

Radial electric field profile and Geodesic Acoustic Modes in tokamak plasmas

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The importance of sheared flows in the regulation of turbulent transport is commonly accepted in the magnetized fusion community. However, the formation of a shear layer at the plasma edge and the build-up of a radial electric field (E_r) well is not fully understood yet. In particular, some sensitivities of the E_r well, like the one with respect to the magnetic configuration and plasma shape, are not fully explained. In the case of magnetic configuration, the so-called *favourable* (FAV) equilibrium, associated with easier access to High confinement mode (H-mode), exhibits a deeper E_r well in the Low confinement regime (L-mode) than its *unfavourable* (UNFAV) counterpart equilibrium [1-3]. At this stage, no consensus exists to explain such an E_r profile asymmetry. Among several mechanisms potentially involved in this sensitivity, flows generated by turbulence are pointed by various works [4-6]. In addition, in this context of E_r sensitivities, a similar trend is found in experiments comparing Negative Triangularity (NT) plasmas, known for their remarkably high confinement in L-mode, and their counterpart in standard Positive Triangularity (PT) shape. Systematically, a deeper E_r well is observed in NT as compared to PT plasmas [7].

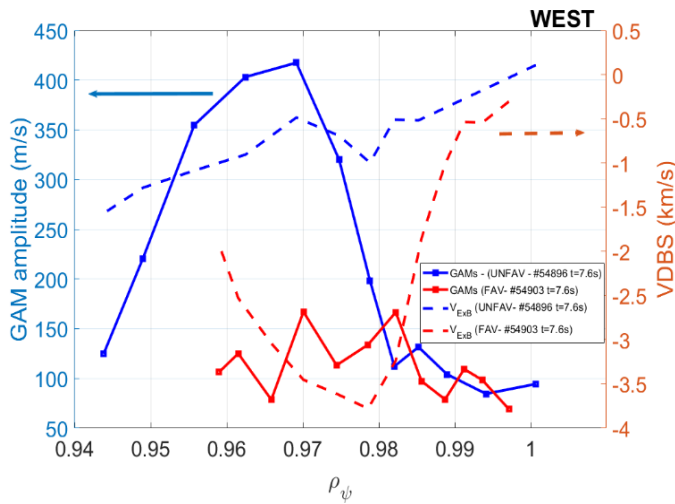
In the present contribution, flows generated by turbulence are investigated through the experimental characterisation of Geodesic Acoustic Modes (GAMs) in both FAV/UNFAV and NT/PT plasma comparisons. It is well known that turbulence in magnetized fusion plasmas can self-organize by generating large-scale flows, called zonal flows, through Reynolds stresses [8]. These axisymmetric sheared flows, which backreact on small scale turbulence that drives them, are challenging to detect experimentally due to their stationarity (and their $m=0$, $n=0$ structure). In addition to these flows, a non-stationary branch appears in the form of a coupling between them and an axisymmetric ($m = 1$) pressure sideband mode due to geodesic curvature, leading to GAMs. These modes are easier to detect due to their high frequency (of the order of 10 kHz) oscillations of the plasma's perpendicular velocity and they can be seen as an indicator of the turbulence-generated flow drive.

While the interpretation in terms of ZF contribution to the mean E_r flow from the GAM amplitude is far being from straightforward (not the same frequency range in the Reynold stress, not the same damping and uncertainty about the sign of their contribution), it might bring new elements to help understand and guide related numerical work. In the following, all results are

obtained using Doppler Back-Scattering (DBS) measurements [9]. Note that while no complete identification (in particular the $n=0$ structure) of GAMs is accessible for the following data, previous works on GAMs characterization both on Tore Supra [11] and TCV [12], with the same DBS diagnostic, guide us in linking coherent oscillations detected at the edge of the order of 10kHz (for WEST and around 20kHz for TCV) to GAMs.

A. Weaker GAMs in favorable configuration with stronger ExB velocity shear

The first comparison is performed during “matched” *FAV* and *UNFAV* plasmas in WEST. Ohmic as well as heated (using Lower-Hybrid or Ion Cyclotron Resonance Heating) discharges are investigated. While the Er well is deeper in all *FAV* cases, the amplitude of the GAMs is found



lower in presence of a stronger well. As an illustration, Figure 1 shows radial profiles of the velocity as well as GAMs amplitude using a highly time resolved analysis of DBS data [10]. The GAMs amplitude is significantly stronger in the *UNFAV* case and peaked around $\rho_\psi = 0.97$, very close to the Er well in the *FAV* configuration. The frequency of the GAMs remains constant over the radius at 8-9kHz.

Figure 1. Radial profiles of perpendicular velocity (*dashed lines*) and GAMs amplitude (*full lines*) for both *FAV* (*red*) and *UNFAV* (*blue*) configurations during low power ICRH discharge at $I_p = 500\text{kA}$.

This trend appears common to all medium plasma current ($I_p = 400/500\text{kA}$) *FAV/UNFAV* experiments performed in WEST as well as in *FAV/UNFAV* experiments from TCV. To illustrate TCV results, Figure 2 presents an I_p scan realized in matched *FAV* and *UNFAV* Ohmic discharges. In this series, the velocity profile exhibits always a deeper well in *FAV* configuration and a stronger GAMs amplitude in the *UNFAV* case. In this configuration, GAMs amplitude systematically peaks in the radial region where the Er well is present in the *FAV* configuration ($\rho_\psi = [0.9-1]$) with no significant change in absolute GAMs amplitude between the different I_p . This latter result appears consistent with a dominant collisional damping at the edge as compared to Landau damping. While this example is for a specific shape and for Ohmic plasmas, this behaviour is robust: stronger GAMs in *UNFAV* are systematically found in the large database of *FAV/UNFAV* experiments performed in TCV [3].

This general trend suggests that the presence of the Er well may be related to the weakness of the GAMs. To document this possibility, similar GAMs analysis have been performed during experiments comparing matched Negative versus Positive Triangularity (*NT/PT*) plasmas.

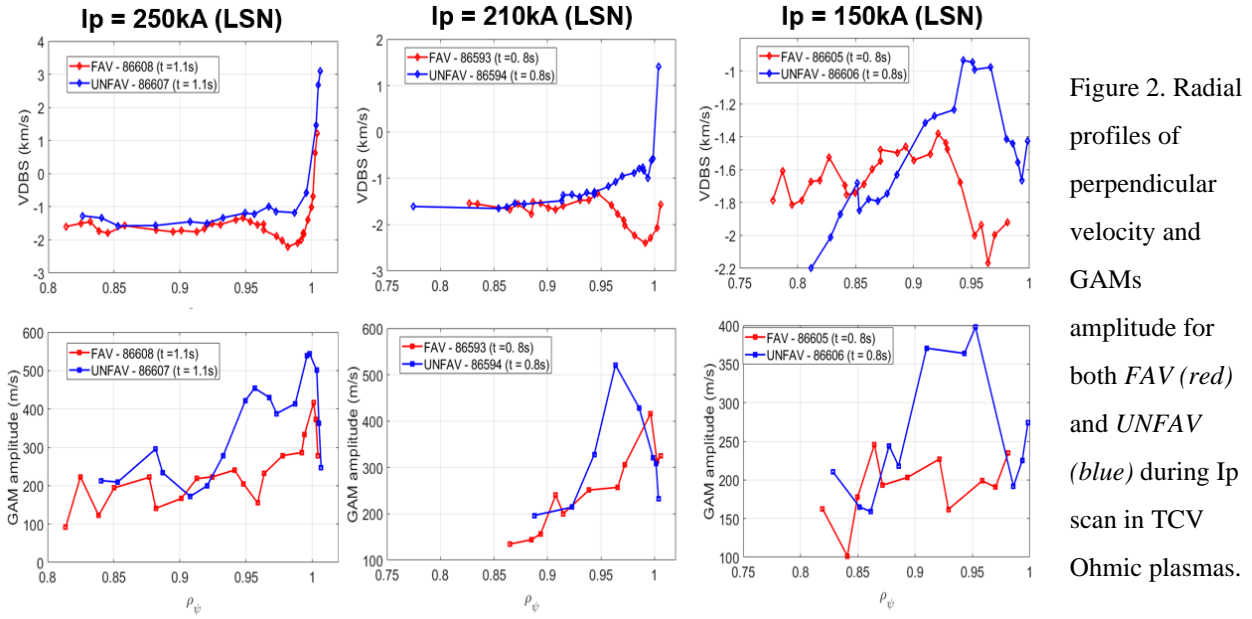


Figure 2. Radial profiles of perpendicular velocity and GAMs amplitude for both *FAV* (red) and *UNFAV* (blue) during I_p scan in TCv Ohmic plasmas.

B. Weaker GAMs in NT configuration with stronger ExB velocity shear

These experiments performed on TCv focused on the Er profile at the edge and clearly show a deeper Er well in *NT* as compared to *PT*, in all plasma conditions tested (Ohmic, ECRH, NBI, different triangularity values) [7]. In all cases, in which *NT* plasmas exhibit a deeper Er well and

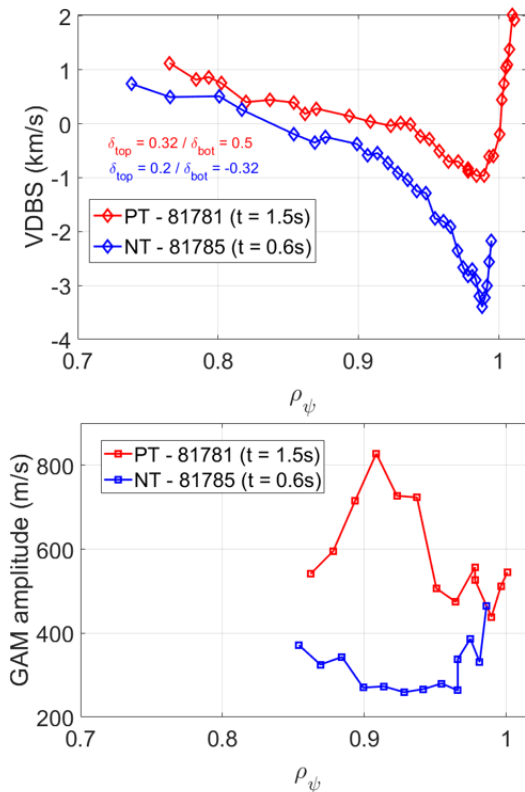


Figure 3. Radial profiles of perpendicular velocity and GAMs amplitude for both *PT* (red) and *NT* (blue) configurations during NBI heated (resp. 800 and 420 kW) TCv plasmas.

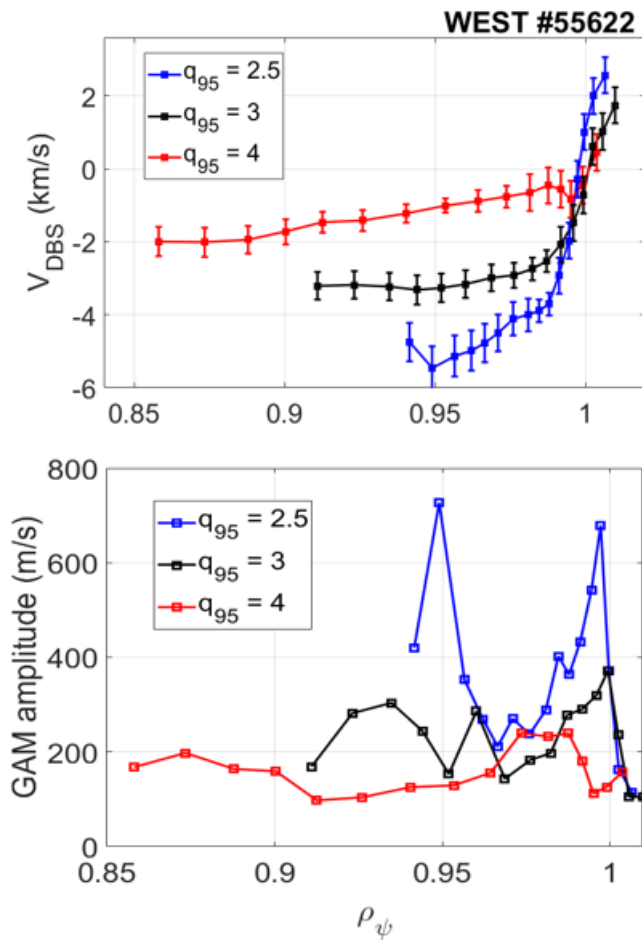
better confinement, the GAMs amplitude is found weaker than in the matched *PT* discharge. Note that in the few *NT* discharges which do not show an enhanced Er well, nor increased performance relative to *PT*, the GAMs amplitude also remains similar to the *PT* case.

An example is given in Figure 3, for ECRH discharges in which power is adapted to match the kinetic profiles (achieved using higher power in *PT*). This result suggests that GAMs amplitude and the presence of a deep Er well are correlated. Anyway, no cause-and-effect relationship can be drawn from them.

Considering the possible role of the Er well in reducing the GAMs source, turbulence intensity is compared using raw DBS spectra.

At the selected wavenumbers ($k\rho_s=[0.5-0.8]$), turbulence intensity is lower in *NT* plasmas (when the Er well is deeper) than in *PT* but is higher in the *FAV* plasmas (when the Er well is also deeper) than in *UNFAV* configuration.

It should be emphasized that the dominant source for the Reynold stress is expected at lower wavenumbers and medium wavenumbers may be not a good proxy for GAMs drive.



Some clues may lie in the counterexample to this relationship between Er well and the reduction in the GAMs amplitude. In Ohmic plasmas when increasing the plasma current in UNFAV configuration in WEST, the Er well increases strongly to end up with a deeper well than in the FAV counterpart [10]. This sensitivity, not recovered in TCV and AUG plasmas so far [14], has been studied using gyrokinetic simulations [5], highlighting the role of flow damping acting on the turbulence-generated flows contribution to the mean flow. In this specific experiment, at high plasma current in UNFAV and with a deep Er well, GAMs amplitude is stronger than at low Ip (Figure 4).

Figure 4. Radial profiles of perpendicular velocity and GAMs amplitude during Ip scan in UNFAV in Ohmic WEST plasmas.

In addition, the radial profile of the GAM amplitude exhibits an atypic U shape. Combination of damping and sources to form this specific radial structure have been studied and reveals a clear correlation between the vorticity gradient (second derivative of Er profile) and the GAMs amplitude radial profile.

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