Modulated ECCD experiments on TCV

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Abstract Experiments were previously performed on TCV using Switched Electron Cyclotron Current Drive (SECCD) in which the total heating power and plasma current were kept nearly constant in time while the current density profile was modulated. It was observed that SECCD leads to relative electron diffusivity modulation amplitude of ±65%. A direct measurement of the current density profile is not available on TCV; however, electrodynamics calculations show that ±55% shear modulation (from s = 0.20 to 0.70) is achieved during SECCD experiments, and that the shear modulation is localized at the CD layer position. These results provide strong experimental evidence that electron heat transport is shearing dependent: heat transport is reduced when shear is low, confirming a general observation. New experiments have been performed to address some open issues raised after the previous campaign. The work is also aimed at confirmation of the electrodynamics model of the SECCD technique. To these ends, the experiments have been performed at different deposition radii, different SECCD amplitudes and different toroidal injection angles. It turned out that in most discharges an MHD activity develops, differentiated in the co and counter injection phases, which prevents an unambiguous conclusion in terms of heat or particle transport. It is shown that the MHD modes are affected by ECCD on the resonant magnetic surfaces, possibly according to the same physics underlying TM and NTM stabilization process. Data analysis from this point of view is in progress.

1. Introduction

The main goal of Switched ECCD experiments on TCV tokamak [1] is the modulation of the magnetic shear and the study of the relevant effects on heat and particle transport. The essential feature of these experiments is that, in principle, the instantaneous EC heating power is constant, but is ECCD switched from co to counter injection at a frequency such that a local modulation of the current density profile is possible. Providing that SECCD is not affecting plasma stability, any detectable $\tilde{T}_e$ synchronous fluctuation can be ascribed therefore to a modulation of heat confinement, possibly induced by SECCD.
Because of the transient nature of SECCD, localized in a narrow layer inside a conductive medium, the electrodynamics plasma response must be taken into account in the estimate of the actual distribution of the driven current. This has been done using a simplified procedure for calculating the periodical amplitude current distribution using a lumped circuit modelling, and by applying in a few reference cases ASTRA code [2] for comparison and validation. Main thing to be noted is that electrodynamic reaction to ECCD is strong, but a large fraction of localized current drive still persists, with a significant modulation of the current density profile.

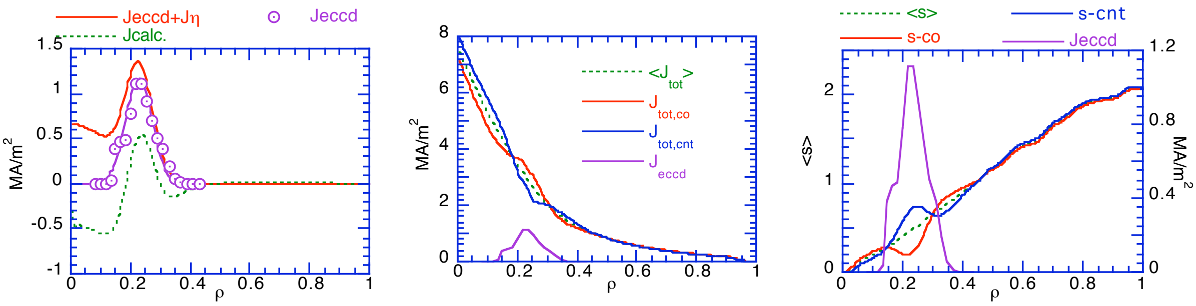

Fig.1 –Left: Total driving term, ECCD (dots) and resistive (solid line), is shown with the oscillating current amplitude (dashed), determined by electrodynamic reaction. Centre: total current density, average (dashed), during co (red) and counter (blue) injection period. Right: magnetic shear profile.

Electrodynamic calculations show (Fig.1) that ±40% (from 0.2 to 0.7) shear modulation can be achieved at r_{dep} in Switching ECCD experiments on TCV. Shear modulation is localized at the CD layer.
The change in shear calculated by ASTRA [3] code for transport analysis is Δs≈0.4 [2], using an ECCD profile obtained by solving the Fokker-Planck equation including particle diffusion, is very similar to the results from the coupled-circuit model.
Experimental evidences like internal inductance measurements and saw teeth activity evolution support the calculations.

The experiment shows that T_e strongly oscillates (more than 30% peak-to-peak at centre) in spite of constant input power. The whole T_e profile oscillates internal to the EC wave absorption radius r_{dep} (Fig.2). A thermal barrier (or a step-up in thermal diffusivity) is alternated at r_{dep} to a thermal bridge (or a step-down in diffusivity), in synchronism with ECCD. Modulation is generated in the plasma core, internal to r_{dep}, and propagates outwards.

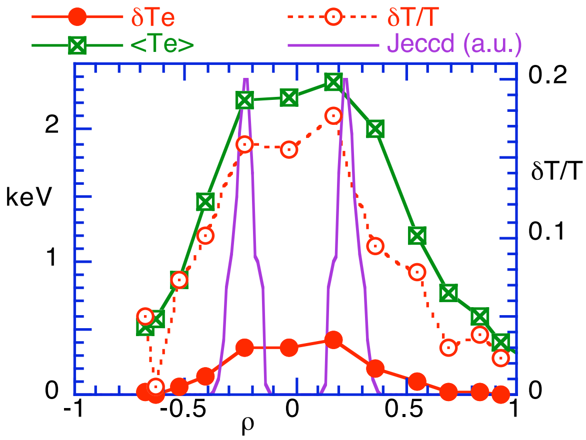

Fig.2 – Red full dots: amplitude of T_e oscillations synchronous to swinging. Green crossed squares: averaged T_e profile. Open red dots: relative change.

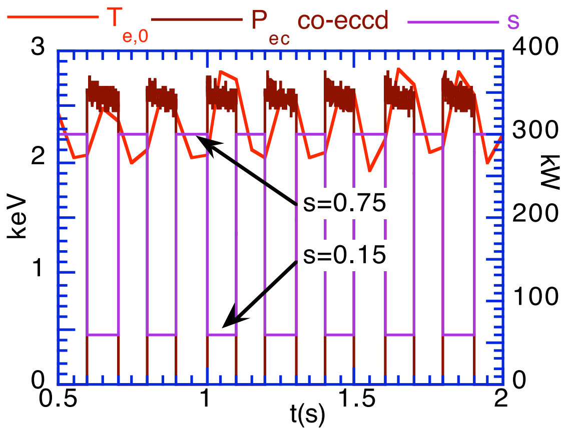

Fig.3 – $T_{e,0}$ (red) and confinement increase during the co-injection phase (P_{ec}), when shear s is the lowest.

This implies that $\tilde{\chi}_e/\chi_{e,0}$=0.5 at r_{dep}, and transport drops, during the co-injection phase, when shear is also low (Fig.3, shot #24867). Consistent with χ_e modulation, a modulation of the global energy content W_e is also observed. The observed relative change $\tilde{W}_e/\langle W_e\rangle$=0.04, confirmed by 4% oscillation amplitude measured in the diamagnetic signal, is compatible with a 40% change in electron diffusivity over a volume smaller than 25% of the total one, considering also that in the meantime in the same volume there is a loss of 40% in ohmic heating (modulated T_e). Global energy confinement behaviour is therefore consistent with the observed modulation of local thermal diffusivity.

The main result of these experiments is that a local decrease (≈40%) in the magnetic shear is associated to a decrease of the same amount (≈40%) in the electron thermal diffusivity at r_{dep}.

Two main questions arise from this first experimental result. The first is related to what is the scaling of the electron thermal diffusivity with magnetic shear. Although the shear periodically changes in the experiments, and the diffusivity as well, the analysis is performed on the amplitude of the shear modulation, and not on its instantaneous value. A scan of the modulation amplitude is therefore necessary for an experimental description of the dependence of transport with magnetic shear.
A second important question is related to the actual spatial location of the effect on transport: is transport modulated in a limited region around the ECCD layer, or is it modified in the whole volume inside r_{dep} (i.e., a wall or a step in transport is formed with shear increase?). Since the SECCD layer is close to the axis (normalized deposition radius ρ_{dep}=0.22), the resolution of Thomson scattering diagnostic providing the electron temperature is too low to resolve the core region enough to settle thi second question.

A new series of SECCD experiments has been performed in order to address these issues. The driven current has been increased by a factor 3 (up to three gyrotrons in each cluster), and the toroidal injection angle has been changed in order to vary the width of the driven current channel at fixed deposition radius. In both cases the effect is a scan in the shear amplitude modulation. The deposition radius has been set at ρ_{dep}=0.22 and ρ_{dep}=0.45.

2. Experimental set up, practices and diagnostics

SECCD experiments have been performed on TCV by using the ECRH-ECCD system, which has recently been completed. It is composed by 9 gyrotrons divided in three clusters. Each cluster is connected to a single high voltage power supply. Two of the clusters each have 3 gyrotrons (82.7GHz, 0.5MW, 2s) used for heating (ECH) and/or current-drive generation (ECCD) in 2nd harmonic X-mode (X2)[12] while the third cluster has 3 gyrotrons (118GHz, 0.5MW, 2s) for top-launch third harmonic X-mode (X3) heating [3]. Up to six gyrotrons at 82.7 GHz have been used for SECCD experiments.
The essential aspects of the experimental procedure are as follows: a pair of beam clusters is oriented toroidally for driving ECCD in opposite directions, and poloidally for having the identical deposition radius r_{dep}. The power is switched on alternatively in the beam clusters by square-wave modulation of the pertaining power supplies at the identical frequency, but exactly out of phase. The power in the two beam clusters is such that the absorbed fraction is identical, so that the instantaneous EC heating is constant and equal to its average value.
Co and counter deposition layers can be finely overlapped by observing the heat wave excited by each one of the two clusters, the other one being kept CW at half power in order to have the same average absorbed power, and the same average T_e, in all conditions.
As an improvement to former experimens, plasma shape (elongation) is feedback controlled, otherwise the equilibrium configuration is strongly modified in synchronism with SECCD. This effect was clearly observed in then experiments mentioned in the introduction making data analysis more difficult [1].
The plasma target is given by a discharge at I_p=150 kA, P_{oh}=100 kW, central line density n_e=7 10^{18} m^{-3}. Total ECH average absorbed power is in the order of 1 MW (three gyrotrons), and the EC driven current is 12 kA/gyrotron (at ρ_{dep}=0.22). The energetic of the target plasma is

therefore dominated by ECH, while ECCD is expected to significantly affect the current density profile.

3. Destabilization of MHD activity

In former SECCD experiment the discharge was characterized by low-amplitude sawteeth, with an inversion radius $\rho_{inv}\approx0.03$. Contrary to the old experiments, for the new shots the q=1 surface (given by the equilibrium code LIUQE) is located almost exactly on the deposition radius $\rho_{dep}\approx0.22$, therefore it is very difficult to draw direct conclusions since one has also to take into account all the MHD physics associated with saw teeth.

Most of the new discharges at $\rho_{dep}=0.45$ show an intermittent MHD activity, synchronous with SECCD. Fig.4 shows spectrograms from MHD probes, and the appearance of an oscillation (5÷10 kHz) during the co-injection period of SECCD with 2 gyrotrons in each cluster (shot #30675).

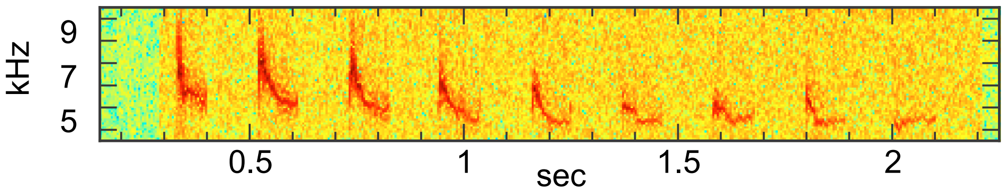

Fig.4 –Frequency spectrum evolution in time of a MHD signal (Mirnov coils combination) for shot #30675. A mode is detected (frequency 5-10 kHz) during the co-injection period of SECCD.

By looking in more detail to the frequency spectra taken before SECDD, during co-injection and during the cnt-injection period (Fig.5), one can see that a clear TM mode is excited at a frequency changing: a) fromshot to shot, b) in different co-periods in the same shot, and c) during a single co-period in a SECCD co-cnt sequence. The exact m,n ordering is being assessed. While the fast frequency evolution (c) is likely related to the TM itself and the interaction with the environment (size of the island, viscous forces, wall interaction), the slow variation from a co-injection period to the other (b) and from shot to shot (a) follows the evolution of the current density profile caused by the ECH power continuously applied during SECCD.

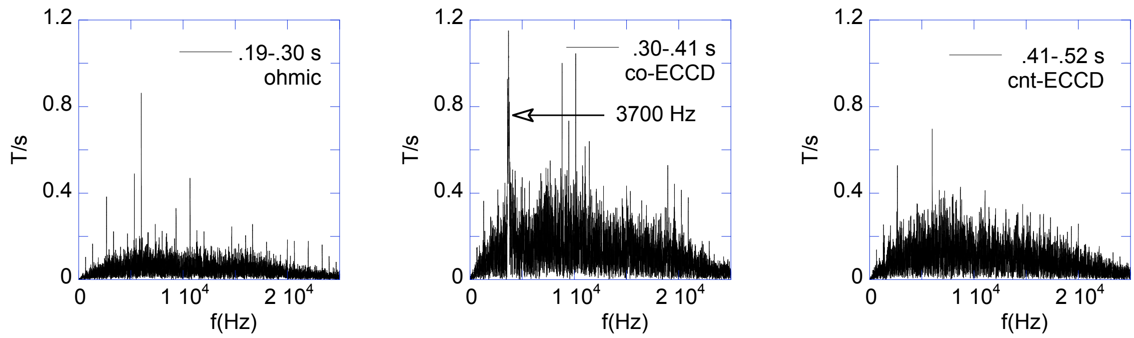

Fig.5 – Left: Frequency spectrum of the signal from Mirnov coils (fluctuating poloidal magneti field, external to the plasma edge), as provided by FFT in a time window preceding ECH/SECCD. Center: same spectrum, but obtained during co-injection. Right: frequency spectrum during a cnt-injection period. Data from shot #30632.

The TM observed by MHD probes, and destabilized during the co-injection period of a SECCD experiment, determines oscillations of the electron temperature profile because of the effect on transport (heat and particle) in proximity of the resonant magnetic surface where the mode develops. The topology of the reconnected magnetic surfaces at the resonant radius (where q=m/n), bridges heat flow across the island size, causing a local flattening of the temperature profile at the O-point of the island. Since the island rotates toroidally with an angular drift velocity ω_D, the local temperature measured by soft-X ray emission, or Electron Cyclotron Emission, will appear to oscillate at a frequency $\omega=n\omega_D/m$.

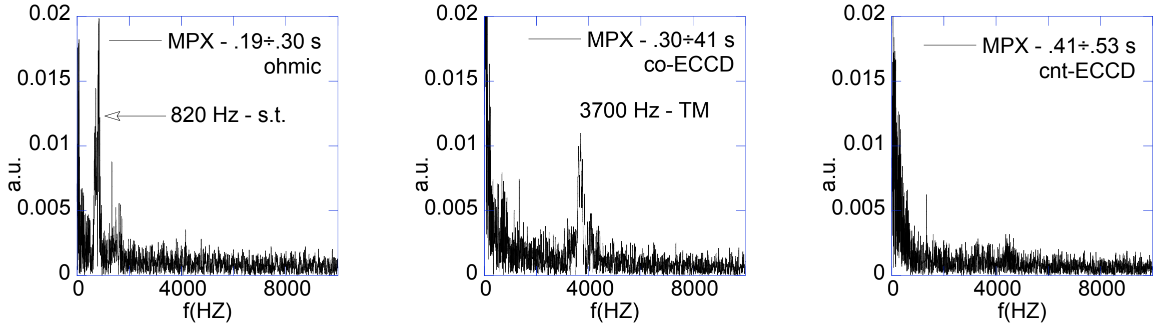

Fig.6 — Left: Frequency spectrum of the signal from MPX detector (soft-X ray emission along a chord of an array), as provided by FFT in a time window preceding ECH/SECCD. Center: same spectrum, but obtained during co-injection. Right: frequency spectrum during a cnt-injection period. Data from shot #30632.

Fig.6 shows in fact the frequency spectrum of a signal from the MPX diagnostic, which measures the soft-X ray emission along different chords. Although the signal is integrated along the chord, with enhanced sensitivity to the emission from the hottest point on the chord itself, the measure confirms the information from MHD sensors. Before SECCD (Fig.6, left) the spectrum reveals only saw teeth (not visible on the MHD detector because poloidally symmetric) (shot #30632). During co-injected SECCD (Fig.6, centre), saw-teeth are suppressed and the TM is observed (at the same frequency found in MHD detectors, 3.7 kHz in this case). During counter-injection (Fig.6, right) sawteeth remain suppressed (although in some shots they will appear again at the end of the SECCD pulse), but also the Tearing Mode disappears.

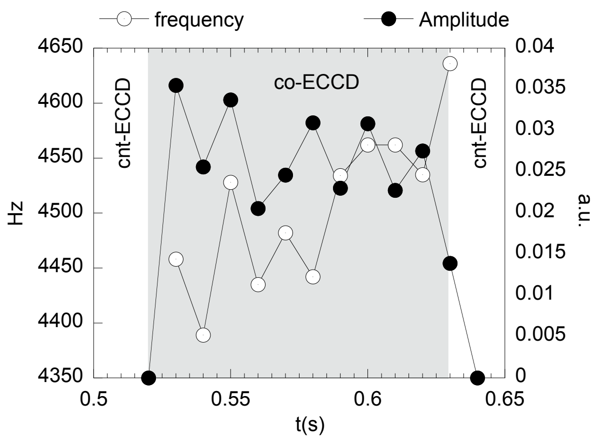

Fig.7 — Frequency and amplitude of soft-X emission oscillations. The frequency corresponds to the peak in the frequency spectrum (see Fig.6). The amplitude is the height of the same peak. Each data point corresponds to FFT spectra taken on a time window of 13 ms (to get 2^n samples). Each dot marks the beginning of the time window for Fourier analysis. Data from shot #30632.

The small persistence of the mode during cnt-injection (Fig.6, right) is the result of the dynamics of the mode during Switching ECCD, better detailed in Fig.7. Here, the Fourier analysis is performed in sub intervals, in order to reveal with a shorter time resolution the evolution of the mode with switching. Each co and counter injection lasts for 110 ms, and it is divided in ten sub-intervals, ≈13 ms long in order to take at least 256 samples for FFT. The sub intervals therefore overlap by ≈ 2 ms. Each dot in the figure corresponds to the starting time of the FFT window, i.e. the first point on the left in the figure is the result of the Fourier transform of samples taken *during co*-ECCD. Similarly, the second last point on the right (and obviously the last one) are the result of samples taken *after* co-ECCD, or *during counter*-ECCD.

This observation demonstrates that the TM development has its own dynamics: it takes about 13 ms to reach saturation, and 13 ms to be fully suppressed. This quantitative information could be useful in the validation, or denial, of theoretical modelling of MHD instabilities.

Indeed, the stimulation of an MHD activity synchronous to SECCD prevents the use of the experimental results in interpreting transport, and in particular interpreting the scaling of transport with shear, which was the original goal of these experiments. The effect on transport of an MHD island overlaps the effect of shear, and no unambiguous conclusion can be given.

However, the details of destabilization/stabilization could be very useful in understanding/confirming the physics of TM (and Neoclassical TM) stabilization by ECH/ECCD, which is of great importance for ITER applications.

Let us consider the very short time taken by the island to fully develop. This rise time (12 ms) is much shorter than any current diffusion time, responsible for the slow variation (1000 ms) of the mode features (frequency, saturation amplitude). This means that the destabilization/stabilization process is not driven by the instability factor Δ', but by a direct pumping of magnetic energy into the helicoidal mode, which has a much lower inductance than the axisymmetric current channel.

This physical process is identical to the one used for NTM stabilization by localized ECH/ECCD. In that application, the loss of local bootstrap current caused by the flattening of the pressure profile determined by the island itself, is compensated by a direct injection of non-inductively driven ECCD. In this case of TCV, there is no lack of current and the mode is stable (Δ'<0). Instead the ECCD destabilizes the mode.

A very effective tool used to describe this process is the Rutherford equation, linking the rate of change of island to the balance between stabilizing and destabiliziong forces. When neoclassical effects are negligible the equation can be written in the form [4]:

$$\frac{\tau_R}{r_s^2}\frac{\partial W}{\partial t} = \Delta'_0 + \Delta'_{EC}(W,\delta\phi)$$

where the r.h.s presents a superposition of nonlinear physical effects that determine growth or decay of the island. The last term

$$\Delta'_{EC} \equiv \frac{8q\delta_{EC}}{\pi W^2}\eta\left(\tfrac{W}{\delta_{EC}}\right)\left(\frac{J_{EC}}{J_{OH}}\right)\cos\delta\phi(t)$$

describes the contribution of externally rf driven currents densities J_{EC}, which might overcome the stabilization factor depending on their direction with respect to the ohmic contribution (cosδϕ) and, of course, the relative amplitudes between the two. Of course, in order to allow the process to develop, ECCD *must* be driven exactly on the resonant magnetic surface (i.e. where q=m/n), the only position where the topology of a TM can develop.

The demonstration that in these SECCD experiments the EC current is driven exactly on a resonant surface is therefore of paramount importance to support this interpretation of the experimental evidence. In order to be robust in the conclusion, we use the same data set to show the coincidence between r_{island} and r_{dep}, in order to avoid using a questionable equilibrium reconstruction. Soft-X ray emission detection is line integrated, so that a spatial mixing complicates data interpretation and appropriate tomography has to be performed. We use instead ECE emission, though we still face two main problems of r_{dep} recognition in this case. First, suprathermal emission might affect channel calibration. Therefore the usual approach of looking for the largest T_e transition with changes of the EC power is unreliable for determining r_{dep}. The second difficulty of recognizing r_{dep} using ECE data in a single SECCD shot is that the EC power is not modulated (this is the intrinsic feature of SECCD), except at the switching ON of the first pulse and OFF of the last one.

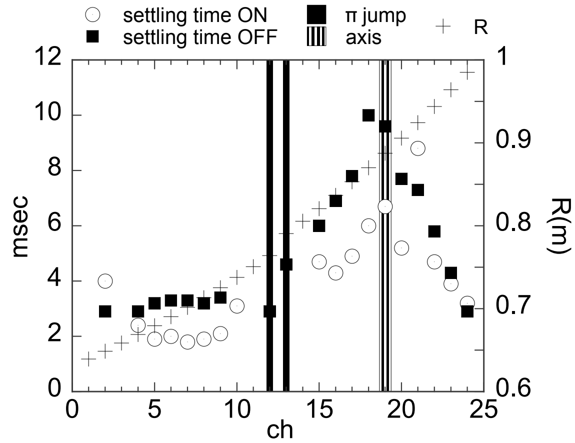

Fig.8 –Open circles: 10-90% settling time of $T_{e,ECE}$ in the different ECE channels at switching ON of the EC power. Closed squares, settling time at switching OFF. In both case, the shortest the settling time, the nearest to EC absorption. Data are missing where suprathermal emission is dominant. In addition, the vertical full bars show the ECE channels across which the oscillating temperature switches phase (i.e. where the island is located). Plus markers show radial position (major daius) of the ECE channels (abscissa). The plasma axis is marked by the vertical hatched bar.

If the ECH power were modulated, the phase shift of $T_{e,ECE}$ modulation would provide the information about the deposition position (in the ECE channel frame) regardless of channel calibration: the lower the phase shift, the nearer the deposition. Having a single transition (ON or OFF), the counterpart in the time domain to the phase shift in the frequency domain is the settling time of the perturbed temperature: the shorter the settling time, the nearer the deposition layer.

The island position can be determined in the usual way [5], by looking at the position in the ECE channel frame where Te oscillations due to mode rotation are opposite in phase.

Fig.8 summarizes the results of the data analysis performed as previously described. The spatial reference frame is the ECE channel ordering, reported in the abscissa. The distribution of the settling times (at the ON and OFF of the SECCD pulse) shows a minimum at ch.12, and very likely on ch.25 lying on the same magnetic surface but on the low field side. Unfortunately no more channels are available at even larger major radii, able to further confirm the local minimum in the settling time. The axis position is shown for comparison. Although the mapping of the ECE channel position on the major radius frame needs equilibrium reconstruction, the agreement with the position of a local maximum in settling time is very satisfactory. The axis from equilibrium is there where expected by settling time considerations.

Fig.8 shows also the position where the phase of T_e oscillations has a π jump. The Fourier analysis of each ECE signal gives the frequency (at the peak in the Fourier spectrum) of the mode, and the phase at that frequency. The phase jumps (as can be seen also in the raw time traces) between ch.12 and 13. Since the phase of the MHD driven T_e oscillations jumps where (in the ECE frame of reference) the settling time of T_e at switching ON and OFF of the ECH power is minimum, we can robustly conclude that EC current is driven very close to the resonant magnetic surface where q is rational. These shots can therefore be used for quantitative analysis of MHD modelling and physics.

4. SECCD shots without MHD

Although all SECCD shots with 2+2 gyrotrons absorbed at r_{dep}=0.45 are affected by MHD synchronous activity, a few with lower or higher power do not show this behaviour, likely because the Shafranov shift is such to miss the coincidence between r_{dep} and r_{island}, or simply because the current driven is too low to destabilize TMs. Fig.9 shows the frequency spectra of poloidal field fluctuations in different periods of a SECCD shot with 3+3 gyrotrons. Apart from the enhancement of the turbulence amplitude, which is expected, no coherent MHD activity is revealed. Although the discharge disrupted before the end of the SECCD pulse, this shot is available for the evaluation in terms of shear/confinement relationship, to be performed.

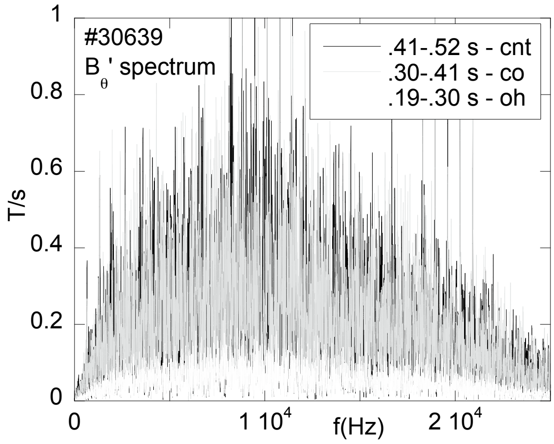

Fig.9 –Superimposed frequency spectra of the signal from Mirnov coils in a time window preceding ECH/SECCD, during co-injection and during a cnt-injection period. Data from shot #30639.

5. Conclusions

SECCD experiments on TCV at ρ_{dep}=0.22 and ρ_{dep}=0.45, 1 MW, performed in continuation to former experiments on the same tokamak, show an MHD activity that prevent an interpretation in terms of shear/transport relationship, but allow a detailed analysis in terms of MHD behaviour and TM control by ECCD, to be fully exploited.
In addition, in some cases MHD is not destabilized, allowing transport analysis to be performed accordingly to the original goal.

Acknowledgements: The authors acknowledge the excellent work of Dr. V.Udintsev on ECE data. This work was partially supported by the Swiss National Science Foundation

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