On sustaining low or reversed magnetic shear equilibria with non-inductive current drive on JET

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1. Introduction

We examine the role played by Lower Hybrid (LH) heating and current drive in discharges with an Internal Transport Barrier (ITB) in JET. In particular, we simulate the evolution of the q-profile, which is influenced by the LH power, and discuss its effect on criteria for turbulence suppression.

The standard Optimised Shear (OS) regime used in JET for obtaining ITBs, i.e. discharges with an internal region of substantially decreased energy transport, involves two stages [1]. In the first preheat stage, a target plasma is produced by either Neutral Beam (NB) heating, ICRF heating or a combination of both during the plasma current ramp up. This delays the inward poloidal flux diffusion so that temporarily there is a central region of low, possibly reversed, magnetic shear. This is followed by intense NB heating during which an ITB may be formed. By adding or replacing the NBI/ICRF pre-heat with LH power, the target q profile can be modified. Especially towards a more reversed profile. As it is shown in Ref. [2], LH preheat can have a dramatic effect on the power required to trigger an ITB. The threshold for triggering an ITB has been found to be reduced from about 13 MW for standard discharges to 7 MW for discharges with LH preheating, indicating that the q-profile plays an important role. These findings are also consistent with experimental results [1] and transport simulations [3] for standard discharges, which suggest that the target plasma q-profile is a critical factor for ITB onset.

Our simulations show that in JET plasmas, LH slow waves can be expected to systematically deposit their power off-axis and thereby locally decreasing, possibly reversing, the magnetic shear $s=(r/q)dq/dr$. According to theory based criteria, this encourages ITB formation through a reduction of the linear drift wave growth rate γ and mode density [4,5], and also through an increase of the shearing rate γ_{ExB} [6] (because of the flatter $B_{poloidal}$ profile). If the theory basis for ITB formation is correct then these tendencies account for the smaller power threshold in the LH-pre-heat case.

2. The DACCOME code (poloidal flux Diffusion + ACCOME)

The DACCOME code [7] combines the current drive/magnetic equilibrium code ACCOME [8] with the flux surface averaged poloidal magnetic flux diffusion equation (PFDE) [9]. The NB injection module is adapted for specifics of the 16 JET PINIs in « standard » or « upshifted » configuration [10]. The bootstrap current is calculated using the Sigmar-Hirschman method. The LH module described in [11] injects 3 ray bundles with 25 rays in each from the 3 JET LH antenna sections. A simulation is initiated by calculating the first magnetic equilibrium with a guess for the plasma pressure gradient and the diamagnetic function $F=RB_{\phi}$. The equilibrium and flux surface averaged quantities are then used in the current drive modules and in the PFDE which also needs the non-inductive currents as input. The prescribed value of plasma current appears in the outer boundary condition for the PDFE. The resulting total current density and updated pressure gradient are then used to update F and grad(p) for a new iteration loop. The process is typically repeated 10-15 times during a flux evolution calculation so that the currents are consistent with the equilibrium.

Routines for evaluating theory based criteria for ITB onset have also been implemented in the code. In particular, with each new equilibrium we calculate drift wave Ion Temperature Gradient (ITG) growth rates γ from Biglari et al. [12] , the Hamaguchi-Horton stability factor Γ_S [4] and the Hahm-Burrell shearing rate γ_{ExB} [6]

$$\Gamma_S = (R/c_S)\partial_\psi(E_r/RB_\theta)/\partial_\psi(q) \cong \gamma_{ExB}/\gamma_{slab} \qquad \gamma_{ExB} = [(RB_\theta)^2\partial_\psi(E_r/RB_\theta)]/B$$

Reduction of transport is expected when $\Gamma_S > 1$ [4] or when $\gamma_{ExB} > \gamma$ [13]. The radial electric field, E_r, is evaluated from Carbon impurity toroidal rotation and pressure data. During high power NB injection toroidal rotation dominates by an order of magnitude over the poloidal rotation (assumed neo-classical) and pressure gradient contributions to E_r.

3. Numerical examples and benchmarking of the code

In order to test the criteria for turbulence suppression, we first analyse a standard JET OS discharge with a clear ITB: shot 46123. Results are shown in Fig. 1 at 7s into this discharge after a plasma current ramp-up to flat-top 2.5MA. The Hamaguchi-Horton stability factor and $\gamma_{ExB}/\gamma_{ITG}$ both show a wide stable region extending inward from about ρ=0.6. In the experiment the ion temperature gradient was steep between ρ=0.25 and 0.65, which is in good agreement with the region of reduced transport indicated by the stability factors.

The next simulation of Fig.2 compares experimental (MSE) and computed q-profiles at 4.3s , i.e. before ITB onset in LH preheat shot 49651. As can be seen the agreement is good.

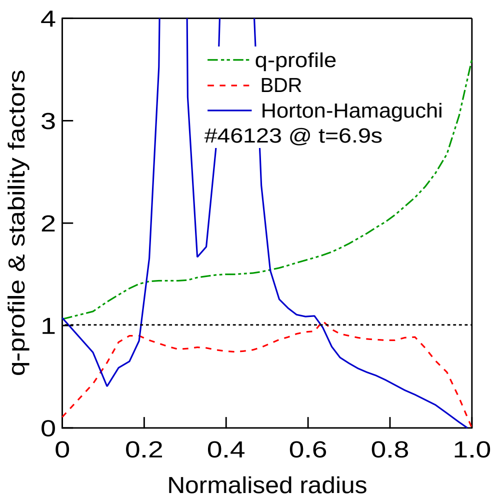

Fig. 1 q profile and H-H and BDR stability criteria for a standard JET OS discharge

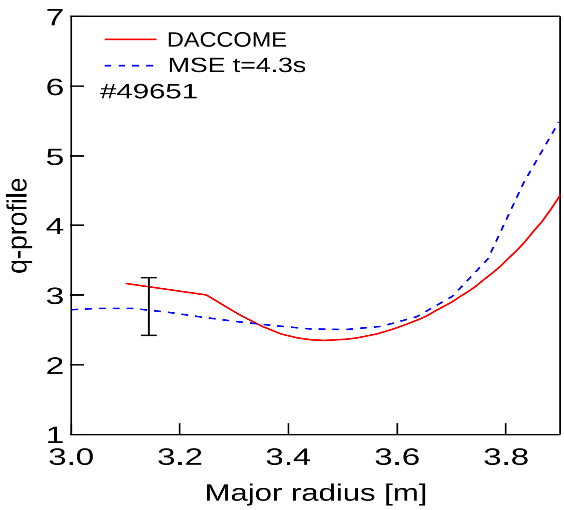

Fig. 2 Measured and calculated q profile for an ITB JET discharge with LH pre-heat.

The reversal of the shear is mainly due to the influence of the LH current drive that was applied in the discharge. Although the details of the LH power deposition are complicated to describe, we can understand the main features leading to reversed shear. In Tokamaks like JET, with a relatively small aspect ratio and elongated plasmas, LH ray propagation is stochastic [14] so that the power tends to be absorbed after a few passes [10], necessarily terminating the ray in a region where the up-shift of the parallel refractive index is sufficient to fulfil the Electron Landau Damping (ELD) condition [14] $n_{//}T_{e[keV]}^{1/2} \geq 7$. The absorbed power is therefore distributed between the ELD high-temperature threshold point close to the axis (requiring little $n_{//}$-upshift) and a lower-temperature point further out along the radial direction which satisfies the strong ELD condition for any reflected ray path on which $n_{//}$ is strongly increasing [10].

4. The effect of LH heating and current drive on ITB production

We compare two JET shots 49644 and 49645, the first without preheat, the other with 2.5MW of LH power applied up to 4s into the discharge, as illustrated in Fig 3. In both discharges 11.5MW of NB power was switched on at 3.7s leading at 4.6s to an ITB in 49645. This is indicated by the time evolution of the central T_e. Fig.4 shows simulation results for three cases : 49644, 49645, and 49645 with the LH current contribution removed, but using the same $T_{e,i}$ and n_e profiles as in 49645. Fig 4a indicates the effect of no pre-heating, LH pre-heating alone and LHCD + LH pre-heating on the q-profile. The two 49645 q-profiles are very close and so are their stability features seen in Fig.4b. It thus appears that heating alone could also lead to an ITB. On the other hand, the larger shear in the 49644 case degrades stability.

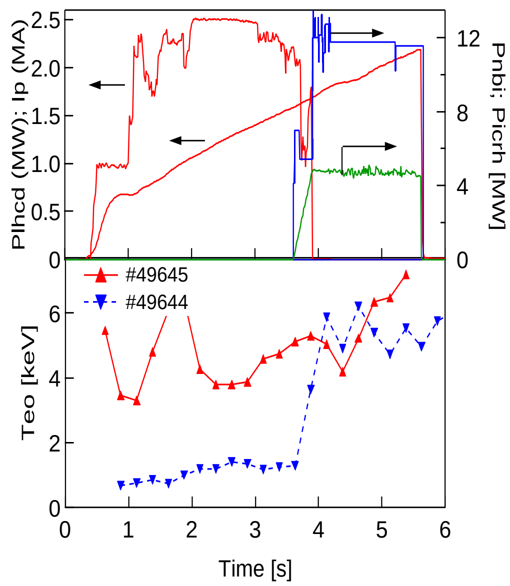

Fig. 3. Time evolution of experimental parameters in discharges #49644-45.

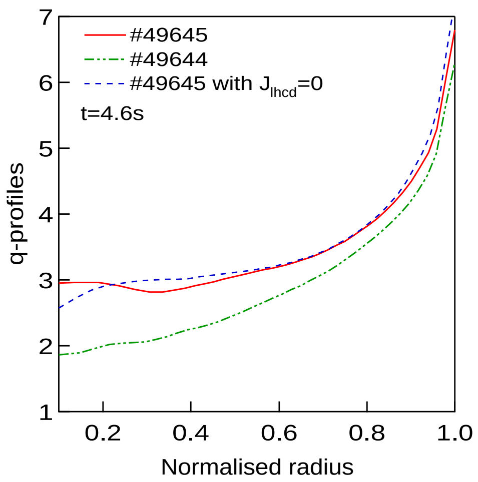

Fig.4a. calculated q-profiles for discharges #49644-45

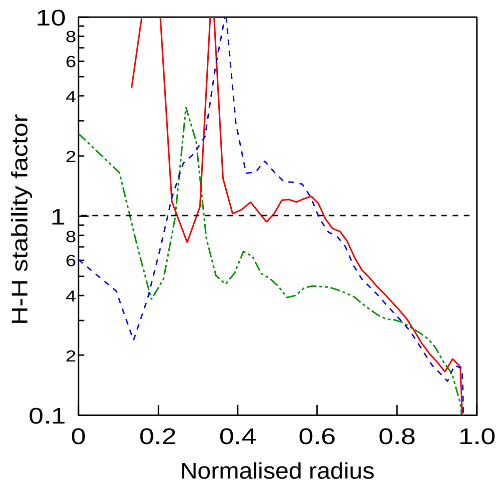

Fig. 4b. Hamaguchi-Horton stability factors for #49644-45

Finally, we find similar results from an independent drift wave calculation using the method of [5]. Drift wave growth rates γ_n, mode widths λ_n, and mode densities N_{mn} for a spectrum of toroidal mode numbers n are evaluated and a diffusion coefficient $D \cong \Sigma N_{mn}(\gamma_n - \gamma_{ExB})\lambda^2_n$, shown in Fig 5, is calculated. We see a substantial reduction of transport in 49645 due to LH power. Furthermore, the calculation for 49645 with the q-profile of 49644 shows that the q-profile plays a crucial role. The γ_{ExB} correction appears to play a minor role in this case.

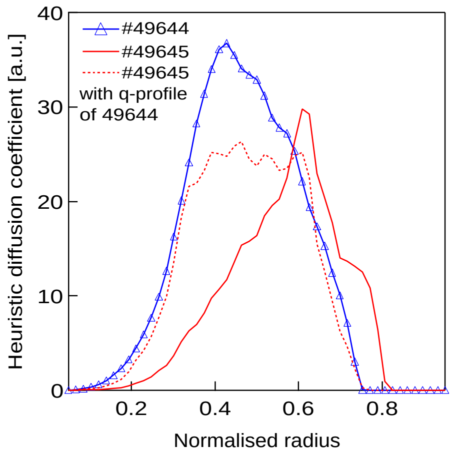

Fig. 5 Diffusion coefficient according to the method of Ref.[5].

5. Conclusion

We have shown how drift wave stability criteria can be used for analysis of JET OS discharges. The q-profile has been found to play a critical rôle. In regions where magnetic shear is reduced or reversed, the ITG mode density and growth rate decrease which favours conditions for ITB formation. In this context, LH power proves to be an effective tool for production of ITB target plasmas. It could possibly also be used for maintaining an ITB in steady state. The upgrade of ACCOME with a poloidal flux diffusion equation has been benchmarked against experimental JET results.

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