Automatic Detection and Control of MHD Activity in FTU Tokamak by ECE and ECH/ECCD

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Abstract. Active control of MHD instabilities is important in order to improve tokamak performance. This paper describes experimental work done on FTU tokamak in this field, in particular for the automatic suppression of Tearing Modes (TM) via simultaneous detection and tracking of island position, sawteeth inversion radius and Electron Cyclotron Heating (ECH) power deposition. Effective control in real time is achieved through the implementation of a system for automatic detection of TM onset, and stabilizing reaction with ECH/ECCD. The system is composed by a particular arrangement of the 140 GHz, 4x0.5 MW ECH set-up, and a DSP-based (Digital Signal Processor) unit for the analysis of ECE and Mirnov data, and for the control of gyrotron power supplies. Main emphasis is given to the intrinsic capability of the arrangement for a fast reaction to an early warning of the TM appearance. In order to improve ECH power deposition identification by synchronous detection of ECE oscillations and ECH power modulation, special techniques based on non-periodic pulse sequences have been implemented.

1. Introduction

Active control of MHD instabilities is important in order to improve tokamak performance. Such instabilities are associated with local distortions of the current density profile, they usually lead to an important degradation of energy confinement and may compromise a reliable operation of the device. Magnetic islands associated to MHD instabilities develop at isobaric magnetic surfaces where the field line pitch is a rational number q=m/n. In order to restore locally the perturbed current profile, electron cyclotron heating (ECH) and current drive (ECCD) is a crucial tool. For optically thick plasma, ECH power is mostly absorbed where the injected beam crosses the resonant layer. If the absorbing volume is located on a generic magnetic flux surface the generated heat (or current) is rapidly spread all over the surface, and the resulting change in the axisymmetric current density profile can affect the local magnetic shear and the instability parameter Δ'. If the volume is on the rational-q flux surface where the magnetic island is located, the current driven by the RF (directly as ECCD or via a resistivity change due to the heating) has a helical structure and may compensate for the perturbed current and stabilize the mode. All these effects can be used for an active control of the MHD behavior of the discharge.

This paper describes experimental work done on FTU tokamak in this field, in particular for the automatic suppression of Tearing Modes via simultaneous detection and tracking of island position, sawteeth inversion radius and ECH power deposition. The main observable used to identify the radial location of island and of ECH deposition is the radiative temperature oscillations of Electron Cyclotron Emission (ECE). A rotating magnetic island causes a partial periodical flattening of the plasma temperature profile, localized around a rational-q flux surface, that in turn produce coherent oscillations of ECE signals. The ECE channels are tuned to frequencies corresponding to different radii R in the tokamak meridian cross-section

and the relative phase of the signal from two neighboring channels changes smoothly except if between them an island is located, where a phase jump close to π occurs. Concerning sawteeth, inversion radius is located by the same phase jump on ECE signals determined by the internal disruption following the magnetic reconnection. In order to identify ECH deposition position, a technique based upon synchronous detection of ECE signals oscillation due to EC source time modulation has been used. Continuous tracking of ECH power deposition is obtained applying a 10% ÷ 90% duty cycle scheme: when no island is detected and power should be off, a 10% duty cycle modulation is applied, whereas when an island is found the modulation is switched to 90% duty cycle. Different EC sources are identified using different frequencies.
The ability of the detection system to locate the position of different MHD instabilities has been proven in shots where coupled Tearing Modes (TM) and saw-teeth (usually m=2,n=1 and m=1,n=1) dynamically evolve during the discharge. The ECH radius is correctly identified even in the case of simultaneous launch of many mm-wave beams.

2. System description

Effective control in real time is achieved through the implementation of a system for automatic detection of TM onset, and stabilizing reaction with ECH/ECCD [1]. The system is composed by a particular arrangement of the 4 gyrotrons at 140 GHz, 0.5 MW ECH set-up working at the FTU site [2], and a DSP-based (Digital Signal Processor) unit for the analysis of radiative temperature ECE and Mirnov data, and for the control of gyrotron power supplies. The FTU launching mirrors are not suitable for fast beam steering, allowing only shot by shot position adjustment. Therefore the 4 gyrotrons have been aimed at four different radial locations around the foreseen island position. The DSP-based unit represents the core of the implemented system. It consists of seven units: a Personal Computer (PC), four Digital Signal Processors (DSP_A, DSP_B, DSP_C, and DSP_D), an ADC (Analog-Digital Converter) and a digital Input/output (I/O) board (see *FIG.1*). The ECE signals are acquired by an ADC board (12 analog input channels, 16 bit resolution) with a sampling frequency of 50kHz. The real-time data transfer is done through the DSP high-speed communication ports. The signals of the 12-polychromator channels are acquired by the ADC and sent at the same time to DSP_C and DSP_B. The DSP_A is the unit that receives informations from the other DSPs and processes them to make decisions (which gyrotron switches on and when). This unit can operate at lower frequency than the others when required.

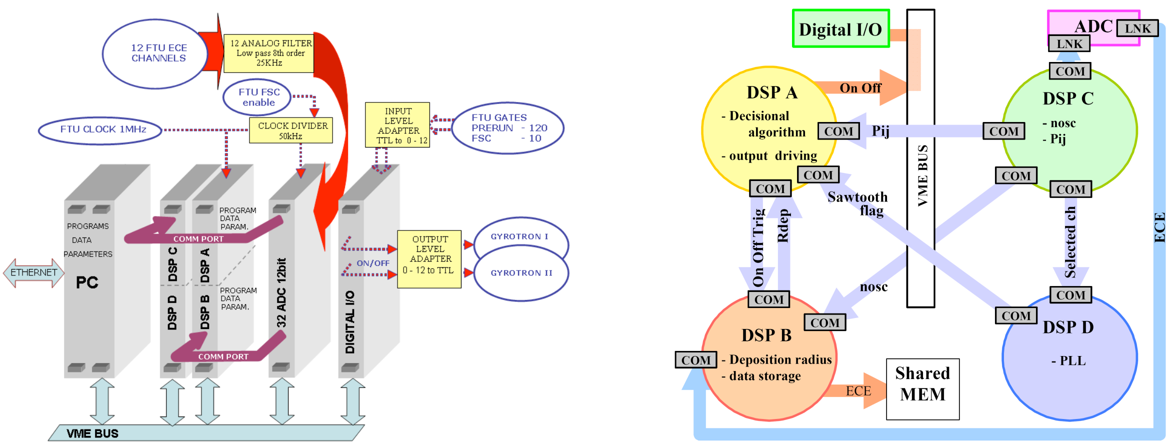

FIG.1. Schemes of the controlling DSP-based unit (left) and of the DSP specific tasks (right)

The DSP_B stores data and at the same time it computes the gyrotron power deposition position by correlating the normalized temperature fluctuation elaborated by DSP_C with the On/Off trigger from DSP_A. DSP_C produces the correlation between neighbor channels P_{ij}, the normalized oscillation (nosc) for DSP_B, it selects the channels for MHD frequency identification and sawtooth triggering and send them to DSP_D that runs the phase lock loop algorithm for the mode frequency and phase identification.

3. MHD control experiment

A successful example of detection/feedback control on FTU shot 27714 is demonstrated in *FIG.2*: it shows the Fast Fourier Transform (FFT) of a Mirnov coil signal and the ECE temperature fluctuations on channels 1, 2, 9 and 10 (top to bottom), where channels 2-9 and 1-10 are roughly symmetrical around the plasma axis. The two lower traces represent the RF power pulses of gyr.1 and gyr.3. The RF power was modulated to allow monitoring of the gyrotrons deposition position. The feedback control action consisted in switching from low to high average power of the gyrotron found to be closest to the detected magnetic island. The two used gyrotrons had been previously steered to deliver power close to ECE channel 7 (gyr.1) and channel 10 (gyr.3). The figure shows that an m=2, n=1 mode first appears (blue line on the Mirnov coil signal at 2.6 kHz and oscillations on ECE channels) at t=0.564 second, then is correctly detected and its phase inversion located between channels 9 and 10. The closest gyrotron (gyr.3 focused near channel 10) is identified and switched by the feedback from low to high duty cycle at t=0.580. When the mode is suppressed at t=0.623, gyr.3 goes back to low duty cycle. It should be noted that gyr.1 remains at low duty cycle for all the times.

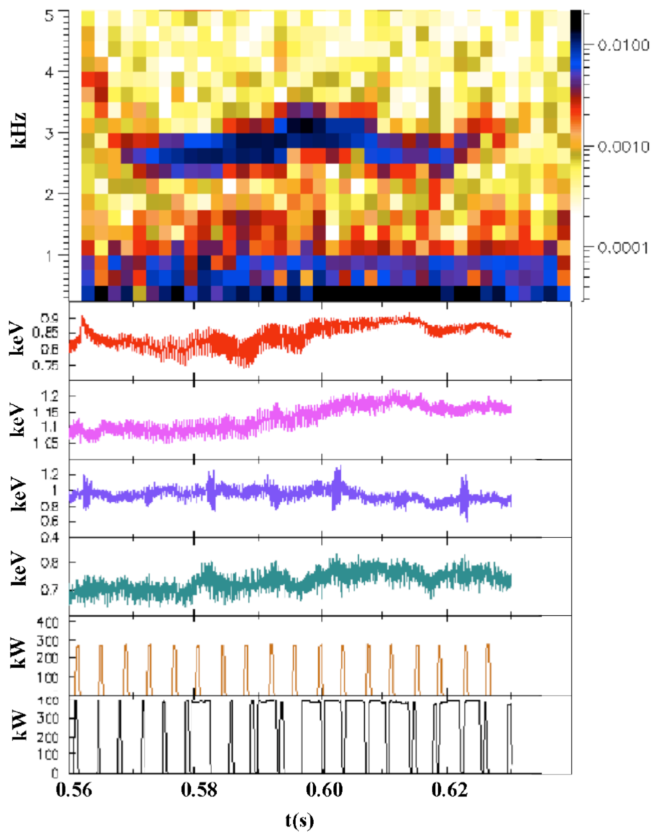

FIG.2. FTU shot 27714. From top to bottom: FFT of Mirnov coil signal (amplitude at frequencies below 5 kHz vs. time; the blue line at 2.6 kHz is related to the presence of MHD activity); m=2, n=1 temperature fluctuations on ECE chan.1, 2, 9, and 10; gyr.1 power trace; gyr.3 power trace.

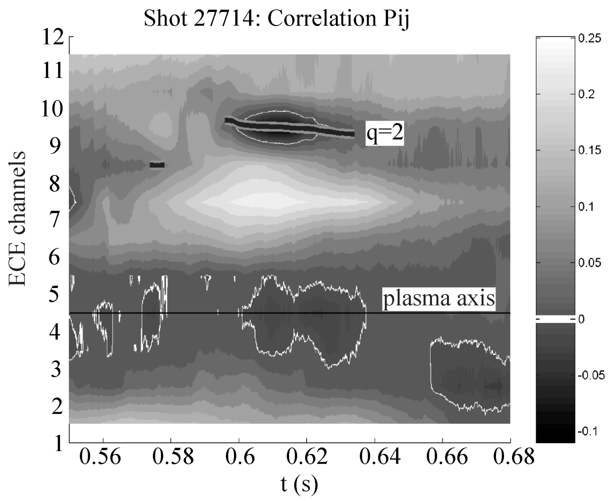

Fig.3. Contour plot of the P_{ij} *function for FTU shot 27714. A minimum of correlation is found between channels 9 and 10 (dark line) that identifies the radial position of the magnetic island (and q=2 surface). The white line is the contour with zero correlation.*

Fig. 3 presents graphically for this shot the real-time detection, by DSP_C, of the minimum of the correlation between ECE channels 9 and 10 (dark line) that identifies the radial position of the magnetic island (and the q=2 surface). Accordingly the Decisional algorithm (DSP_A) drives gyr.3 to full power.

This is also an example of the intrinsic capability of the system for a quick response: since no mirror motion is used, due to the spread pre-alignment strategy, as soon as a MHD island is identified the nearest gyrotron can be immediately switched on, without waiting for any mirror movement. This might be a promising control scheme for a fast reaction to an early warning of the tearing mode appearance, because if the application of ECCD, correctly localized on the O-point radial position, is performed as soon as the seed island is detected, the power required to suppress the island is much lower compared with the power required if the island has reached saturation.

4. ECH deposition detection

A crucial aspect of the feedback control subject is a clear identification of the position of the ECH power absorption. As discussed in previous works [3, 4], the amplitude of the T_e oscillations caused by EC power modulation in a burning plasma ITER like, can be estimated in the order of 1 eV for 1 MW fully modulated at 1 Hz and absorbed near the q=2 flux surface. Being this figure quite low compared to the temperature background of about 8 keV foreseen for that radial position, in order to increase the signal to noise ratio a possible approach is to consider a number of EC source as a cluster controlled as a single beam and aimed to be absorbed all at the same position. In this way it will be possible to reach a $\delta T_e/T_e$ ratio of 0.25% for a cluster of 20x1MW sources. This ratio is only a factor 6 lower than the ratio observed for ECH power deposition identification experiments done on FTU where, beside a fixed frequency modulation, other schemes based on non-periodic pulse sequences have been implemented and tested, looking for the most reliable, fast and less power demanding. Three different modulation schemes are presently discussed: a) shot 27625: 370 kW amplitude, 50% duty cycle, 2.3 ms pulse width at fixed frequency (reference shot); b) shot 27714: 280 kW amplitude, 10% duty cycle, 0.55 ms pulse width at fixed frequency; c) shot 29431: 220 kW amplitude, 10% duty cycle, 1 ms pulse width with random pulse sequence.

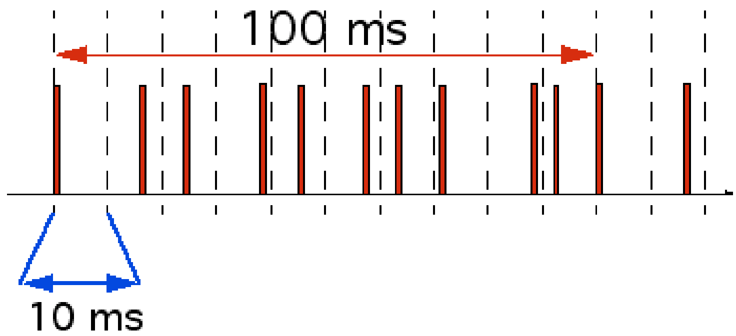

FIG.4: Example of Random Pulse Sequence: each pulse has a duration of 1ms and is placed in a random time position inside a window 10 ms wide. After 10 pulses the sequence is repeated.

The last consists in a sequence of ten pulses, each ones 1 ms long and randomly placed inside a time window 10 ms wide, that repeat itself every 100 ms (see *FIG.4*). The same gyrotron was used for all the considered cases and the target plasmas had similar parameters: a toroidal B field of 5.57 T, central T_e of about 2 keV, line density n_e of about 0.7×10^{20} m^{-3}. The beams were steered to be absorbed on the ECE channel 7. In order to identify the deposition position, a procedure similar to a boxcar integration, synchronous with the gyrotron pulses, has been performed:

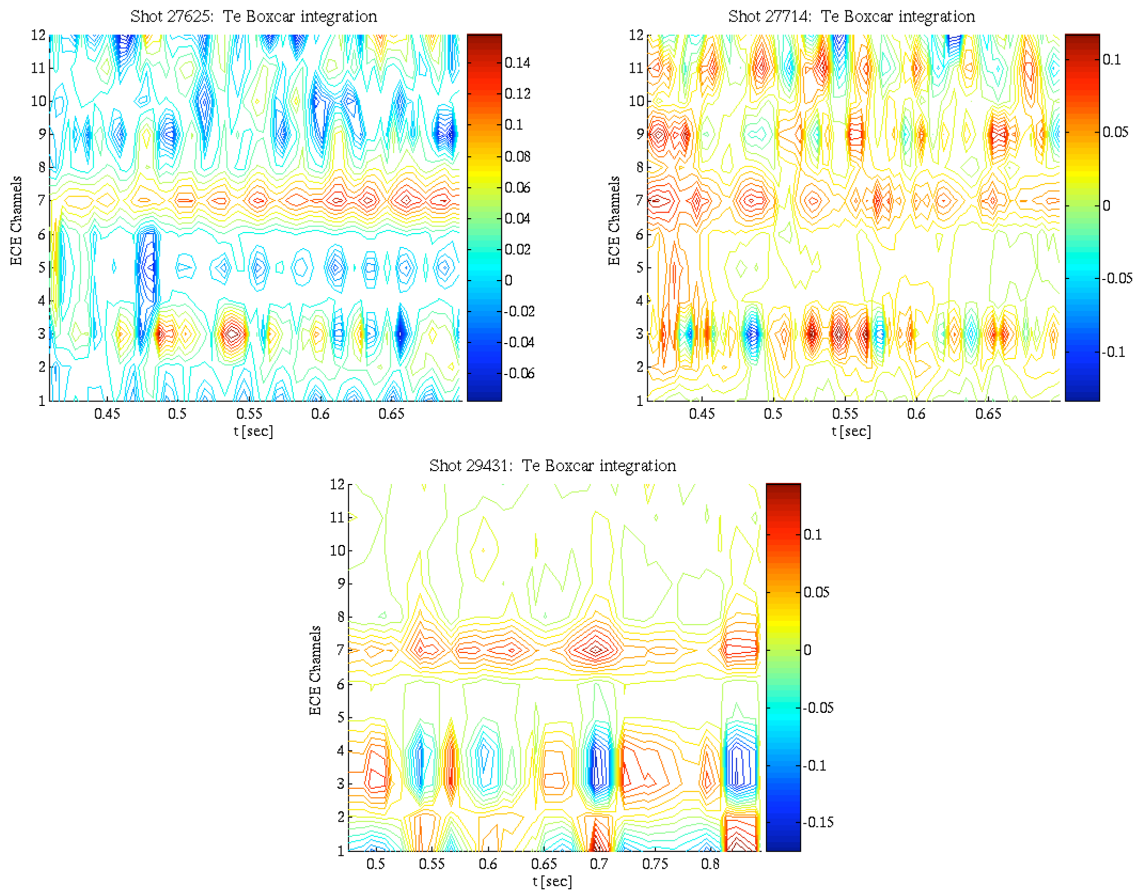

FIG.5. Contour plot of the accumulated increase of electronic temperature for 2-pulses boxcar averaged ECE signals - FTU shots 27625, 27714 and 29431

for each ECE channel, the increased electronic temperature (δT_e) during the gyrotron nth pulse (of time length Δt_p) has been running accumulated for N pulses

$$\sum_{n=1}^{N} \frac{\left[\int_{0}^{\Delta t_p} \delta T_e dt \right]_n}{\Delta t_p}$$

(e.g.: for N=2, at first step pulses one and two were accumulated, at second step pulses two and three and so on) looking then for the maximum positive signal increment. This procedure has the advantage of update the information about the deposition position at every pulse, taking into account also the "history" of the previously detected positions. For a fixed mirror launcher (like FTU one), this may appear as a trivial consideration, but for a movable launcher this is not: the succession of deposition positions reached by the beam during the steering are necessarily sitting on a continuous line because of the finite speed of the mirror motor drive. Therefore, considering the history of the deposition position should speed up the recognition process focusing the search around the previously detected positions. In *FIG.5* are compared the outcome of the described process for the three presented shots and for a number of accumulated pulse N=2. For all three cases is clearly recognizable the channel 7 as the channel where the deposition occurs (red isolines for higher amplitude). It should be noted that shot 29431, while having the same duty cycle and a similar accumulated amplitude of shot 27714, shows a clearer footprint of deposition on channel 7. This could be explained with the consideration that the random pulse sequence scheme, while using a larger bandwidth than a fixed frequency one, has an intrinsic capability of reject noise at fixed frequency like temperature oscillations due to sawteeth. In both cases accumulation of 2 pulses is enough for unambiguous detection of the deposition position. Moreover, the use of only 10% of the available power for the position tracking has the advantage of a reduced perturbation when no power is needed for plasma control, to be "paid" when full power is requested with just 10% of it. Another way the sensitivity can be improved is by using pseudorandom Maximum Length Sequences (MLS) [5], rather than periodic modulation, which have large correlation for zero-lag, and near zero correlation for all the other lags. Further experiments are foreseen looking for minimum power detectable and viable MLS scheme.

4. Conclusions

An automatic system for detection and control of MHD is installed and successfully operating on FTU tokamak. A number of modulation techniques are under test with the goal of selecting the more promising for a ITER-like gyrotron position tracking system.

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