Effect of the EC torque on slow plasma rotation under central ECH/ECCD for NTM onset

S. Nowak[1], E. Lazzaro[1], O. Sauter[2], S. Fietz[3], A.N. Karpushov[2], M. Maraschek[3], M. Preynas[2], M. Reich[3], D. Brunetti[1], P. Buratti[4], M. Cavedon[3], B. Duval[2], E. Fable[3], S. Garavaglia[1], C. Marini[2], R. McDermott[3], I. G. Miron[5], A. Moro[1], G. Pucella[4], H. Reimerdes[2], C. Sozzi[1], J. Stober[3], D. Testa[2] and the TCV and ASDEX Upgrade Teams and the EUROfusion MST1 Team[6]

[1] *Istituto di Fisica del Plasma 'P. Caldirola', CNR, Milano, Italy*
[2] *Swiss Plasma Center (SPC), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*
[3] *Max Planck Institute for Plasma Physics, D-85748 Garching, Germany*
[4] *Centro Ricerche di Frascati, C.P. 65 00044 Frascati, Rome, Italy*
[5] *National Institute for Lasers, Plasma and Radiation Physics, Romania*
[6] *see appendix of H. Meyer et a (OV/P-12) (this Conference) and http://www.fusionscipub.org /mst1*

e-mail: nowak@ifp.cnr.it

Abstract. The modification of low toroidal plasma rotation under the application of central EC power injection with the possible onset of neoclassical tearing modes (NTM) is an important issue for plasma confinement and for future devices (ITER will be characterized by a low rotation). In low collisionality regimes, with the EC power larger than the ohmic power ($P_{EC} / P_{oh} > 1$), in both TCV and AUG L-mode experiments performed within the MST1 framework, central electron heating and co-ECCD were observed to initiate a shift of the plasma toroidal velocity in the co-I_p direction, allowing the NTM onset in some cases with subsequent NTV braking. The time evolution of the toroidal velocity is simulated. It is found that with a torque source in the center and sometimes near the edge, one can model the complex time evolution in both AUG and TCV plasmas with central EC deposition.

1. Introduction

The modification of low toroidal plasma rotation under the application of central EC power with the possible onset of neoclassical tearing modes (NTM) is an important issue for plasma confinement and for future devices that will be characterized by low rotation. In low collisionality regime TCV experiments with $P_{EC}/P_{oh} > 1$ [1-3], central co-ECCD was observed to modify the toroidal plasma rotation both in the absence and at the appearance of 3/2 and 2/1 modes, while no modes with cnt-ECCD were observed. In the presence of TM or NTMs, the shear of the plasma rotation was reversed by neoclassical toroidal viscosity (NTV) braking of the rotation. The perturbation of the q-profile appears as the main mechanism of the TM destabilization, possibly linked to internal (1/1) mode coupling with a harmonic (2/2) followed by coupling with a 2/1 (3/2) [4]. The rotation profiles were promptly modified by the central EC power deposition and driven in the plasma current direction as also observed in similar recent TCV experiments performed in the framework of the EUROfusion MST1work package. Dedicated MST1 discharges for this study were also done in ASDEX Upgrade (AUG). An example of the TCV and AUG toroidal velocity modification is shown in Fig.1 before and after the EC injection and at the appearance of the

mode. It is worth noting that the AUG Ohmic profile here is likely not in equilibrium due to the current diffusion after the plasma ramp up and would likely have continued evolving even in the absence of EC power.
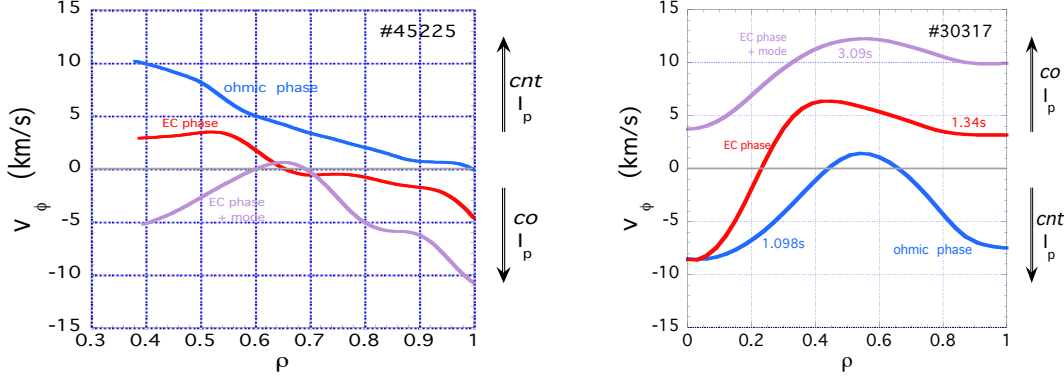

Figure 1: Evolution of the plasma toroidal velocity in ohmic phase (blue trace), in early EC phase (red trace) and in EC phase at the mode onset (violet trace) for the TCV discharge #45225 (left) and AUG discharge #30317 (right). In TCV the appeared mode is 3/2 and in AUG is a weak 4/3.

Three timescales can be associated with mechanisms responsible for the change of the toroidal plasma rotation. First, a transient non-vanishing direct EC torque effect could spin-up the rotation when the rf power is deposited over the flux surfaces in a parallel transport time of about 10^{-8}s; this could be provided by the surface-averaged displacement current due to the Maxwell response to the EC driven contribution, but in the short time of about 10^{-5} sec, typical of the ECCD rise, the contribution is negligible [1, 5]. Second, over the timescale of the linear trapped electron mode (TEM) inverse growth rate $> 10^{-4}/10^{-3}$ sec, transport effects can occur due to the turbulent residual Reynolds stress converting part of the driving heat flux to a net effective toroidal flow [6]; the pump-out in term of density profile can be associated to a change in velocity, as already analyzed in AUG discharges [7]. Third, the rotation can evolve more slowly on a diffusive timescale $> 10^{-2}$ sec. In addition, possible MHD effects on the toroidal rotation, for example, co-Ip directed "kicks" at ST crashes particularly in the presence of large T_e gradients due to the application of EC power, cannot a priori be neglected.

We propose in this work a procedure to fit the experimental results of the evolution of the toroidal rotation under the effect of EC power absorption using a simplified momentum equation which includes an effective momentum diffusivity, scaled to the anomalous ion heat diffusivity [1].

For our fitting we take into account a torque associated with the turbulent effects due to the absorption of the EC power, enhancing the residual turbulent Reynolds stress related to the electron pressure gradient and defining an effective toroidal momentum source [8].

2. Experimental plasma rotation observations in AUG and TCV
In the framework of the EUROfusion MST1 work package, experiments have been performed in AUG and in TCV for the study of low toroidal plasma rotation under

application of central ($0 < \rho_\phi < 0.35$) electron cyclotron heating (ECRH) and current drive (ECCD). L-mode plasmas at low density were used for this analysis, looking also at the onset of NTMs, using different levels of EC power. The AUG (TCV) discharges were characterized by I_p=0.5MA (-0.11MA), Bt=-2.5T (-1.44T), and a line averaged density of 2.6-3x10^{19} m^{-3}. These experiments were run with $q_{95} \geq 8$ which is higher than usual. However, these AUG configurations are well suited for studies of NTM onset with plasma rotation and ECH/ECCD effect.

We show and discuss for the fitting 3 typical shots with 1.8 MW constant level of EC power (co-ECCD) with 2 different power ramps from 0.5 MW to 1.5-1.8 MW for 5.3s in AUG and for 1.4 s in TCV. The first AUG #30275 discharge at the constant EC injection P_{EC} = 1.8 MW starts in H-mode coming back after about 0.4 s to L-mode when the EC heating decreased n_{el} up to a stationary value of about 1.5 10^{19} m^{-3}. In this case a strong density flattening is observed due to gas valve closing. The other 2 discharges discussed here remained in L-mode despite relatively long periods of high EC power (5.3s in AUG 30317 and 1.4s in TCV 51297). In Figure 2 the fits to the plasma rotation for these 3 discharges are plotted. It can be seen that the plasma rotation increases from counter to co plasma current direction after application of EC power, consistent with previous observations [1,9]. In Figure 3 the increase of the electron temperature with EC heating and the corresponding electron density profiles are shown for AUG #30317 and TCV #51297. The plasma rotation was measured by CXRS using 12ms beam blips every 255ms in AUG and using a DNBI 15ms blips every 22ms in TCV.
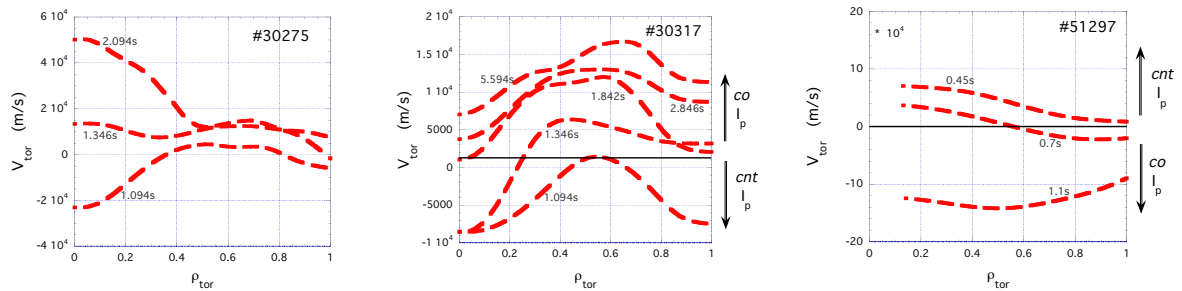

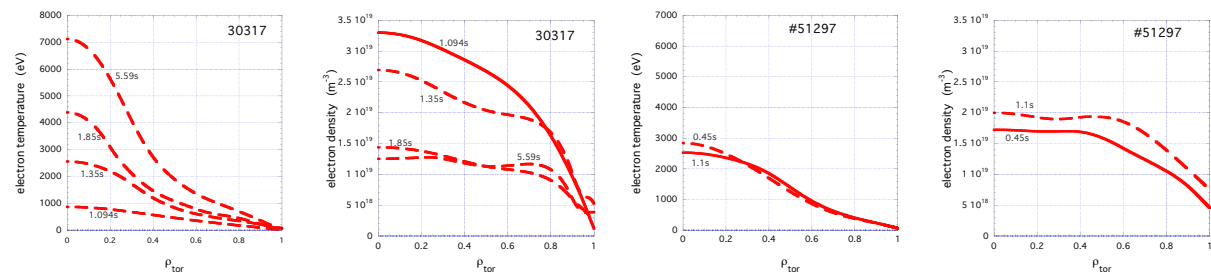Figure 2: fits of experimental plasma toroidal velocity for AUG #30275-30317 and TCV #51297

Figure 3: evolutions of T_e and n_e profiles in AUG #30317 with a clear pump-out on the density (left) and in TCV #51297 with quasi stationary profiles.

One possible explanation for the changes in the observed toroidal rotation profiles is a change

in the residual stress due to the EC induced changes in the plasma profiles and collisionalty. In the next section we apply a simple semi-empirical fit to the measured rotation profiles with no pretense of full theoretical development.

3. Modelling of toroidal rotation profiles

It is generally observed that EC heating and current drive are associated with a change of the shape and magnitude of the plasma toroidal rotation profiles. Moreover, the rotation profiles have been observed to not only change sign, but to pass though zero rotation at finite rotation gradient.

To describe this, it is necessary to include an additional term in the momentum balance equation, which describes the toroidal rotation evolution. In both the prompt phase of plasma heating and in the time interval where turbulent effects can be driven, a torque in the co-direction should model the shape of perturbations responsible of the observed velocity spin-up. The power deposition and current drive profiles can be well reproduced by fitting a suitable Gaussian function, localized at the radial location of the absorbed power.

The same fit can be applied in the turbulent time interval as well, where recycling of particles is also considered. In this case a Gaussian perturbation should be located at plasma positions where the toroidal rotation shows changes in shape. The EC heating and current drive cause the temperature increase and density peaking or flattening, modifying the respective ∇T_e and ∇n_e which appear in the torque expression. The effect related to the temperature gradient can quantitatively match the modifications of velocity profile.

Since in these experiments we operate in collisionless regimes where the TEM turbulence is dominant, in the momentum equation we can think to associate the torque S_{EC} due to the EC power injection to the residual Reynolds stress, Π_{RES}, proportional to ∇p_e [8], well reflecting the local modifications of the rotation due to the global effect of the applied ECRH and ECCD. Following these observations, the momentum equation is expressed by [1,6,9,10]:

$$\frac{\partial V_\varphi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\chi_\perp(r,t)r\frac{\partial V_\varphi}{\partial r}\right) + S_{EC(r,t)} \quad ; \quad S_{EC} = -\partial_r\Pi_{RES} = -\partial_r\, sign(I_p) < R\nabla p_e >$$

where the density torque S_{EC} is proportional to the radial derivative of the Reynolds stress. It should be noted that the torque S_{EC} is a co-current torque.

The radial shape of this torque S_{EC} can be fitted by Gaussian functions centered at locations where the values of the radial derivatives of ∇p_e are peaked. In both the AUG and TCV discharges the torque S_{EC} is in co-Ip direction (positive in AUG having $I_p > 0$, negative in TCV with $I_p < 0$).

The free fitting parameters are the amplitude h in [Pa/m^2] and the width δ_w, normalized to the minor radius, of the S_{EC} profiles (e.g. Gaussian) enveloping the radial interval where the torque associated to the Reynolds stress [8] is peaked.

We tried to fit the experimental data with only up two sources, one main in the center and one in the off-axis part of the rotation profiles in order to reflect the edge changes as well.

4. Simulations of toroidal rotation profiles in AUG

The rotation profiles of AUG discharges #30275 and #30317 shown in Figure 2 have been fitted, as typical examples of similar shots, using the momentum balance equation described above. The results of the simulations are shown in Figs. 4-5 at different times.
For the calculation of the shot #30275 we have considered 2 Gaussian functions as explained in the previous section . In both shots the diffusion coefficient was $\chi=0.01$ m^2/s.
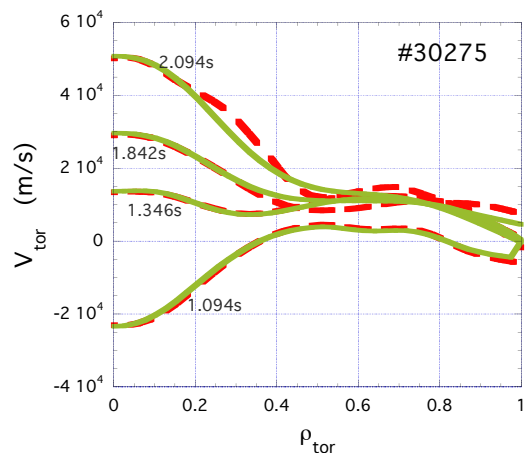

Figure 4: experimental (red dashed lines) and calculated (green continuous lines) traces of the plasma velocity rotation of AUG #30275 discharge at 4 different times. The ohmic phase is a t=1.094s.

For #30317 two Gaussian functions have been considered as well inspired by $\partial_r \nabla P_e$ with the second asymmetric function fitted by a tail modeled with 6 Gaussian shapes.
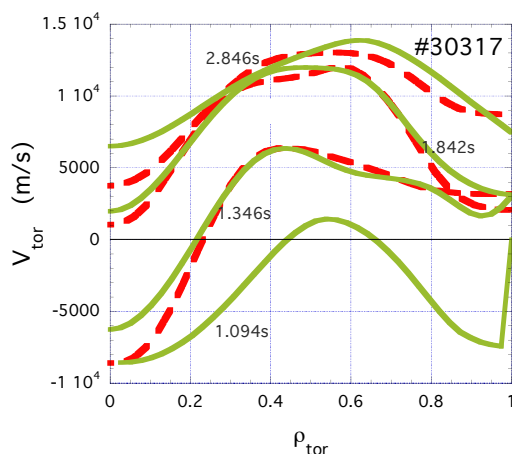

Figure 5: as figure 4 for AUG #30317 discharge.

In the table below the fit parameters in terms of radial location of the peak ρ_{peak}, of amplitude h and of width δ_w of Gaussian functions used are shown for these 2 discharges.

	parameters 1ˢᵗ function			parameters other functions		
	ρ_{peak}	h [Pa/m²]	δ_w	ρ_{peak}	h [Pa/m²])	δ_w
#30275	0.1	24.37	0.25	0.75	10.31	0.35
#30317	0.35	5.62	0.45	0.69	2.81	0.22
#30317				0.79	2.81	0.22
#30317				0.83	0.94	0.22
#30317				0.89	0.94	0.22
#30317				0.94	0.94	0.22
#30317				0.98	0.94	0.22

5. Simulations of toroidal rotation profiles in TCV

The rotation profiles of TCV discharge #51297 shown in Figure 2 have been calculated with the proposed model. The experimental and simulated rotation profiles are shown in Fig.6. The Gaussian function used in the torque S_{EC} in the balance equation is peaked at the radial position of $\rho \sim 0.4$. This torque is in co-I_p direction (negative in TCV being Ip < 0). In this #51297 discharge the diffusion coefficient was χ=0.025 m²/s.
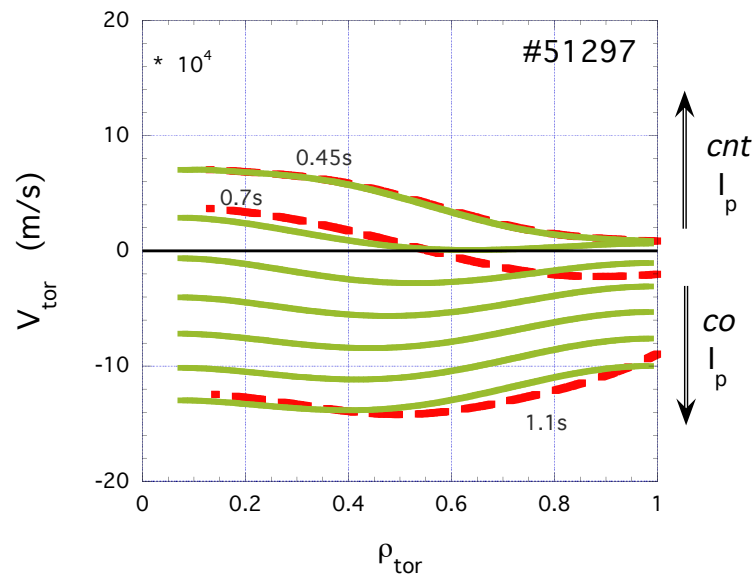

Figure 6: as figure 5 for TCV #51297 discharge.

In the table below the fit parameters used in this TCV shot are shown.
.

	parameters Gaussian function		
	ρ_{peak}	h [Pa/m²]	δ_w
#51297	0.5	21.6	0.55

6. NTM onset under central EC

The change of plasma toroidal rotation under effect of central EC power injection has been also studied in these MST1 experiments to investigate the onset of neoclassical tearing modes (NTM). In MST1 AUG experiments the appearance of tearing modes does not change the shape of the toroidal rotation, while a clear modification of the rotation shape is observed in TCV when the mode appears (t~1s) even if not linked to NTV effects. In both AUG and TCV machines an NTM was triggered for P_{EC} power level > 0.8 MW for different time intervals. Particularly, in AUG #30275 only a 3/2 mode appears 100ms after the injection of 1.8 MW EC power and lasts 400 ms, but in this case it is triggered by ELMs (Fig.7). In AUG #30317 a 4/3 appears in triggerless conditions 1.5s after injection of 1 MW EC power and lasts 3.8s, but it is very weak, as shown in Fig.7. In this case, because in a similar discharge with cnt-ECCD no mode is observed, it can be conjectured that the mode is triggered by a positive mode stability parameter $\Delta'_0 > 0$ and not by NBI blips of rotation measurement. Indeed, it should be noted that in AUG the NTM appears randomly, while in TCV the relation of ECRH and NTM was clear and robust and reproducible dynamics is observed in each similar discharge. Some explanations of these NTM onsets can be found in [1].
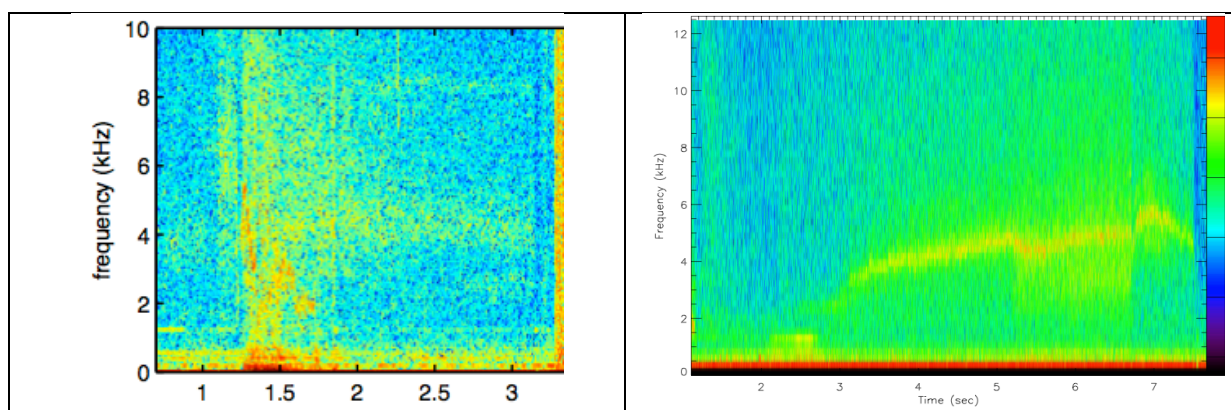

Figure 7: spectrogram of 3/2 mode from 1.3s to 1.7s in AUG #30275 discharge (left) and spectrogram of 4/3 mode from 3.2s to 7s in AUG #30317 discharge (right) .

In TCV the central ECRH drives 2/1 mode for P_{EC} ~ 1 MW and this tearing remains up to the end of discharges. In #51297 the mode lasts 1s, as shown in Fig.8. The rotation changes the concavity in co-I_p direction during the NTM presence for t>1 sec (see Figs.2 and 6), without showing a clear NTV effects as already observed in previous TCV experiments [1].
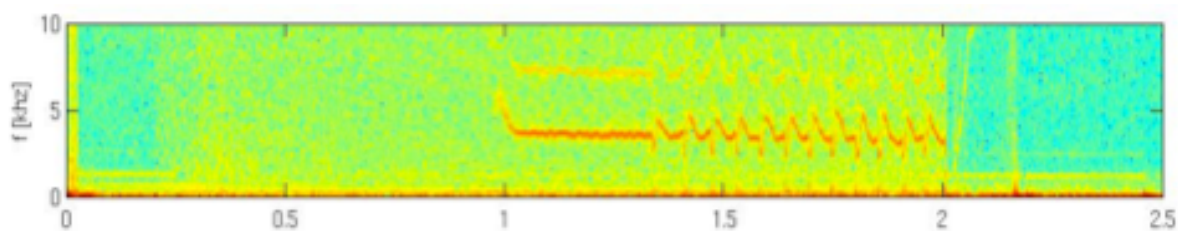

Figure 8: spectrogram of 2/1 mode in TCV #51297 discharge.

7. Conclusions

In this work we have fitted with no pretense of full theoretical development the evolution of toroidal rotation under the effect of central ECRH-ECCD injection in L-mode plasmas at low density. The rotation dynamics has been fitted using a semi-empirical momentum equation which includes an effective momentum diffusivity, scaled on the anomalous ion heat diffusivity.

 A fit between experimental and calculated velocity profiles has been obtained considering a torque associated to the absorption of the EC power, $P_{EC} \gg P_{oh}$, causing an enhancement of the residual turbulent Reynolds stress with a source near the center (where EC is deposited) and in some cases a source near the edge

Appearance of NTM has been observed in AUG and TCV for EC power level > 0.8 MW and for different time interval, but no changes on the rotation profile have been observed in AUG, while in TCV strong changes in the concavity of the rotation profile occur, while in other TCV cases significant NTV effects were observed [1].

References

[1] E. Lazzaro *et al*., Nucl. Fusion **55** (2015) 093031

[2] O. Sauter *et al*., Effects of ECH/ECCD on Tearing Modes in TCV and Link to Rotation Profile, *Proc. 23rd Int, Conf. on Fusion Energy 2010 (Daejon, Korea, 2010)* vol IAEA-CN-180 (ECA) (Vienna: IAEA) (CD-ROM) file EXS/P2-17, 2011

[3] S. Nowak *et al.*, (N)TM Onset by Central EC Power Deposition in FTU and TCV Tokamaks, *Proc. 25th IAEA Fusion Energy Conf., St Petersburg, Russia, 2014*, CN-221, Paper EX/P2-54

[4] D. Brunetti *et al*., Role of infernal modes dynamics and plasma rotation on the onset of NTMs in ECH-ECCD TCV plasmas, paper presented at *the Joint Varenna –Lausanne Inter. Workshop, 29 Aug-2 Sept. 2016* and submitted to J. Phys. Conf. Ser.

[5] G. Gervasini *et al*., Il Nuovo Cimento **18**, N.8

[6] P.H. Diamond et al., Nucl. Fusion **53** (2013) 104019

[7] C. Angioni et al *et al*., Nucl. Fusion **44** (2004) 827-845

[8] W. X. Wang *et al.,*Phys. Plasmas **18**, (2011) 042502

[9] R. M. McDermott *et al*., Nucl. Fusion **54** (2014) 043009

[10] J. Lee *et al.,* Plasma Phys. Control. Fusion **57** (2015) 125006