**Experiments on Magneto-hydrodynamics Instabilities with ECH/ECCD in FTU Using a Minimal Real-Time Control System.**


**Introduction**

- Experiments on real-time control of magneto-hydrodynamics (MHD) instabilities using injection of Electron Cyclotron Waves (ECW) (2.8GHz) are being performed in FTU [1] with a control system [2] based only on three real-time key points: an estimator based on a statistical regression [3], a MHD instability marker (SVDH) using a 3D array of pick-up coils [3] and a fast ECH launcher to poorly excite the EC absorption volume with 400kW 13.56GHz resonant radial ECH [3].
- The MHD instability, usually a tearing mode with m = 2 and n = 3, is deliberately induced either by neutron gas injection or by a density ramp hitting the density limit. No diagnostics providing the radial localization of the instabilities have been used.
- The sensitivity of the used MHD marker allows to close the control loop on the X-ray detector on the axis of the actuator's X-ray source.

**SVD-based MHD marker**

- The evolution of MHD is well represented by a SVD-based marker which uses only normalized signals and is sensitive to the phases of the magnetic fluctuations. The energy $H$ represents the average information associated with the singular values $s_j$ [13]

$$ H = \sum_j \frac{s_j}{\sum_{k=1}^{N} s_k} \cdot p_j $$

where the $p_j$ are the normalized squared singular values of the SVD factorization of the matrix of signals $y_j(x)$ sampled at multiple M space positions (being $m$ equal to the number of available coils) and multiple M time instants ($N$ being the number of samples in a given control cycle time, e.g. 140 us for a 2 ms control cycle time steps), such that the energy content of the matrix $y$ equals the one of its singular values $s_j$.

- $H \leq 1$ means perfect phase coherence and separable signals such that $y_j(x) = y(x) \cdot u(t)$, i.e. well developed MHD while $SVDH = 1$ means incipient phases and a lack of a phase-coherent perturbation in the plasma.

**Control of impurity-triggered instabilities**

- Experiments performed at toroidal field of 3.3T and for density up to 0.04$n_{\text{th}}$, using one gyroradius of 0.35 MeV power.
- The onset of neon-induced instabilities strongly depends on the amount of injected gas (Fig. 1). The control system switches on the ECH power when the SVD signal crosses a threshold value (preset to 0.708 in these experiments). The reference of the poloidal steering angle is evaluated in real time from the position of the resonant surface as evaluated in real time in EQUIFAST, but neglecting the beam reflection (Fig. 2).
- When the ECH power is switched on, the instability amplitude shows a marked sensitivity to the relative position of the absorption volume with an increase or decrease of its growth rate as shown in the figure 2 (for 2/1 mode) [10] (Fig. 3).
- The MHD amplitude increases coherently with the current profile shifting by radiation and leads in most cases to the plasma disruption. Electron density profile peaking is also observed hereafter the ECH injection [14,22] (Fig. 4).

**Control of density-driven instabilities**

- Experiments performed at toroidal field of 6.67T and density up to 0.2$n_{\text{th}}$ [19] line averaged.
- The MHD control system has been modified to follow a so-called “search and hold” strategy.
- Only the position of the plasma halo and the reconstruction of the last closed surface are taken from the PPCDC system, without any other information about the position of the magnetic surfaces. The home position of the ECRH beam is outboard with respect to the expected density gradient.
- The detection of the MHD activity and the triggering of the control action is led by the evaluation of SVDH and ECH power. In the experiments with MHD triggering by impurity injection a significant reduction of the MHD amplitude has been obtained up to a maximum reduction of 60% of the MHD amplitude at the control cycle [15] (FIG. 3).
- In the experiments with MHD triggering by neon injection a significant reduction of the MHD amplitude has been obtained up to a maximum reduction of 60% of the MHD amplitude at the control cycle [15] (FIG. 3).
- This minimized set of control tools mimics the situation of a fusion reactor where less diagnostics will be available and with reduced capability [4-7].

**Conclusions**

- Experiments of MHD stabilization are being performed in FTU using a minimized set of control tools. The limits and the potentialities of this approach are being studied in experimental conditions that were intrinsically difficult due to the triggering technique of the MHD.
- In the experiments with MHD triggering by impurity injection a significant reduction of the MHD amplitude has been obtained during the ECH injection phase and the disruption time has been delayed considerably. However, the continued cooling caused from the Nea recycling that originates the instabilities does not allow for the complete suppression at the same time of ECH power used.
- The control algorithm based on the feedback on the time derivative of the MHD amplitude has led to the suppression of the instabilities triggered by the density limit, even if in some cases, after a prolonged heating, the instability starts to increase again.

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**References**

[20] This is probably due to a change in the radial position of the ion source of the mode with respect to the position of the absorption volume of the ECRH.
[21] These experiments also suggest that the combined use of the MHD control system and of the density control system in physics studies close to the density limit requires their further integration in order to avoid conflicting actions of the respective actuators.

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