WP15ER-CPR(17) 16823

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Preprint of Paper to be submitted for publication in Proceeding of
2nd European Conference on Plasma Diagnostics (ECPD)

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ABSTRACT: The measurement of Collective Thomson Scattering (CTS) emission from the plasma is used as diagnostic technique for investigating the ion dynamics. Recently the CTS lines and radiometric systems turned out to be suitable also for investigating other plasma emissions of non-CTS origin. Particular regimes are presently under study in several fusion machines, where non-CTS signals, which may be associated with a newly explained low power threshold parametric decay (PD) process, sometimes appear in the diagnostic spectra. The focus of the CTS system experimental activity at FTU has been then moved on the investigation of possible PD processes correlated to the magnetic islands, covering the configurations of interest for ITER, allowed in FTU. Recent advances in the data processing and in the code activity, finalized to help the spectra interpretation and the comprehension of the above described phenomena, are presented. A renewed software has been implemented for the calibration of the CTS spectra measured during the last experimental campaigns of FTU and for signal visualization for the direct comparison with the MHD spectrograms and the plasma signals. The software also allows analysing data detected simultaneously with two radiometric systems that operate in parallel in FTU since the beginning of 2016. The calibration of the spectra allows comparing the spectral emissions, that may span by orders of magnitude, from the lowest ones compatible with thermal nature and leading information on the ion dynamics, to possible strong emissions of non-CTS origin. The Thermal Collective Scattering Code (TCS), able either to predict and analyse thermal ion spectra as well as to infer the main plasma compositions starting from the CTS measurements has been optimized and integrated in the data analysis tool system. The analysis of the complex spectral scenarios emerged from the last CTS campaigns is presently underway and will be reported elsewhere.

KEYWORDS: Simulation methods and programs; Software architectures (event data models, frameworks and databases); Nuclear instruments and methods for hot plasma diagnostics

Contents

1. Introduction

The Collective Thomson Scattering (CTS) diagnostic is known to be a versatile technique of investigation of the ion dynamic: initially used to obtain measurements of the thermal ion temperature [1], it has been included among the planned diagnostic systems for ITER, with the main aim of characterizing the energy distribution of the fusion alpha particles [2]. However, the CTS diagnostic system also allows investigating other plasma characteristics and peculiar plasma regimes. Anomalous strong scattering signals correlated with the rotating magnetic islands have been observed in experiments with plasma heating by X-waves at the second harmonic of the Electron Cyclotron (EC) frequency [3]. Theoretical explanations of such phenomenon as due to a non-monotonic density profile which favours the excitation of Parametric Decay Instabilities (PDI) at power thresholds of the pumping wave close to (or even below) the typical level of injected EC beams have been proposed [4,5,6]. A quantitative agreement with the experimental intensity and frequency of the anomalous emissions has been obtained. A deep understanding of these phenomena is fundamental, since they may affect either the operations of CTS in ITER or the efficiency of NTM mitigation by EC waves, which is one of their main purposes. In principle, it can be reasonable to expect that such mechanism is not specific for the second harmonic X-mode but could take place also in the case of first harmonic O-mode heating, which is the configuration foreseen for the second phase of operations in ITER.

FTU is the one of the machines equipped with the CTS diagnostic system which can operate exploiting the largest variety of scenarios: the probe can be launched both in O-mode and in X-mode, with or without the main harmonic resonances in the plasma. Recently the CTS diagnostic system of FTU has been upgraded [7,8] and experiments have been carried out with the new configuration during the 2015-2016 campaigns, with the two aims of investigating the possible excitation of PDIs by first harmonic O-mode beams in presence of magnetic islands and of measuring their effects on the EC power absorption. Given the amount of experimental data obtained in different plasma conditions and varying the launching and receiving configurations, sophisticated software has become necessary for the data analyses and the interpretation of signals measured by different systems and probes. In section 2 the data analysis tool developed for this task is described. The method implemented in the software for the spectra calibration is discussed in section 3.

The availability in FTU of sub-harmonic plasma scenarios (i.e. with the fundamental EC resonance out of the plasma on the low field side) allows CTS studies in conditions similar to the 1 MW/60 GHz CTS in ITER [9]. Therefore, also the possibility of measuring the bulk ion features in such ITER-relevant conditions is left open during the present experiments, in parallel to the main aim of investigating non-CTS signals from PD processes. The code TCS [7], thought for both simulation and interpretation of the thermal spectra, has been optimized and included among the data analysis tools presented in the paper. Such preliminary integration is described in section 4. Finally, conclusions are drawn in section 5.

2. Software for data analysis

The main upgrades carried out on the CTS diagnostic of FTU during the last years [7] consist in the implementation of a second acquisition system operating in parallel to the previous one, and the installation of new probes, that acquire data on separate databases and different timing and clocks than the one of FTU. The first part of the development of the data analysis tools has concerned the implementation of a code [10] capable to properly visualize data acquired on different local memories and to refer all of them to the same reference acquisition time given by the Fast Sequence Control (FSC) of the FTU shot. The original software has been optimized and improved to include the data measured by the second filter bank radiometer, coupled with the first one to the same transmission line through a polarizing grid beam splitter. In addition to displaying the spectrograms of these two analog radiometers, the code calculates also the power spectral densities of the high time-resolution signals coming from two channels of the a fast digitizer, which operates in parallel to the analog radiometers and which acquires the intermediate frequency (IF) signals coming from the two front-ends, and obtain their spectra by direct Fourier transform. Due to the large amount of data which the fast acquisition system is able to acquire (sampling rate capability up to 12.5 GS/s), a parallelization and optimization of the FFT calculations have been integrated in the code, allowing such analysis tool to be used also for a fast visualization of the CTS signals in the time lapse between subsequent shots during the CTS experimental sessions. The software allows also performing the calibration of the above power spectral densities, according to the method described in section 3. The CTS spectrograms of the two radiometers and the two Fourier transformed IF signals can be visualized together in synchrony with the main plasma quantities (plasma current, electron temperature, line-averaged electron density etc.), the EC system parameters, the signals of the sniffer probes, used to measure the stray radiation level in the vacuum vessel, and the signals detected by two sensors installed in the launcher port for detection of visible light and stray power at the frequency of the CTS probe. These two last sensors have been installed in order to detect emissions from the launching antenna, possibly due to local plasma generation [8]. In addition, the code has been coupled to a pre-existing software (MDANA), developed at the ENEA Frascati Research Centre (Frascati) for the reconstruction of the MHD spectrogram and the identification of the tearing modes present in the plasma starting from the raw signals of the Mirnov coils. Finally, the code allows visualizing the main parameters of the launching and receiving configuration, that typically change shot by shot [11]. In fig. 1 an example of the outputs of the software is shown for the CTS shot #40771, with B_T= 4.7 T and an intersection between the O-mode probe and the receiving beam out of the equatorial plane, at the m:n=2:1 tearing mode location. These graphs show a strong MHD activity (mostly in the form of a m:n=2:1 tearing mode) in phase with CTS signals higher than the background ECE level, while no significant increase of the stray radiation level neither in the vessel nor in the launcher port is observed but during the disruptive phase, which starts at ~373 ms. The capability of the fast data acquisition system and the flexibility of the code in Fourier transforming the raw IF signals allow investigating fine structures which appear on the CTS spectrograms on very small time scales [11]. In fig. 2 the CTS spectra are shown for a time interval of 4 ms in which the MHD activity is particularly strong. Coincident signals at frequency distance higher than the one expected for thermal CTS are visible in both the spectrograms of the digitizer. Additional analysis and measurements of the gyrotron spectrum are being carried out in order to exclude that these structures are related to gyrotron spurious signals. The example in fig. 2 is reported as an example of the potential of the new analysis tools for the CTS data. Anyway, the interpretation of similar structures is challenging, and an intensive work of data analysis is still being made to this aim.

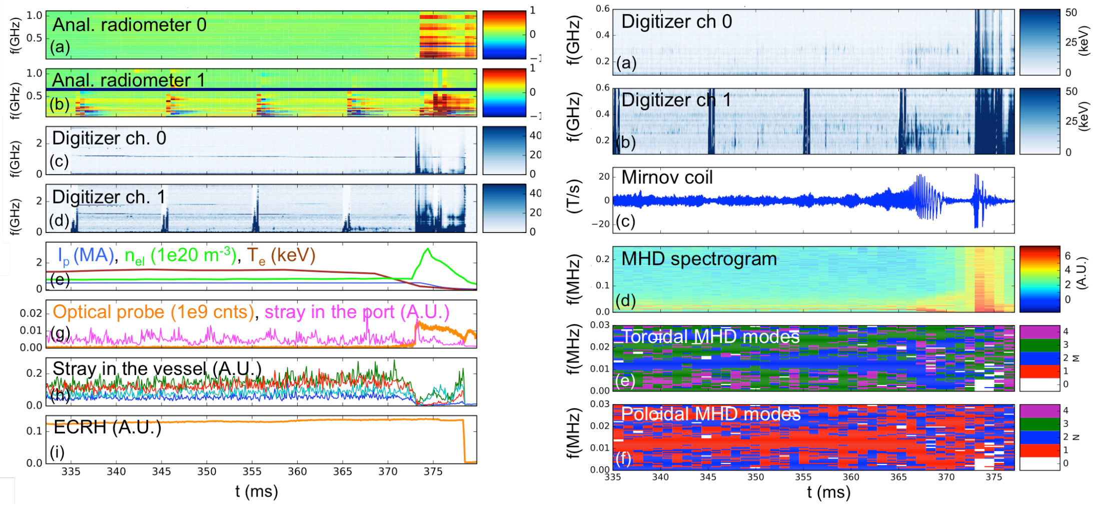

Figure 1. *Examples of signals visualization elaborated with the new tools for the CTS data analysis for the shot #40771. Left: signals acquired by different acquisition systems are displayed on the same FTU time reference in the following order: uncalibrated spectrograms by the two 32-filter bank radiometers (a,b), calibrated spectrograms by the two channels of the fast digitizer (c,d), plasma current, electron temperature, line-averaged density (e), visual light level and stray radiation level in the launching port (g), stray radiation level in the FTU vessel (h) and injected gyrotron power in A.U. (i). Right: calibrated spectrograms by the fast digitizer (a,b), raw signal detected by a Mirnov coil (c), MHD spectrogram calculated with the MDANA software (d) and color highlighting of the most likely guess of identification of the toroidal (e) and poloidal (f) modes of the rotating islands.*

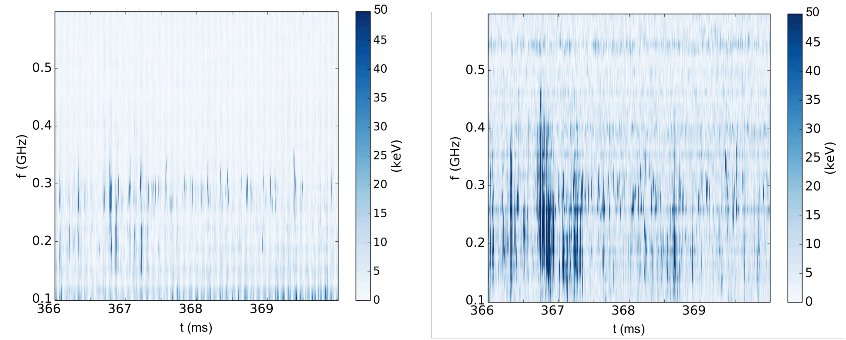

Figure 2*. Calibrated spectrograms acquired with the two channels of the fast digitizer, shown in a time interval of 4 ms of shot #40771 during a strong MHD activity.*

3. Calibration of CTS spectra

In order to properly analyze the received signals, a calibration method specific for the CTS diagnostic system of FTU has been defined and integrated in the software for the data analysis. A procedure has been drawn up to extract from the raw data the effective signal received from the plasma, cleaned by all the noise and the frequency-dependent characteristics of the transmission line and the receiver, and obtain a spectral density calibrated in temperature. In order to achieve this goal, it is necessary to estimate the impact of the specific diagnostic setup used during the experiments on the power spectral density. The following formula has been defined for the calibrated power spectral density, expressed in temperature units (keV):

$$PSD_{cal}(\omega) = \frac{\alpha}{A(\omega)\cdot F(\omega)\cdot K} \cdot \left(PSD_0(\omega) - N_0 - N \cdot A(\omega)\right)$$

where PSD_0 is the general un-calibrated power spectral density, N_0 is the quantization noise, N and A are respectively the value and the shape of the amplifiers noise functions, F is the transmission function, K is the temperature conversion factor and α is the attenuation factor. While A and F are direct functions of the frequency, N_0, N and K are frequency independent. Some calibration functions are obtained from the power spectral density (PSD_{on}) measured during FTU Ohmic shots, with the EC fundamental resonance in the plasma, while others from the power spectral density (PSD_{off}) assessed when no signal coming from the plasma enters into the front-end. This last condition occurs either in particular FTU shots performed in absence of plasma, or when disruptions arise during the CTS system acquisition or during particular phases of the gyrotron pulse, when the CTS mixer is protected by a diode which is mounted after the receiving horn and which closes the transmission line at the entrance of the front-end. The function PSD_{off} thus defines a sort of 'noise' spectrum, and it can be expressed as following: $PSD_{off}(\omega) = N_0 + N \cdot A(\omega)$. Assuming A=1 as average value on the frequency interval, and defining $N_0 = \min\left(PSD_{off}(\omega)/\langle PSD_{off}(\omega)\rangle_\omega\right)$, we obtain N as given by $N = \left(\langle PSD_{off}(\omega)\rangle_\omega - N_0\right)/\langle A(\omega)\rangle_\omega$ and finally $A(\omega) = \left(PSD_{off}(\omega) - N_0\right)/N$. In the beginning of 2016, the replacement of the IF amplifiers has been carried out in order to enlarge the measurement bandwidth [10]. The amplification of the whole bandwidth, together with the negligibility of the quantization noise with respect to the amplifiers noise, led to consider $N_0=0$ for the spectra acquired after such upgrade. The power spectral density of a generic Ohmic shots, with the fundamental EC resonance in the plasma and electron temperature T given by ECE, can be expressed as $PSD_{on}(\omega) = N_0 + N \cdot A(\omega) + A(\omega) \cdot F(\omega) \cdot K \cdot T/\alpha$. A function F_{test} is defined from the above formula assuming $\langle F\rangle_\omega=1$. Then, F is normalized to the value of the average value of F_{test} on the frequency interval corresponding to an ECE spectrum [0.45 GHz – 0.75 GHz], which for the CTS setup of FTU is flat. This leads to:

$$K = \frac{\alpha \cdot \langle F(\omega)\rangle_\omega}{T} \cdot \left(\frac{\langle PSD_{on}(\omega)\rangle_\omega}{\langle A(\omega)\rangle_\omega} - \frac{N_0 + N \cdot \langle A(\omega)\rangle_\omega}{\langle A(\omega)\rangle_\omega}\right) \quad \text{and} \quad F(\omega) = \frac{\alpha}{T \cdot K} \cdot \left(\frac{PSD_{on}(\omega)}{A(\omega)} - \frac{N_0 + N \cdot A(\omega)}{A(\omega)}\right).$$

Indeed, the emission measured by CTS system in an Ohmic plasma in which the EC resonant layer is present is the ECE emission at the intersection between the receiving line of sight and the resonant layer, provided the plasma is optically thick in that point. The calibration functions have been found to vary with the experimental setup. For example, the function A depends on the frequency of the local oscillator operating in the quasi-homodyne down-conversion stage, while N_0 has been found to be function of both the acquisition resolution and the sample rate. For this reason, the shots with similar acquisition setups have been grouped, before calculating the parameters N_0, N, K and the functions A and F for each classification of discharges. To cross-check the functions obtained with the method described above, a calibration of the signal measured in selected Ohmic plasmas, with the same setting of the CTS acquisition system as in each group of discharges, has been calculated. A good agreement between the spectra calibrated using the respective calibration parameters and the electron temperature inferred by the calibrated ECE diagnostic has been found, confirming the validity of the method.

4. Integration of the TCS code

The availability of sub-harmonic scenarios in FTU, as the one foreseen for the CTS in ITER, opens the possibility to investigate phenomena under ITER-relevant conditions of beam injection and reception. Despite no fast ion measurements can be performed in FTU, the applicability of CTS for investigating either the bulk ion dynamic or possible effects of PDIs, if any, on such kind of measurement is open.

In order to support the analysis and the interpretation of thermal CTS spectra, the TCS code, has been optimized and included in the data analysis tools here presented. This code is based on a kinetic electrostatic approach [12,13] where the incident beam is scattered off on the electron density fluctuations. TCS considers a multi-species magnetized plasma, allowing interpretations also in conditions of spectra modulated at the ion cyclotron harmonics [14], which are known to contain also information about the plasma composition [15,16]. In principle, also the effects due to other kinds of plasma fluctuations (e.g. magnetic field, electric field and current [18]) may play a role in shaping spectra, but presently such effects are not included in TCS. This code has been included in the data analysis tools and linked to the beam tracing code GRAY [17], which provides the local plasma and beam parameters in the scattering volume. Using as inputs the data of the FTU database and the GRAY calculations, TCS is able to calculate the thermal CTS spectra associated with the scattering volume.

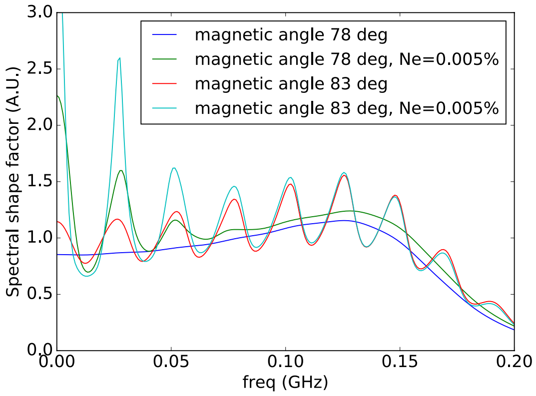

Figure 3*. Spectral density function (in arbitrary units) calculated by TCS for the FTU shot #40279 with and without 0.005 % Ne impurity concentration and for two experimental magnetic angles of 78 degrees and 83 degrees.* T_i *has been assumed equal to 0.5* T_e.

Four examples of spectra, calculated by TCS, for two different magnetic angles and Ne concentrations, are shown in fig. 3, where the magnetic angle is the angle between the toroidal field direction and the vector defining the direction on which the 3D ion velocity distribution must be projected to obtain the 1D distribution resolved by a given CTS configuration. The shown spectral density functions are obtained for the FTU shot #40279, with B_T=3.6 T (giving rise to a non-resonant configuration between the 1st and the 2nd harmonic resonances, both outside the plasma) and with the intersection between the probe and the receiving beam on the equatorial plane. At these experimental magnetic angles TCS predicts ion cyclotron frequency modulated peaks, that are enhanced when also the Neon impurity is included. The complete estimate of the power spectral density through the evaluation of the actual transfer function, as reported in [1], will be implemented in future work.

5. Conclusions

A set of codes for the analysis of the spectra measured with the CTS diagnostic system installed in FTU has been implemented and optimized, in order to properly analyze the experimental data acquired during the last campaigns. The recent upgrades in the diagnostic required the improvement of such data analysis tool, which now is able to display and compare several kinds of data measured by different systems and sensors that have been installed in the CTS layout during the last years. The software tool provides a visualization of all the experimental data in support to the interpretation of the signals, exploiting the high time and frequency resolution properties of a recently installed digital acquisition system, and thus permitting the investigation of phenomena characterized by very small time scales. The data analysis software has been coupled to the external code MDANA, developed for tearing mode recognition, and now it allows also displaying the results of the MHD analysis on the same time scale of all the other signals measured by the different diagnostic systems. The presented codes are capable to calculate the spectra using different set of parameters for proper computation, and visualize them on the FTU time reference, once calibrated according to the calibration method defined specifically for the FTU CTS diagnostic system and described in the paper. Calibrated spectra now allow a more reliable interpretation of the emissions based on quantitative analysis rather than the simply fast Fourier transformed raw data. Also the TCS code has been optimized and integrated in the data analysis tools, and it is now linked to the beam tracing code GRAY, allowing direct calculations of the thermal CTS spectra starting from the experimental local plasma and beam parameters in the scattering volume.

The integration of the overall software and the TCS code, equipped with an automatized input data system, provides a comprehensive data analysis tool. Additional optimizations of the software and of the codes are foreseen, in the view of the next experimental campaigns, for which further improvements of the CTS setup are being implemented [10, 19].

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] S.B. Korsholm et al., *Collective Thomson scattering capabilities to diagnose fusion plasmas*, 2010 *Nucl. And Methods in Phys. Research A* **623** 677.

[2] S.K. Nielsen et al., *Experimental characterization of anomalous strong scattering of mm-waves in TEXTOR plasmas with rotating islands*, 2013 *Plasma Phys. Control. Fusion* **55** 115003.

[3] E. Westerhof et al., *Strong Scattering of High Power Millimeter Waves in Tokamak Plasmas with Tearing Modes*, 2009 *Phys. Rev. Lett.* **103** 125001.

[4] E.Z. Gusakov and A.Yu. Popov, *Theory of anomalous backscattering in second harmonic X-mode ECRH experiments*, 2016 *Phys. of Plasmas* **23** 082503.

[5] E.Z. Gusakov et al., *Trapping of electron Bernstein waves in drift-wave eddies and parametric decay instability at second harmonic ECRH in toroidal devices* 2014, *Plasma Phys. Control. Fusion* **56** 015010.

[6] V.S. Marchenko and S.M. Reznik, *High frequency instabilities induced by energetic ions inside magnetic islands* 2015 *Plasma Phys. Control. Fusion* **57** 045006.

[7] W. Bin et al., *The upgraded Collective Thomson Scattering diagnostics of FTU*, 2015 *Fusion Eng. Des.* **96-97** 733-737.

[8] W. Bin et al., *First operations with the new Collective Thomson Scattering diagnostic on the Frascati Tokamak Upgrade device*, 2015 *J. Instrum.* **10** P10007.

[9] S.B. Korsholm et al., *High Power Microwave Diagnostic for the Fusion Energy Experiment ITER*, in proceedings of 41st International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), September 25-30 2016 Copenhagen, Denmark.

[10] W. Bin et al., *Advances in the FTU collective Thomson scattering system*, 2016 *Rev. Sci. Instrum.* **87** 11E507.

[11] A. Bruschi et al., *Observation of short time-scale spectral emissions at millimeter wavelengths with the new CTS diagnostic on the FTU tokamak* 2017 *Nucl. Fusion* **57** 076004.

[12] I.H. Hutchinson, *Principles of Plasma Diagnostics*, Cambridge University Press, 2002.

[13] J. Sheffield, *Plasma Scattering of Electromagnetic Radiation*, Academic, New York, 1975.

[14] S.B. Korsholm et al., *Measurements of Intrinsic Ion Bernstein Waves in a Tokamak by Collective Thomson Scattering*, 2011 *Phys. Rev. Lett.* **106** (2011) 165004.

[15] M. Stejner et al., *Principles of fuel ion ratio measurements in fusion plasmas by collective Thomson scattering,* 2011 *Plasma Phys. Control. Fusion* **53** 065020.

[16] M. Stejner et al., *Measurements of plasma composition in the TEXTOR tokamak by collective Thomson scattering* 2012 *Plasma Phys. Control. Fusion* **54** 015008.

[17] D. Farina, *A quasi-optical beam-tracing code for electron cyclotron absorption and current drive: gray*, 2007 *Fusion Sci. Technol.* 52 154.

[18] H. Bindslev, *A quantitative study of scattering from electromagnetic fluctuations in plasmas*, 1996 *J. Atmos. Terr. Phys.* **58** 983–989.

[19] O. D'Arcangelo et al., *New receiving line for the remote steering antenna of the 140 GHz CTS diagnostics in the FTU Tokamak*, *submitted to J. Instrum*.