Interaction of mean and oscillating plasma flows across confinement mode transitions

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Zonal flows (ZFs) and their oscillating counterpart, geodesic acoustic modes (GAMs), are radially localized $E \times B$ plasma flows generated by non-linear turbulence interactions. In magnetic confinement devices, ZFs are believed to play an important role in reducing turbulent transport by enhancing the velocity shearing of turbulent eddies. In the high gradient plasma edge region, GAMs become important as their energy approaches that of the $E \times B$ component of the turbulence. GAMs are universally observed in ohmic and additionally heated low confinement L-mode regimes, but not in the high confinement H-mode. What happens to the GAM across the transition and its possible role in triggering the transition is an open issue.

On the ASDEX Upgrade tokamak, Doppler reflectometry has been used to investigate the behaviour of the GAM. For example, its frequency ($5 - 25$ kHz) scaling $\omega = Gc_s/R$ (sound speed over major radius) is complex with two branches - core and edge - bounded by the density pedestal. In the core the GAM, although weak, has a scale factor $G \approx \sqrt{2}$, in agreement with current theory and simulations. In the gradient region, where the turbulence drive, vorticity and radial electric field E_r shear are larger, the GAM is stronger but G is anomalous with a inverse dependence on the plasma elongation κ. Likewise the edge GAM amplitude depends on the tokamak equilibrium - increasing with the edge safety factor q_{95} (reduced damping) and decreasing with κ (increasing magnetic shear). The role of the turbulence drive is seen with the GAM amplitude increasing linearly with the temperature gradient scale length - up to the L to H-mode transition - with the GAM peak moving outward (to higher q and lower damping) and a rising GAM frequency.

Latest measurements show the GAM flow oscillation is well correlated in both the toroidal and poloidal directions, confirming the $m = n = 0$ mode structure, with a finite radial (zonal) extent, eg. $k_r \neq 0$. Using a combination of ECRH and increasing neutral beam heating a gradual transition into the H-mode can be engineered. With strong ECRH electron heating an improved L-mode forms where the edge negative E_r well (eg. the mean $E \times B$ flow velocity) deepens by a factor of 2 and is accompanied by a fast pulsing of the turbulence amplitude; then, with increasing NBI ion heating the plasma begins to dither between L and H-mode. A strong GAM is still observed but its correlation and radial extent is reduced - first on the outboard, then inboard - commensurate with the narrower E_r well. With increasing input power the energy confinement rises, scaling with the E_r well depth, the GAM now becomes more correlated, radially narrower and its frequency increases. But once the H-mode is fully developed (no dithering) the GAM simply disappears (below diagnostic detection limit) as the turbulence drops.

The relative causality between the GAM and the turbulence still needs to be clarified, but the enhancement of the GAM in the build-up to the L-H transition may offer the much sought after trigger initiating the well-known $E \times B$ velocity shear positive feedback loop believed to be responsible for the H-mode formation.