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INTRODUCTION.

Numerous experiments were performed on JET to clarify the link between rational q, magnetic shear and ITBs, by producing internal transport barriers (ITBs) in plasmas with various q-profiles [1,2]. A reconstruction of the plasma equilibrium using the EFIT code with motional stark effect (MSE) and polarimetry constraints was verified by analysing MHD activity. Modelling of transport properties of plasmas produced in the experiment was done using the TRANSP (transport analysis), JETTO (predictive transport-micro-stability) and TRB (turbulent transport) codes. Two types of ITBs were analysed corresponding to different q-profile shapes: ITBs in a region of negative magnetic shear (s<0) and ITBs in the vicinity of rational q surfaces. Different models were used for the calculating the linear growth rate of micro instabilities. Calculated transport coefficients predicted by theory were compared with data deduced from the experiment.

1. ELECTRON HEAT TRANSPORT REDUCTION IN THE NEGATIVE MAGNETIC SHEAR REGION.

Figure 1a shows the contour plot of the parameter $\rho_e^* = \sqrt{2m_pT_e/e}\,(dT_e/dR)/(B_\varphi T_e)$ used to characterise an ITB in JET [3]. An ITB appears soon after the start of LHCD (Fig.1a,b). A large ∇T_e is sustained in the plasma core during LH and ICRF heating phases, although ρ_e^* is gradually reduced. The strong ∇T_e region expands abruptly after NB heating starts. The evolution of the q-profile, magnetic shear s and electron thermal diffusivity χ_e is shown in Fig.2, as computed by the TRANSP [4] code. The error bars are about ±20% for χ_e and ±15% for q. The time interval covers LH, ICRF and beginning of NB heating. Large negative magnetic shear s is produced in the plasma core during LHCD. Simultaneously, electron heat diffusivity is reduced to a low level of $\chi_e \approx 0.1\mathrm{m}^2/\mathrm{s}$ in the region of the negative s. Negative shear is sustained for a long time after the end of LHCD, although its amplitude gradually reduces. A minimum of χ_e is located in the region of the negative magnetic shear and it experiences only a small variation during LH and ICRF heating phase. No external toque and ion heating were applied in these phases. Alfven wave cascades analysis [5] shows that q_{min} crosses rational values as shown in Fig.1a. Results of the reconstruction of the q profile using EFIT with MSE and polarimetry constraints [6], TRANSP and JETTO [7] modelling are in agreement with this observation. An ITB moves from the region of a finite negative s towards s=0 at the time, when q_{min}=2.

A stability analysis was done for Pulse No: 57739 (Fig.1,2) using the Weiland model [8], describing ITG/TEM instabilities and implemented in the JETTO code. The linear growth rate γ_{lin} for the turbulence predicted by the theory has its maximum inside ITB and it varies with time from $2\times10^5\ \mathrm{s}^{-1}$ to $5\times10^4\ \mathrm{s}^{-1}$. Predicted χ_e at the ITB location is well above the experimental level and the model predicts no ITB formation. The main driving force for the instability in this model is $\nabla T_{e,i}$, which is close to its maximum within ITB and the dependence of γ_{lin} on the magnetic shear is relatively weak [8].

The heat transport in plasmas with s<0 induced by the Trapped Electron (TEM) and Ion

Temperature Gradient (ITG) modes was analysed using the three-dimensional global fluid simulation code TRB [9]. This simulation predicts the formation of an electron ITB in discharges with a strong negative magnetic shear, as illustrated in Fig.3. The ITB is located in the region of s<0. It gradually weakens, when s_{min} increases and disappears completely when $s_{min}>s_{crit}\approx-0.5$, which is close to a theory prediction for the TEM mode suppression by negative magnetic shear. Fig.4 illustrates the mechanism of ITB formation in this model for the case of s<−0.5. The thermal flux induced by fluctuations can be expressed in the form (2/3) $\Gamma_{i,e} = \langle \tilde{p}_{i,e}\,\tilde{u}_r\rangle = |\langle \tilde{p}_{i,e}\rangle|\,|\langle \tilde{u}_r\rangle| \times \cos(\delta_{i,e})$, where $\delta_{i,e}$ is a phase shift between the radial velocity $\tilde{u}_r$ and pressure fluctuations. The radial variation of these parameters is shown in Fig.4a,b. Notably, $\tilde{p}_e$ has a maximum and) $\cos(\delta_e)$ a deep minimum at the ITB location 0.3≤r≤0.35. A reduction in) $\cos(\delta_e)$ within ITB causes a reduction in χ_e, which is shown in Fig.4c. The ion diffusivity χ_i is not reduced significantly. Density fluctuations with long perpendicular wavelength ($\lambda_\perp^{exp} \geq 0.1$m) are found to be reduced within the volume enclosed by electron ITB in the experiment [10]. However, the perpendicular wavelength for ITG and TEM modes is much smaller $\lambda_{\perp ITG,TEM} << \lambda_\perp^{exp}$ and can not be measured by reflectometry diagnostic, available on JET [10].

2. ION HEAT TRANSPORT REDUCTION IN THE NEGATIVE MAGNETIC SHEAR REGION.

Statistical analysis shows that the ion ITB in JET plasmas is formed in the region of small or negative magnetic shear. Fig.5 shows the ratio of the ITG mode linear growth rate $\gamma_{ITG,lin}$ to the plasma flow shearing rate $\omega_{W\times B}$ as a function of magnetic shear at the location and the time of ITB formation. Weiland [8] and Rogister [11] models were used to calculate the linear growth rates $\gamma_{lin,ITG}$. The Rogister model describing ITG instability for a small s predicts efficient sheared flow stabilisation for |s| <<1. Weiland model predicts large values of $\gamma_{lin,ITG}/\omega_{W\times B}>1$ for all observed s. Neither model predict a turbulence stabilisation for s ≤−0.5.

An effect of the negative magnetic shear on the ion heat transport can be seen in discharges with so called ‘current hole’ [6]. Plasma temperature $T_{e,i}$ and heat diffusivity profiles $\chi_{e,i\ exp}$, are shown in Fig.6 for such case. Several time slices corresponding to the start of the main heating phase were selected. The diffusivities were deduced from TRANSP modelling with accuracy of ±20%. The q-profiles were reconstructed using EFIT equilibrium code with MSE constraints with error bars of ±15%.

The ITB criterion $\rho^*_{e,i}, \geq \rho^*_{crit}$ is fulfilled for electrons and ions for t ≥ 4s. Both, $\chi_{e,i}$ are reduced locally in the region of s<0 with min(χ_i) being close to the neoclassical diffusivity. The growth rate γ_{lin} and shearing rate $\omega_{W\times B}$ are shown in Fig.6 as deduced from JETTO simulations with Weiland model. Obviously, the sheared plasma flow stabilisation [12] is not effective within the ITB (R=3.3−3.35m) as the Weiland model predicts $\gamma_{lin} >> \omega_{W\times B}$. This model predicts large values of $\chi_{i,model} >> \chi_{exp}$. It does not predict the ion ITB formation.

The TRB code was used to calculate a stability of the ITG/TEM modes and to simulate the ion

ITB formation for the case of s<0. The code predicted a stabilisation of the TEM mode and a reduction in the electron heat diffusivity leading to the formation of the electron barrier. ITG modes remained unstable. Predicted ion heat transport was large and no ion ITB was formed in the simulation. It should be noted that simulations using flux tube gyrokinetic code GS2 indicate an ITB formation for very small $s<-2.5$ [13]. GS2 code simulations show that ITB formation for larger s requires sheared flow stabilisation.

3. ITB FORMATION IN VICINITY OF S=0 AND LOW ORDER RATIONAL Q.

An ITB is formed in many cases in JET at the time, when qmin crosses a integer number [1,2]. One such event occurs in Pulse No: 57739 at t = 4.2 as illustrated in Fig.1a and Fig.2a,c. A rarefaction of the rational magnetic surfaces was discussed and analysed as a possible mechanism for ITB formation [9,14]. To investigate this formation, transport properties of two close magnetic configurations with $q_{min} = 2$ and 2.131 were modelled using the TRB code (Fig.7a). Calculated normalised ion pressure profiles are shown in Fig.7b. An ITB is formed in the region of $q_{min} = 2$. A reduction in $\chi_{i,e}$ is stronger in the $q_{min} = 2$ than for larger qmin case as shown in Fig.8. An ITB is developed in both ion and electron channels. The simulation shows that it is produced due to the suppression of $\langle \tilde{u}_r \rangle$ and $\langle \tilde{p}_{e,i} \rangle$ fluctuations, which is stronger for wider gap between the resonant surfaces. The gap is wider in the vicinity of low order rationals [9]. The width of the gap Δ is proportional to $(dq/dr)^{-1}$ and $(d^2q/dr^2)^{-1/2}$, respectively, for linear and parabolic variation of the q inside the gap [9], which shows that small s is favourable for ITB formation.

4. EFFECT OF BOOTSTRAP CURRENT ON MAGNETIC SHEAR.

The bootstrap current induced in the vicinity of ITB flattens locally the q profile as shown in Fig.9. Such flattening (reduction in s) widens a gap between the resonant magnetic surfaces and facilitates ITB sustainement. The stronger the ITB the larger the bootstrap current, which provides a feedback loop. However this effect does not provide a mechanism for ITB triggering.

SUMMARY.

Experiments on JET and modelling show that the q-profile plays an important role in ITB formation. In particular, electron ITBs can be produced in the region of s<0 due to TEM suppression, according to TRB code simulations. The ion ITB formation in s<0 region occurs without effective flow shear stabilisation as shown by TRANSP [4] and JETTO [7] modelling. The Weiland [8], Rogister [11] models and TRB code simulations do not provide an explanation for such formation. ITB formation is observed in JET experiments, when qmin crosses integer numbers. The main features of ITB formation near low rational q observed in experiments are reproduced in TRB code simulation. A key factor is small $|s| \rightarrow 0$ in the vicinity of rational q. The bootstrap current may play a crucial role in a local reduction of s near an ITB. The Rogister model [11] predicts turbulence suppression in the vicinity of the s = 0 surface.

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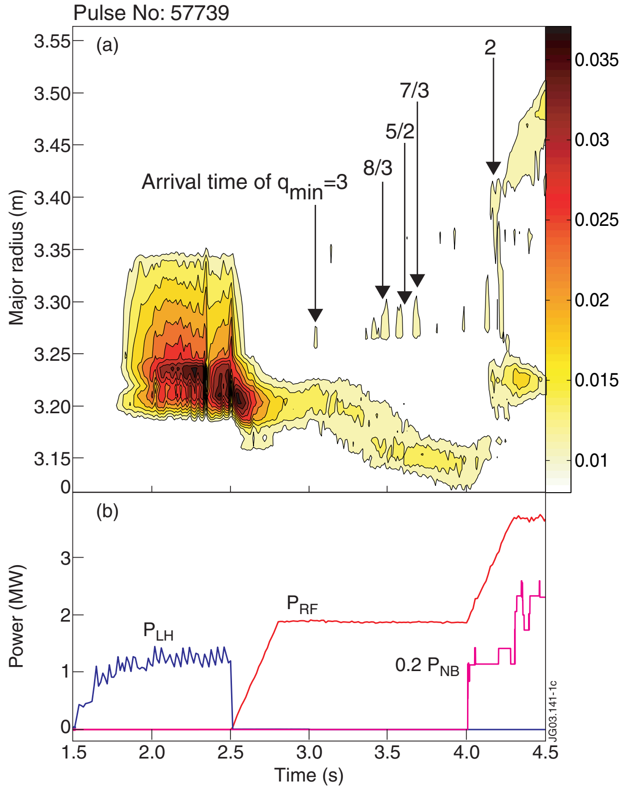

Figure 1.a) ρ^*_e contour plot and b) heating power waveform.

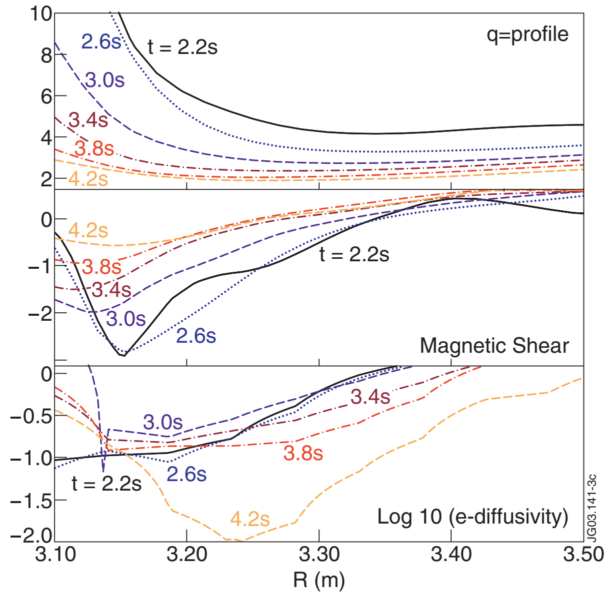

Figure 2. TRANSP modelling. Pulse No: 57739

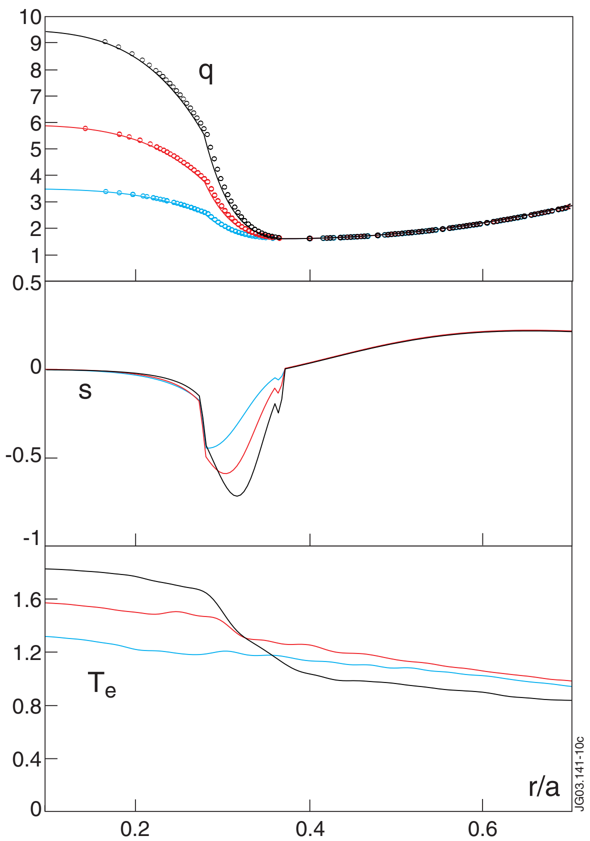

Figure 3. TRB simulations

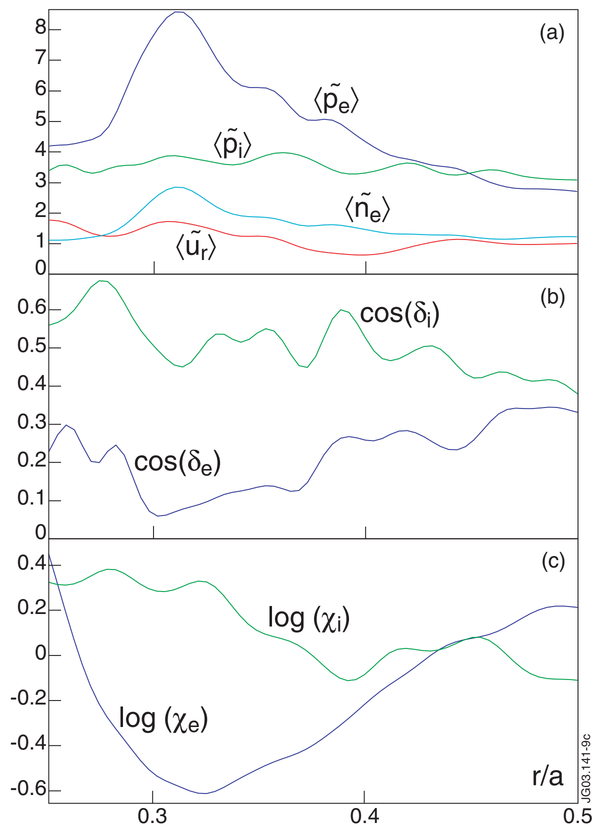

Figure 4. TRB simulations.

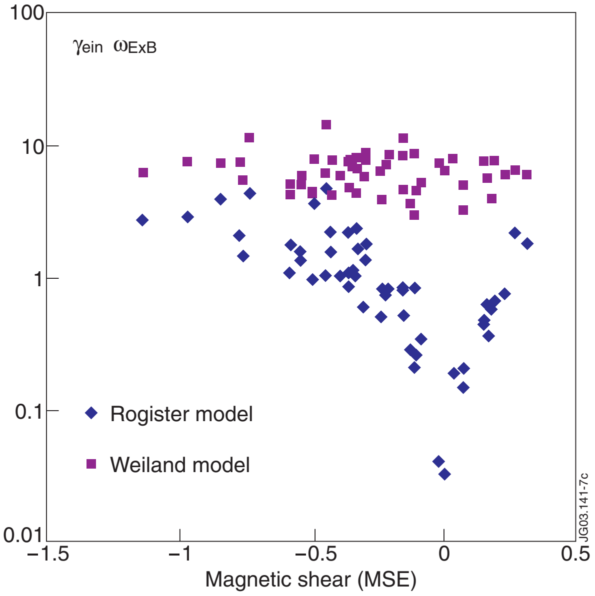

Figure 5. $\gamma_{lin}/\omega_{E\times B}$ versus s.

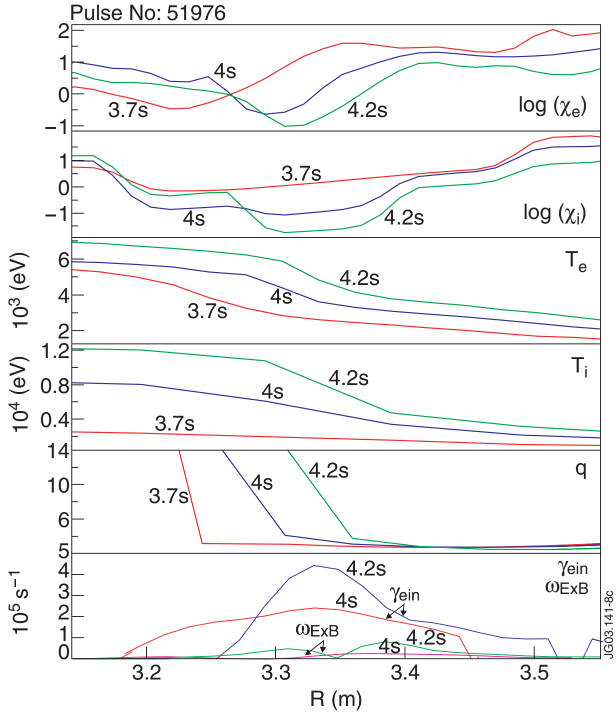

Figure 6. TRANSP modelling.

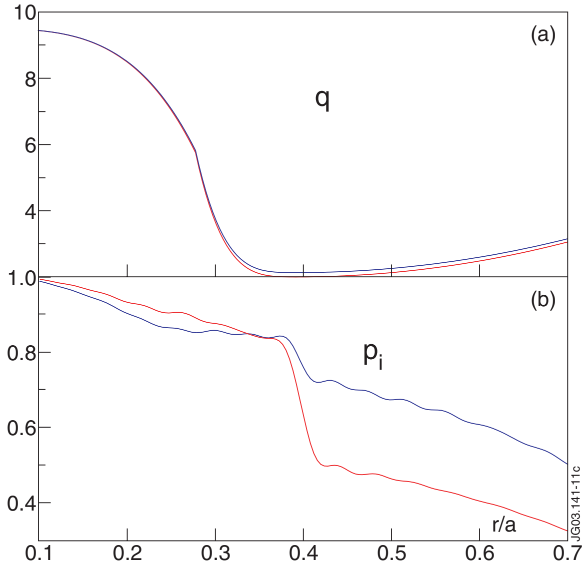

Figure 7. TRB simulations

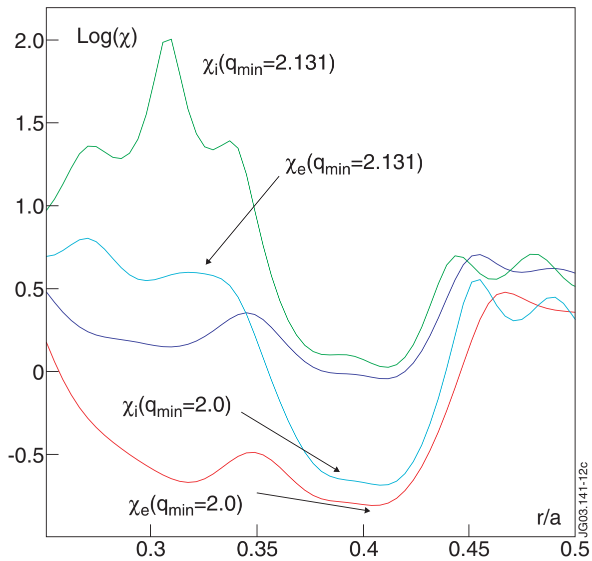

Figure.8 TRB simulations

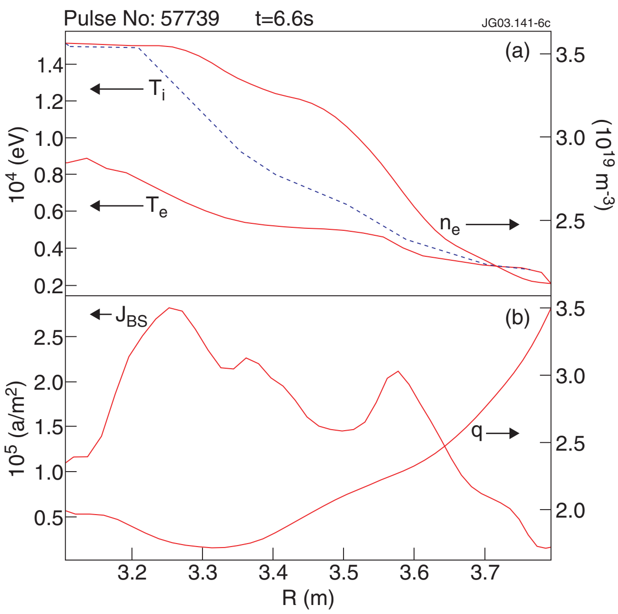

Figure 9. TRANSP modelling