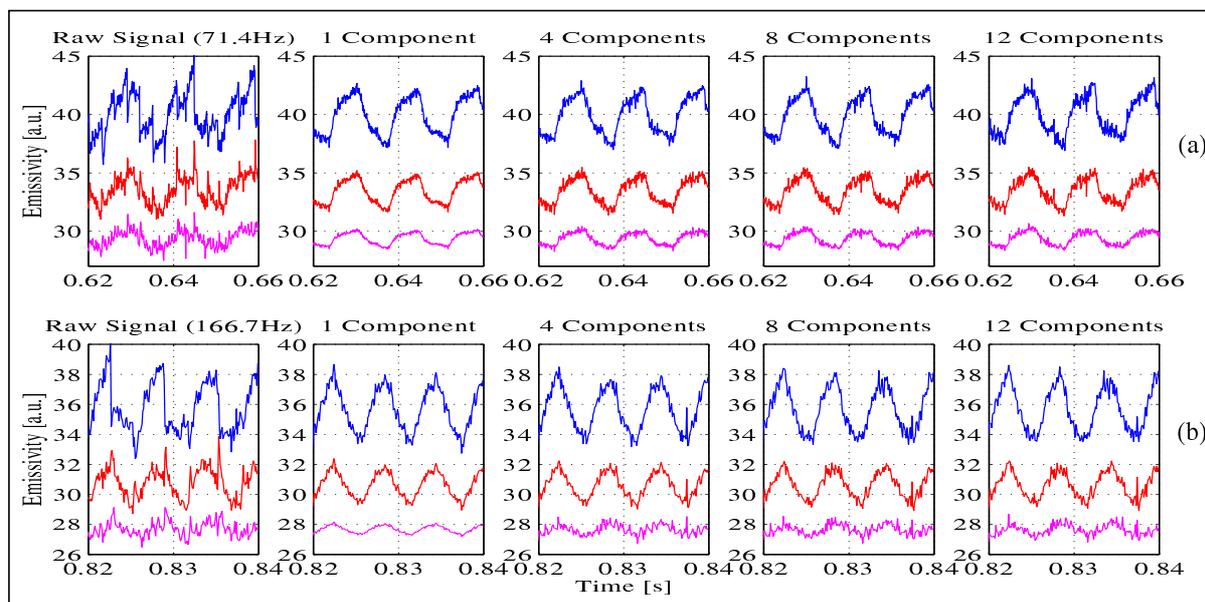

Figure 3: checking the sawtooth elimination for signals at different radii (low (a) and high (b) frequencies modulations, ν_{mech}=71.4Hz and ν_{mech}=166.7Hz).

frequency.

Finally, the topos are inverted by means of Minimum Fischer Regularization, [2]. Inverted topos and harmonics of the relative response of the chronos are then recomposed to obtain the amplitude and phase profiles of the X-ray intensity response to ECH modulation.

Figures 4a and 4b show an example of results of this procedure for discharge #14990 in which ECH was aimed at the plasma core and the reconstructed X-ray profiles clearly indicate
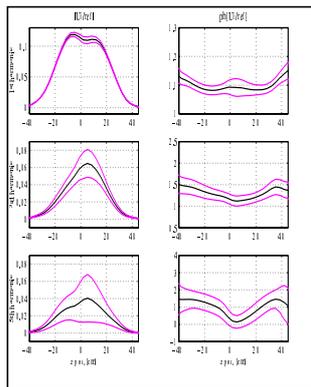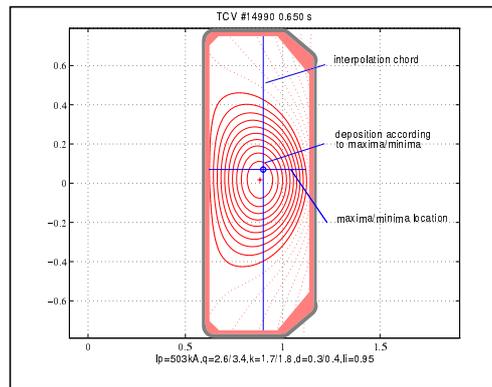
Figure 4a: amplitude and phase profiles.

Figure 4b: power deposition according to the profiles.

central power deposition. There are, however, cases in different discharges where there is only partial or sometimes no agreement with the ECH aim. Further studies are required to improve the procedure and interpret the resulting amplitude and phase profiles.

Conclusion

The dynamic response of the plasma of TCV in the presence of modulated ECH has been investigated in order to localise the power deposition profile. Suppression of the coupling between the contributions in the X-ray intensity from the sawtooth instability and the ECH modulation has been achieved using the GSVD method which was otpimised by choosing a mean-subtraction normalisation. The quality of the separation was found to depend on the choice of discharge time windows used in the analysis, the diode viewing chords and the modulation frequency. The MFTM has been successfully used in the frequency decomposition of the selected chronos and has been verified to correctly reconstruct the chronos themselves. The spatial emissivity distribution was shown to be well reconstructed with a tomographic inversion of a limited number of topos terms. The next step will require an optimisation of the MFTM with respect to the modulation frequency for the different types of discharges, in interpreting the results obtained from the amplitude and phase profiles and in applying other ECH power perturbations, in particular RBS.

Acknowledgments

Bibliography

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