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ITB Formation in Terms of $\omega_{\mathrm{E\times B}}$ Flow Shear and Magnetic Shear s on JET

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1 Introduction

The importance of $\omega_{\mathrm{E\times B}}$ flow shear and magnetic shear s in the Internal Transport Barrier (ITB) formation on JET has been studied. The $\omega_{\mathrm{E\times B}}$ shearing rate is calculated from the experimental data, assuming the poloidal velocity to be neo-classical. The relative importance of the three terms (the pressure gradient and the toroidal and poloidal rotation terms) in the radial electric field E_{r} is evaluated. The magnetic shear is calculated with JETTO transport code, taking the temperatures and densities from the experiments. Finally, predictive simulations with a transport model [1, 2], modified by the results of the present study are performed.

2 Calculation of the Radial Electric Field E_{r}

The radial electric field for the main ions is calculated as follows:

$$E_{\mathrm{r}} = \frac{1}{Zen_i}\frac{\partial p_{\mathrm{i}}}{\partial r} - v_\theta B_\phi + v_\phi B_\theta, \tag{1}$$

where v_θ and v_ϕ are the poloidal and toroidal velocities and B_θ and B_ϕ the poloidal and toroidal magnetic fields, respectively, n_{i} is the ion density, Z is the ion charge number and e the elementary charge. Experimentally measured values for all other quantities except v_θ are available in the calculation of E_{r}, and due to the lack of measurements of v_θ in JET, it is assumed to be neo-classical. The measured v_ϕ by CXS is the toroidal rotation of carbon.

The radial electric fields and its different components are shown 0.6 s before the ITB transition and 0.6 after the ITB formation in Fig. 1 for JET discharge No. 46664. The contribution from the toroidal rotation (dash-dotted curve) is clearly dominant in total E_{r} (thick solid), both before and after the ITB formation. The dominance of $E_{\mathrm{r},\phi} = v_\phi B_\theta$ in E_{r} becomes even more pronounced because the poloidal velocity term $E_{\mathrm{r},\theta} = v_\theta B_{\mathrm{phi}}$ (dotted curve) almost cancels out the pressure gradient term $E_{\mathrm{r},\nabla\mathrm{p}}$ (dashed curve), the difference indicated as the thin solid curve. The magnitude of E_{r} and its all components are about 5 times larger after the formation of the ITB than before it.

In JET, the toroidal rotation produced mainly by the co-rotating Neutral Beam Injection (NBI) gives always a positive contribution to E_{r} as illustrated in Fig. 1. For co-injected NBI, $(E_{\mathrm{r},\nabla\mathrm{p}} - E_{\mathrm{r},\theta})$ component reduces the total radial electric field and its gradient. Consequently, the power threshold to form an ITB is lower for the counter-injected NBI on JET because in that case both $E_{\mathrm{r},\phi}$ and $(E_{\mathrm{r},\nabla\mathrm{p}} - E_{\mathrm{r},\theta})$ terms would have the same negative sign thus reinforcing the positive effect of $\omega_{\mathrm{E\times B}}$ shearing rate on the ITB formation.

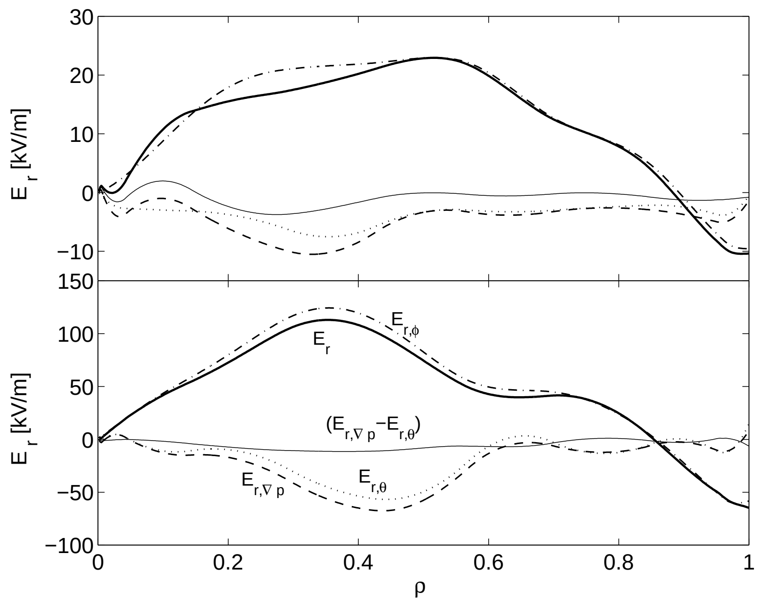

Figure 1: *E_r and its components 0.6 s before (above) and 0.6 s after (below) the ITB formation for JET pulse No. 46664.*

3 $\omega_{E\times B}$ Flow Shear versus Magnetic Shear in ITB Formation

The $\omega_{E\times B}$ shearing rate is calculated from [3]

$$\omega_{E\times B} = \left| \frac{RB_\theta^2}{B} \frac{\partial}{\partial \Psi} \frac{E_r}{RB_\theta} \right|, \tag{2}$$

where Ψ is the poloidal flux and R the major radius. An important quantity characterising the ITB formation is the ratio of the $\omega_{E\times B}$ shearing rate to the maximum growth rate of the Ion Temperature Gradient (ITG) type of plasma turbulence γ_{ITG}, defined as $\Omega = \omega_{E\times B}/\gamma_{ITG}$. The magnetic shear s, calculated in an interpretative way by JETTO, is presented before and after the ITB formation as a function of Ω in Fig. 2 for threshold conditions of JET Optimised Shear (OS) discharges. The diamonds denote the values of s and Ω about 100 ms before the ITB formation and the stars 100 ms after it for OS pulses with ELMy H-mode edge. For L-mode plasma edge discharges, the triangles symbolise s and Ω before the ITB transition and the plus-signs after the transition. The values of s and Ω are taken at the location of the footpoint of the ITB. For the three discharges marked with circles, no ITB was observed. In these cases, the values of s and Ω are taken at the most likely location for an ITB to take place. There are also three back transitions from an ITB state to ELMy H-mode plasma included in Fig. 2. The interpretation of the ITB formation in the s–Ω space is the following: the $\omega_{E\times B}$ flow shear divided by the turbulence growth rate γ_{ITG} must be large enough to compensate the negative effect of the magnetic shear on the ITB formation.

There are two distinct regions in the s–Ω space, separated by the line $s = 1.2\Omega + 0.17$ in Fig. 2. Above the line an ITB does not exist whereas below it, an ITB does exist. The ITB is formed when the line is crossed. The same rule is valid for both the ELMy H-mode

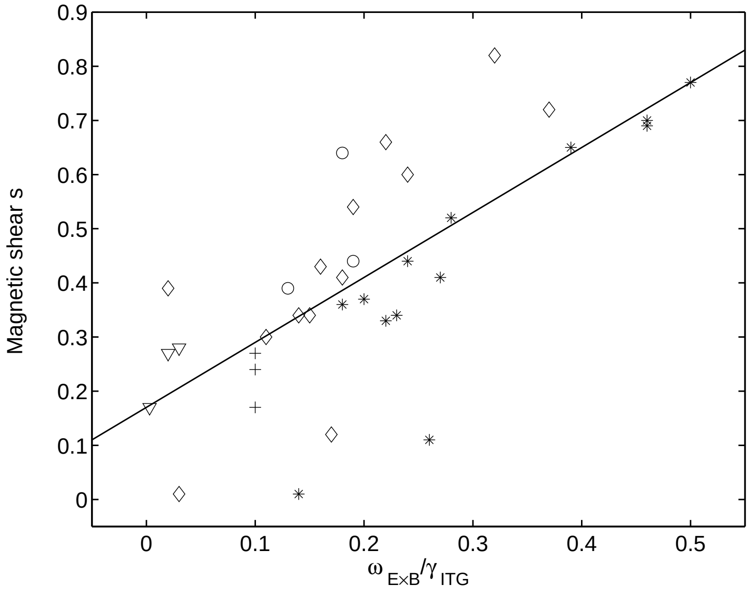

Figure 2: *Magnetic shear and* Ω *at the ITB location for threshold conditions. The solid line,* $s = 1.2\Omega + 0.17$ *divides the region into two parts, one (upper) where an ITB does not exist and one (lower) where an ITB does exist.*

and L-mode edges, although the required Ω to compensate the magnetic shear is smaller due to smaller s with an L-mode edge. Moreover, the three back transitions fit well into the same straight line.

The time evolution of three ITB discharges in s–Ω parameter space is shown in Fig. 3. A diamond indicates that no ITB yet exists whereas a star denotes an existing ITB. The time interval between the consecutive points is 250-400 ms, depending on the discharge. The values of s and Ω before the ITB formation are calculated at the location where the ITB later appears. After the ITB formation the actual footpoint is followed. The thin solid lines between the last diamond and first star mark the time interval during which the ITB is formed. The thick solid line is the same line $s = 1.2\Omega + 0.17$ as shown in Fig. 2. Both s and Ω are small at the beginning of the discharge, s because of the early phase of the current ramp-up and Ω because NBI is not yet switched on. The magnetic shear starts to increase because of the current penetration. When NBI is switched on, Ω starts to increase as well, finally leading to the formation of the ITB. After the onset of the ITB, it expands in radius and goes far from the $s = 1.2\Omega + 0.17$ line with pulses No. 47413 and 46664. However, for the shot No. 49196, NBI power is decreased from 16 MW to 10 MW after the ITB formation below the power threshold for the ITB and the ITB is lost. This back transition is also shown in Fig. 3 and described well by the solid line. Discharge No. 47413 is an argon pulse and thus, the measurements of T_i have some uncertainties, further leading to uncertainties in the pressure gradient term.

4 Predictive Simulations of ITB Discharges

A comprehensive predictive analysis has included several JET OS discharges in the range of B=1.8-4.0 T and P_in=14-30 MW. The validated condition for ITB formation, i.e., $s = 1.2\Omega + 0.17$ was used as the modification in the JETTO transport model [1, 2]. For

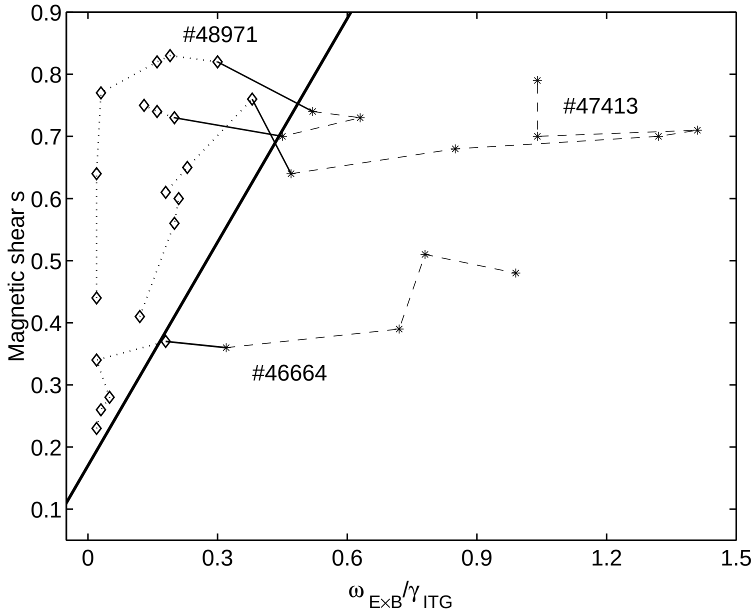

Figure 3: *The time evolution of the magnetic shear and* Ω *for 3 OS discharges. The same solid line,* $s = 1.2\Omega + 0.17$*, as in Fig. 2 is shown.*

Table 1: The prediction uncertainties

ITB triggering time	< 0.48 s
width of the ITB in the formation	< 0.14 m
width of the ITB at the highest performance	< 0.13 m
electron density	< 18 %
electron temperature	< 21 %
ion temperature	< 26 %
toroidal rotation flow velocity	< 36 %

the parameter range above, with a fixed set of all numerical multipliers in transport coefficients, the following prediction accuracy is achieved:

5 Conclusions

The toroidal rotation term is dominating in E_r generation in JET plasma. The counter-injected NBI would create somewhat larger E_r than the present co-injection. An empirically found curve $s = 1.2\Omega + 0.17$ distinguishes two regions, one where an ITB does not exist and one where it does exist. According to the interpretative JETTO analysis of 16 OS pulses, the ITB is formed when the curve is crossed. Still, it is not clear whether the ITB formation is a bifurcation process or a slow transition. However, the transport model which applies $s = 1.2\Omega + 0.17$ as the bifurcation condition to trigger the ITB, is able to reproduce JET OS pulses with a reasonably good accuracy.

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