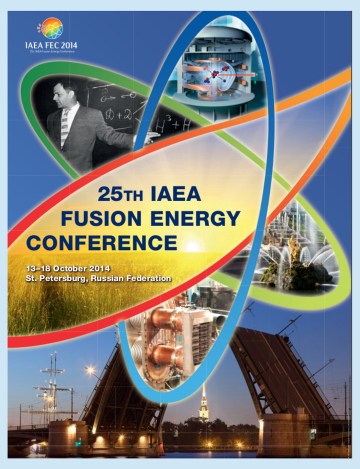
Experiments on Magneto-hydrodynamics Instabilities with ECH/ECCD in FTU Using a Minimal Real-Time Control System.



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Introduction

- Experiments on real time control of magneto-hydrodynamics (MHD) instabilities using injection of Electron Cyclotron Waves (ECW) [2,3] are being performed in FTU [1] with a control system [8,9] based on only three real time key items: an equilibrium estimator based on a statistical regression [10], a MHD instability marker (SVDH) using a 3D array of pick-up coils [11] and a fast ECW launcher able to poloidally steer the EC absorption volume with dp/dt=0.1/30 ms maximum radial speed [9,12]
- The MHD instability, usually a tearing mode with m/n = 2/1 or 3/2, is deliberately induced either by neon 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 solely on the effect of the actuator's action with little elaboration
- The nature of the instability triggering mechanism in these plasma prevents that the stabilization lasts longer than the ECW pulse. However when the ECW power is switched on, the instability amplitude shows a marked sensitivity to the position of the absorption volume with an increase or decrease of its growth rate. Moreover the ECRH injected energy has an impact on the current profile with an extent relevant for the alignment requirements in MHD control even at relatively low power level and high density
- This minimized set of control tools mimics the situation of a fusion reactor where less diagnostics will be available and with reduced capabilitie [4-7].

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 entropy H represents the average information associated with the singular values set [13]

$$H = \frac{-\sum p_k \cdot \log(p_k)}{\log(M)} \qquad (1)$$

where the p_k are the normalized squared singular values of the SVD factorization of the matrix of signals $Y_{ij}=y(x_i,t_j)$ sampled at multiple M space positions (being M equal to the number of available coils) and multiple N time instants (N being the number of samples in a given control cycle time, e.g. N=100 for 1 ms control cycle time steps) such that the energy content of the matrix Y equals the one of the sum of its singular values

$$E = \sum\sum (Y)_{ij}^2 = \sum A_k^2 = M\ ; \qquad p_k = A_k^2/M \qquad 0 \le p_k \le 1 \qquad \sum p_k = 1 \qquad (2)$$

- H→0 means perfect phase coherence and separable signals such that y(x,t)=y(x)u(t), i.e. well developed MHD while SVDH=1 means incoherent phases and so lack of a phase-coherent perturbation in the plasma.
- From the practical point of view, SVDH shows a pronounced knee at the very start of the MHD activity, eases its early detection and makes straightforward the setting of thresholds for triggering and control. In given conditions, the SVD algorithm also can supply the instability mode numbers m/n identification [11]

Control of impurity-triggered instabilities

- Experiments performed at toroidal field of 5.3T and flat-top density of 0.6•10^{20}m^{-3}, using one gyrotron of 0.35 MW power
- The onset of Neon-induced instabilities strongly depends on the amount of injected gas (FIG. 1)
- The control system switches on the ECW power when the SVDH signal crosses below a threshold value (preset to 0.7/0.85 in these experiments). The reference for the poloidal steering angle is evaluated in real time from the position of the resonant m,n surface as evaluated in real time by EQUIFAST, but neglecting the beam refraction (FIG. 2)
- When the ECW 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 [3 16] (FIG. 3)
- The MHD amplitude increases coherently with the current profile shrinking by radiation and leads in most cases to the plasma disruption. Electron density profile peaking is also observed following the Neon injection [14,15] (FIG. 4)

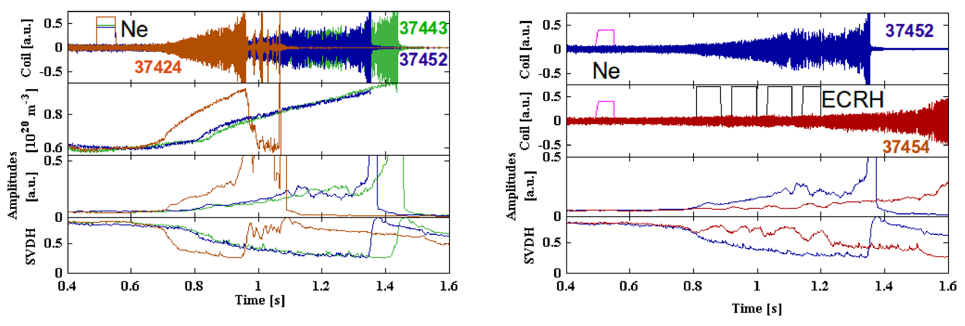

FIG. 1. Left side: time evolution of MHD for different amount of injected Ne (37443, 37452, 37424). From top to bottom: fluctuation amplitude by pick-up coils (a.u.), line averaged density, magnetic perturbation amplitude and SVDH marker; Right side: comparison of two plasma discharges with ECRH (37454, red lines) and without ECRH (37452, blue lines) and same amount of injected neon. The injection time window of Ne is at 0.5 s and lasts 50ms. ECRH is applied in pulses from 0.8s on in 37454 only.

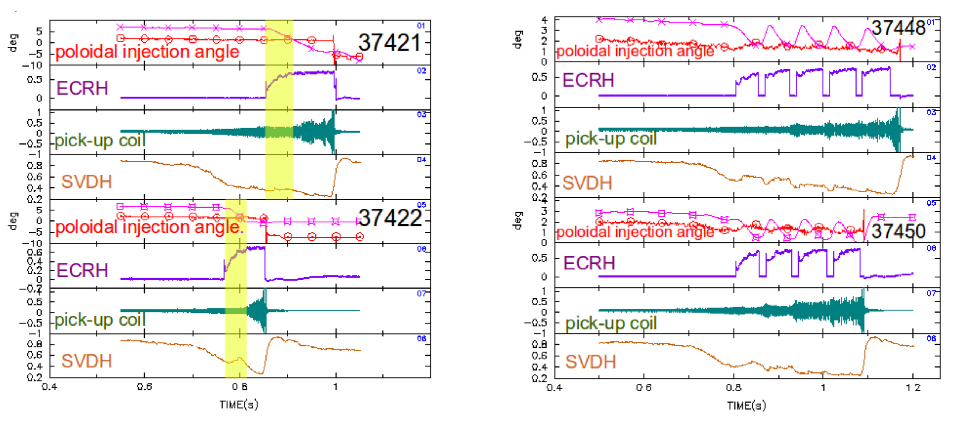

FIG. 2. Left side: time evolution of the MHD behaviour when an ECRH deposition scan is performed across the 2,1 island region for different deposition radii with respect to the resonant surface. From top to bottom for each shot: angles of the poloidal injection of ECRH (0°: horizontal, negative: inboard) and of q=2 reference; ECRH power (in a.u.); pick-up coil signal (a.u.); SVDH marker. Right: time evolution during periodical scans.

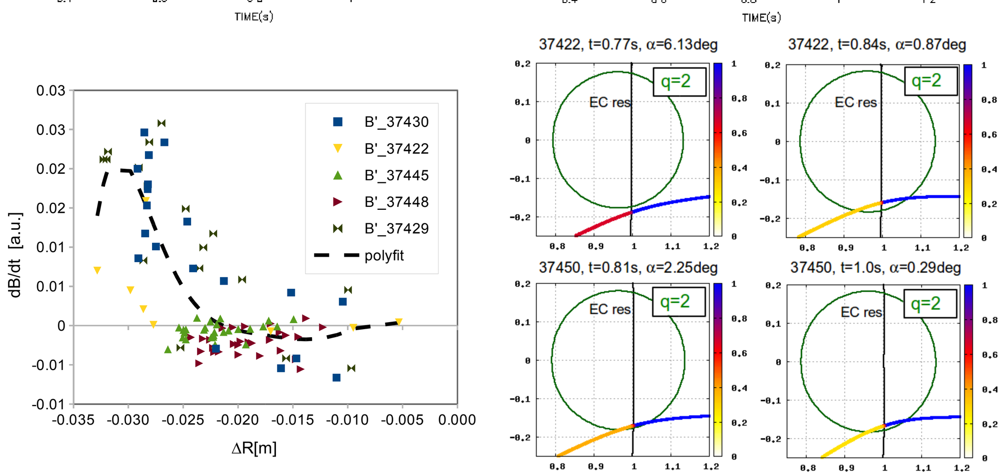

FIG. 3. Left: Effect of the alignment of the beam deposition with respect to the island location. Obtained from the off-line time derivative of the MHD amplitude for several plasma discharges against the ECW deposition radius. Negative values of ΔR for innermost deposition with respect to the unstable surface. The line is a polynomial regression to guide the eye. Right: refraction computation [17] for shots 37422 (top) and 37450 (bottom) at the edges of the angular scan.

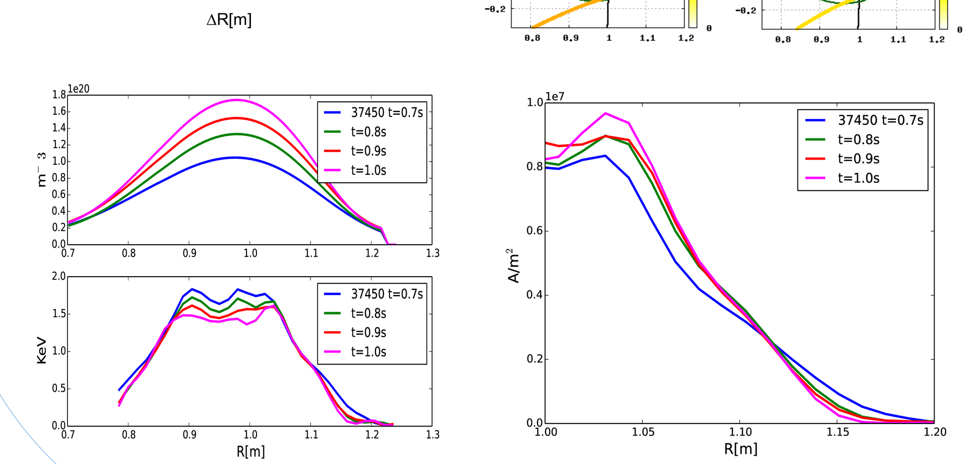

FIG.4 Left side: evolution of the kinetic profiles (top: density from the scanning interferometer; bottom: electron temperature from the Michelson interferometer) Right: evolution of the current profile from JETTO simulation in shot 37450 [18]

Control of density-driven instabilities

- Experiments performed at toroidal field of 5.6T and density up to of 2•10^{20}m^{-3} line averaged.
- The MHD control loop has been modified to follow a so called "search and hold" strategy.
- Only the position of the plasma axis 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 radius of the instability.
- The detection of the MHD activity and the triggering of the control action is led by the evaluation of SVDH (FIG. 5).
- Automatic search of the steering angle producing the fastest instability reduction introduced in the control algorithm, based on the evaluation of the time derivative of the MHD amplitude (FIG. 6)
- Once such angle is reached the reference signal for the launcher controller is updated to hold on the position until the SVDH signal crosses the switching off threshold.
- Effect on the current profile of the amount of energy injected in the island region [19] investigated [FIG. 7]
- The results seem to indicate that the ECRH injected energy even at relatively low power level and high density has an impact on the current profile at an extent relevant for the alignment requirements in MHD control.

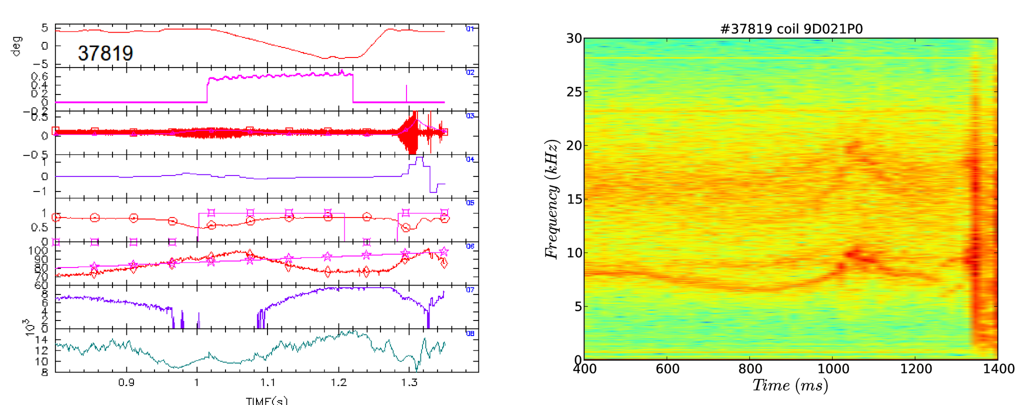

FIG. 5. Left side: time evolution of the MHD behaviour for 37819 From top: poloidal ECRH injection angle, ERCH power (a.u.), pick-up coil and magnetic perturbation amplitude, amplitude time derivative, SVDH marker and boolean trigger, density with its reference (a.u.), gas valve opening, real-time mode frequency from the SVD algorithm. Right: spectrogram of one pick-up coil signal.

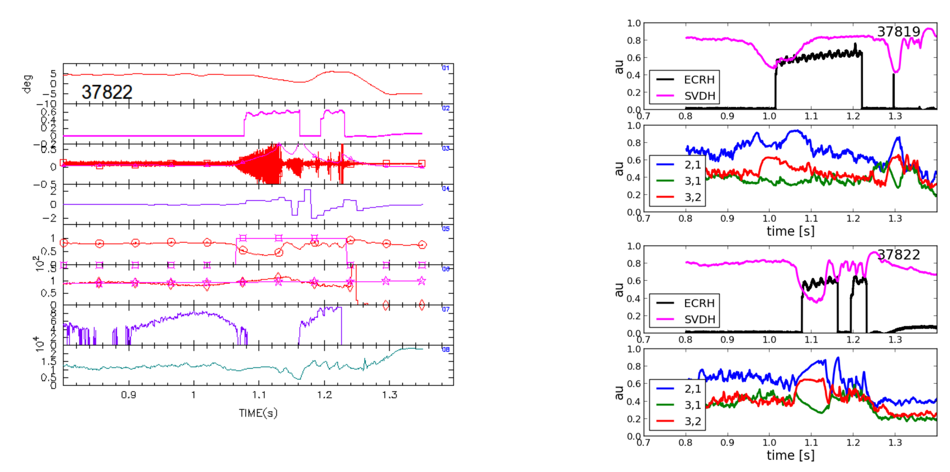

FIG. 6. Left side: time evolution of the MHD behaviour for 37822, same traces as figure 5. Right: mode identification using likelihood markers derived from the SVD algorithm [11]. For each shot, from top: SVDH marker and gyrotron power; likelihood of (2,1 red), (3,1 pink) and (3,2 magenta).

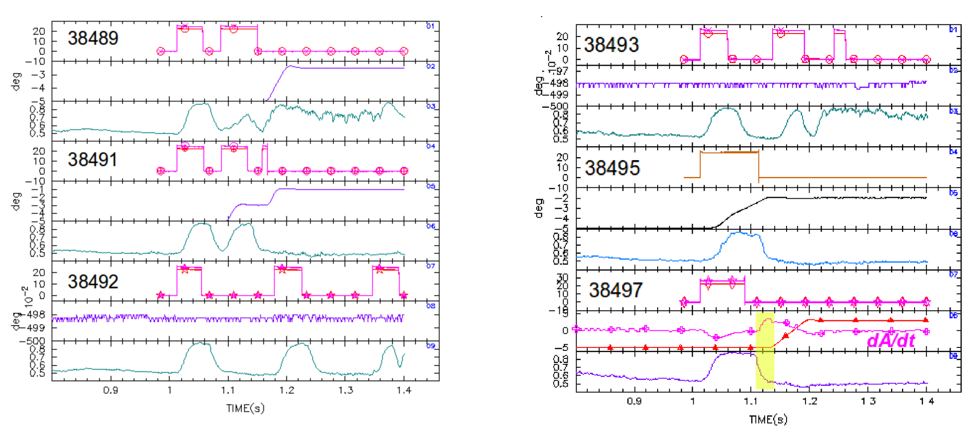

FIG. 7. Left side: shots 38489, 38491 and 38492. For each one, from top: gyrotron(s) power (a.u.), beam injection angle, SVDH marker. Right: the same for shots 38493 and 38495. The MHD amplitude time derivative (dA/dt) is also shown for 38497. The highlighted area indicates the triggering of the beam repositioning. The ECRH power was stopped by the gyrotron protection system for reasons not related to the experiment.

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 transient 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 ECW injection phase and the disruption time has been delayed correspondingly. However, the continued cooling caused from the Neon recycling that originates the instabilities does not allow the complete suppression at least for the amount of ECRH 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.
- This is probably due to a change in the radial position of the rationale surface of the mode with respect to the position of the absorption volume of the ECRH.
- 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.
- This MHD control algorithm has led to the suppression of the instabilities at least for the first control cycle in all its phases including early detection, triggering, search for best alignment, suppression and switching off of the ECW system.

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