Entrainment of MHD modes in ASDEX Upgrade using rotating non-axisymmetric perturbation fields

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In recent ASDEX Upgrade experiments the entrainment of a fast rotating (around 2-5 kHz) m=2, n=1 tearing mode to a slowly rotating perturbation field (5-10Hz range) applied by in-vessel coils have been investigated. The ultimate goal of these experiments is active disruption avoidance by externally applied magnetic perturbations. In this work we start investigating the physics basis of this approach and our initial results can be considered encouraging.
This experiment used a set of 16 active perturbation coils, called B-coils, distributed along the toroidal angle on the low field side in an upper and a lower row of 8 coils, almost symmetric with respect to the midplane [1]. In 2015 new AC power supplies became available with 4 individual controllers, which made these experiments possible.
An improved H-mode plasma at moderate elongation with β_N between 2 and 3 was selected as the target configuration. The plasma current was 0.8 MA, the toroidal magnetic field 2.5 T. The input NBI power was in the interval $5 < P_{NBI} < 13$ MW , while the ECRH power in the range $1.5 < P_{ECRH} < 3$ MW. The ECRH deposition was such that the plasma rotation in the core was reduced in order to have relatively slowly rotating tearing modes. An example is shown in Fig.1, where it can be seen that the 2/1 tearing activity is mostly in the range 5-10 KHz. From the figure it is also clear that the mode is

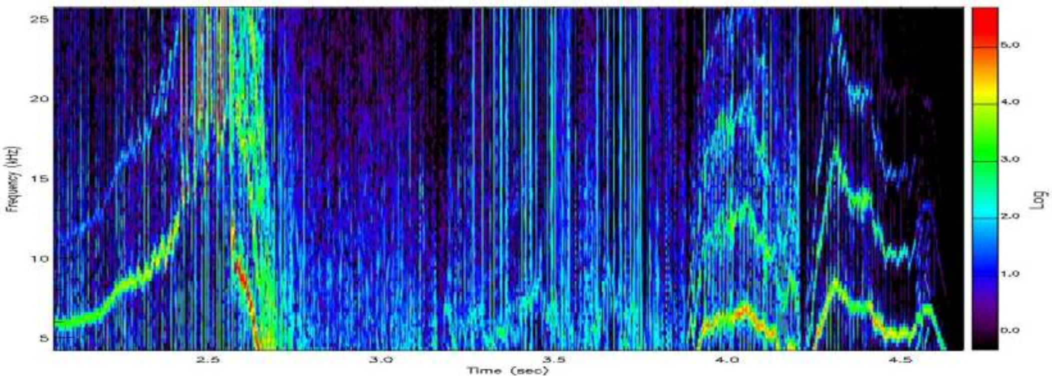

Fig.1 *Spectrogram from a Mirnov coil for a reference shot (#33208) with no external field.*

present from the very beginning and in some time intervals the mode is locked since the Mirnov coil signal vanishes. The shot in Fig.1 was not disrupting even if no external magnetic field was applied. It should be mentioned that within the 16 shots dedicated to these experiments, there have been cases of disruptions both when the B-coils were off or on. Typically in the latter case the disruption happened for $P_{NBI} \geq 10$ MW. No disruptions have been observed with the B coils at $P_{NBI} < 10$ MW. For some of the shots the B coil intervention was pre-programmed to occur at a given time, while in other cases it was triggered by a threshold on the amplitude of the n=1 filtered Mirnov coils signals.
An external n=1 perturbation has been applied by means of the B-coils with a relative phase between the upper and lower rows that maximizes the plasma response (according to what was observed in previous experiments [2]) (see Fig.2).

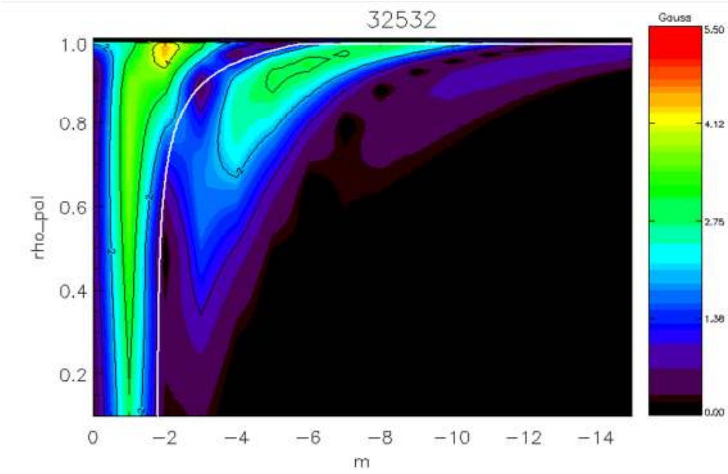

Fig.2 *Vacuum B coil produced n=1 normal field mapped over the flux coordinate and the poloidal mode number (contour labels in Gauss #32532). The white line corresponds to the resonant modes.*

From Fig.2 it is clear that such perturbation is not resonant (white line), therefore it can be concluded that the maximum plasma response corresponds to a kink aligned (non resonant) applied magnetic field. Obviously in the presence of the plasma there is also a plasma response contribution not accounted for in Fig.2.

An interesting observation resulting from these experiments is that the application of the external kink aligned perturbation is able to produce, as already observed [3], a global rotation braking (see Fig.3).

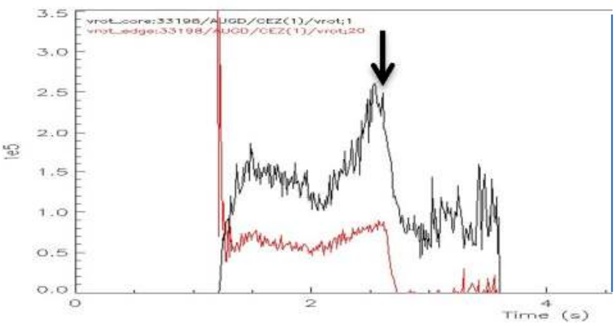

Fig.3 *Core (black line) and edge (red line) plasma toroidal rotation vs. time. The arrow indicates the instant when the B coils are turned on.*

As the plasma rotation is reduced below approximately half of its initial value, non indicating a direct causality, a fast rotating m=2, n=1 tearing mode is triggered, which slows down and locks to the externally applied slowly rotating field, i.e. the mode can be entrained. Later, with reduced amplitude, the mode unlocks from the perturbation field and accelerates again to its natural frequency. In the presence of the locked mode a strong decrease of β_N was observed, which recovers as soon as the mode starts rotating again. A cylindrical model that can give some clue on the physical mechanisms of mode acceleration and deceleration is presented below.

Analysis of the ECE signals confirms that the slowly rotating, entrained mode maintains its tearing nature, since an island structure with amplitude oscillating in phase with the applied perturbation was detected. This can be seen in Fig.4, where the island reconstruction from

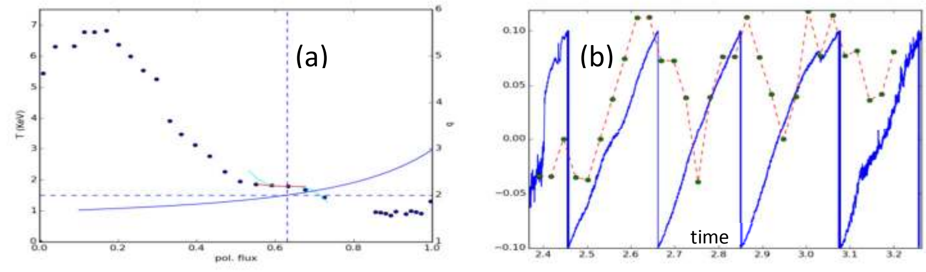

Fig.4 *(a) Island reconstruction from ECE signal and q profile(dashed lines are showing the q=2 position) at t= 2.85 for #32532 ; (b) SAT n=1 signal (blue) compared with the island reconstruction from ECE (dashed line)vs time.*

ECE signal (Fig.4a) is compared in time with the n=1 locked mode saddle coil signal (Fig.4b). The mode entrainment is also evident from the ECE radial signal versus time (Fig.5).

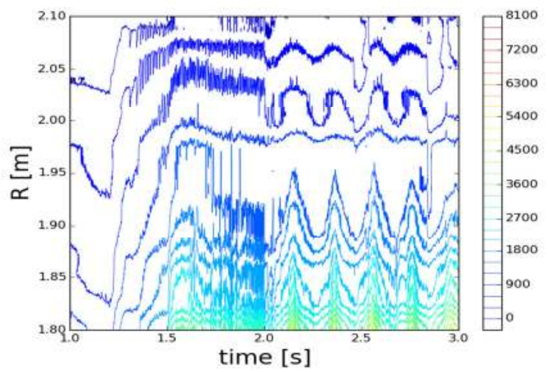

Fig.5 *ECE (filtered at 1 KHz) radial contours vs. time for #33193. B-coils are turned on (5 Hz applied field rotation) at t=2 s.*

With the purpose of simulating the locking (at high β_N) of the m=2, n=1 tearing mode to the RMP and the unlocking observed at the β_N crashes, the tokamak version of the cylindrical code RFXlocking [4] has been enriched with additional physics related to pressure and neo-classical effects. First, Newcomb's equation, providing the mode linear eigenfunction neglecting inertia and the classical Δ' computed at the inner and outer radial boundaries of the island, is solved in the presence of finite pressure [5]. Nevertheless, the pressure plateau in correspondence of the island is modeled. According to a standard expansion technique [10] the eigenfunction, and consequently Δ', sums up the different contributions related to the plasma Δ'_p, the resistive wall(s) Δ'_w and the coils Δ'_C. Moreover, the bootstrap current Δ'_{BS} term has been included. The final modified Rutherford equation for the island width W evolution [7, 8, 9], is schematically written, apart a global constant, as $dW/dt \approx \Delta'_p+\Delta'_w+\Delta'_C+\Delta'_{BS}$. Second, in addition to the electromagnetic torque and the torque produced by the perpendicular viscosity, neoclassical toroidal viscosity (NTV) produced by the magnetic field axisymmetry breaking is included in the motion equation. This effect is modeled using the 1/ν regime formulas derived in [6] and applied to the m=2, n=1 harmonic. NTV is computed only with the plasma component of the mode eigenfunction, since this should correspond to the dominant term. Active coils are placed between two uniform shells of 50ms time constant each, modelling the PSL and vacuum vessel respectively. The coils are represented by a spatial uniform grid: this simplification does not matter since only the 2, 1 harmonic, both for the mode and the RMP, is considered in the simulation. Due to the layout and geometry approximations the simulations cannot be taken as a faithful description of the experiment, rather as a useful interpretative tool. Density is fixed (constant radial profile with n/n_G=0.35), so β_N changes according to the temperature profile (electron temperature is assumed equal to ion temperature).

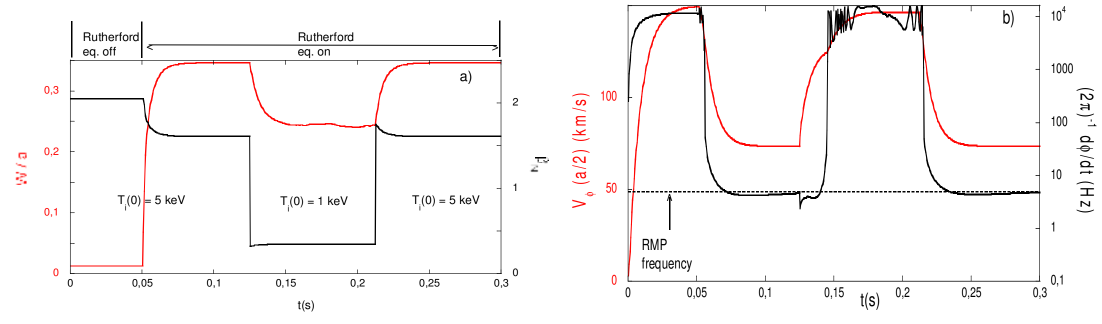

***Fig.6** a): normalized island width (red) and β_N (black). b): toroidal flow velocity at r=a/2 (red) and mode phase velocity in logarithmic scale (black).*

Figure 6 displays a simulation with the application, from t=0, of a m=2, n=1 coils' current harmonic of 500kA, rotating at 5Hz. In the first interval $0<t<\tau_V=0.05$, being τ_V the viscous time, Rutherford equation is not evolved, the island width (W) is kept to a small value (a) and both flow and mode phase velocity settle to their unperturbed values. Afterwards, Rutherford equation is switched on. In the second interval 0.05<t<0.125 W grows and saturates causing a drop of β_N from about 2 to about 1.5 (a); the mode locks to the RMP and the NTV action strongly modifies the V_ϕ profile (b). In the third interval 0.125<t<0.21 a strong β_N crash (a) is induced by dropping the on-axis temperature (from 5keV to 1keV). The NTV decrease due to mode amplitude and temperature reduction (a) allows the flow to recover the unperturbed velocity and the mode to unlock (b). If NTV were kept fixed, the mode would not spin-up in spite of electromagnetic torque reduction with the mode amplitude. In the final interval 0.21<t<0.3, the on-axis temperature is restored to the initial value (5keV) and all the quantities recover the values attained at the end of the second interval. The simulation indicates the crucial role of the NTV, produced by the tearing mode harmonic, in determining the locking/unlocking dynamics.

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