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Transport and fluid turbulence simulations of JET pellet fuelled ITB plasmas

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**see annex of J. Pamela et al., "Overview of JET Results", Fusion Energy 2002 (Proc. 19th Int. Conf. Lyon 2002), IAEA, Vienna (2003)*

Introduction

One of the main issues about internal transport barriers (ITBs) and their relevance to a reactor scenario regards the possibility of creating and maintaining them at plasma densities close to the Greenwald limit. One of the main candidates to create and fuel high-density ITB plasmas is pellet injection. The question then arises as whether an ITB can survive the strong perturbation induced by the pellet and the fuelling of the interior of the ITB is possible without destroying the barrier itself. To investigate this subject, experiments were performed on JET where high-density ITB plasmas were created by means of combined use of lower hybrid current drive (LHCD) and pellet injection before the barrier formation. Attempts were then made to use pellets to fuel the plasma and sustain its density during the ITB phase. It was found that shallow pellets ablating within 15 cm from the plasma edge and far from the foot of the barrier (located at about 50 cm from the plasma edge) did not destroy the ITB, whereas deeper pellets with penetration length of 30-40 cm affected the barrier and led to its disappearance [1, 2, 3]. Modelling of these experimental scenarios has been performed with transport and fluid turbulence codes. The codes used in the analysis were: JETTO, a 1.5 dimensional transport code, TRB, a global electrostatic fluid turbulence code and CUTIE, a global electromagnetic fluid turbulence code. In this paper the results of the simulations are presented and the physics of the interaction between pellet and ITB is discussed.

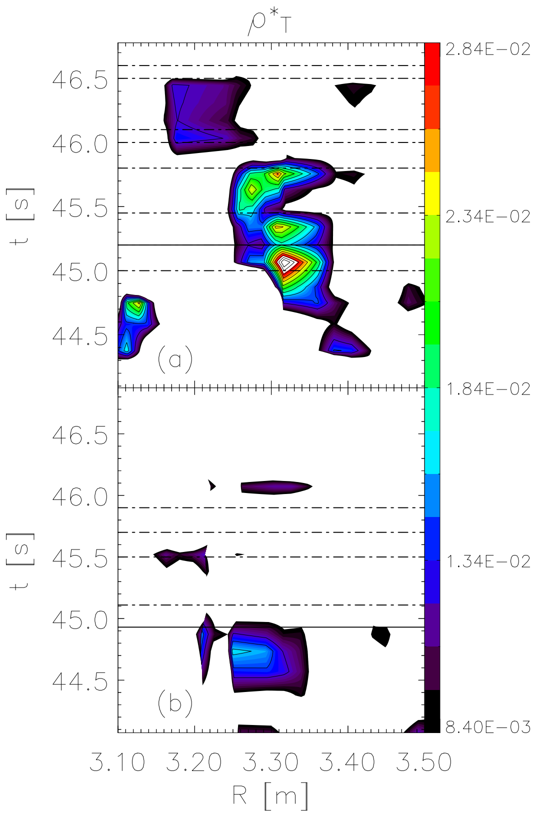


Figure 1: ρ^*_T *for shot 57941 (a) and 55861 (b). The horizontal lines mark pellet injection. The two solid lines indicate the pellets considered for the simulations presented in the paper.*

Experimental results

To establish high-density ITB plasmas on JET a LHCD prelude is applied at the beginning of the discharge to set up the hollow q profile necessary for the formation of the ITB. LHCD is then switched off and an ohmic or low NBI power gap of about 1 s is allowed to inject pellets and increase the plasma density. The main (NBI + ICRH) heating is finally applied to form the ITB and attempts were made to fuel the high performance phase with more pellets. Pellets in the main heating phase were fired both from the high field side (HFS) and vertical high field side (VHFS) locations. Pellet speed was either 80 or 160 m/s, pellet mass was about 1-2 10^{21} atoms and pellet frequency was 5 Hz. To investigate the pellet-barrier interaction we chose two typical discharges: 57941 with eight shallow pellets (mass 1-2 10^{21} atom and injection speed 80 m/s) injected between 45 s and 47 s from the VHFS track and 55861 with five HFS pellets (mass 1-2 10^{21} atom and injection speed 160 m/s) injected between 44.9 s and 46 s. For shot 57941 the pellet penetration depth was about 15 cm whereas for shot 55861 it was 30-40 cm. As can be seen from figure 1, showing the parameter $\rho^*_T=\rho_s/L_T$, usually adopted at JET to establish the presence of an ITB [4], the barrier survives for shot 57941 and is lost after the injection of the first pellet for shot 55861. This is typical of experiments of pellet injection in ITB plasmas at JET where the barrier can survive a shallow pellet, but is always destroyed when the pellet reaches the foot of the ITB.

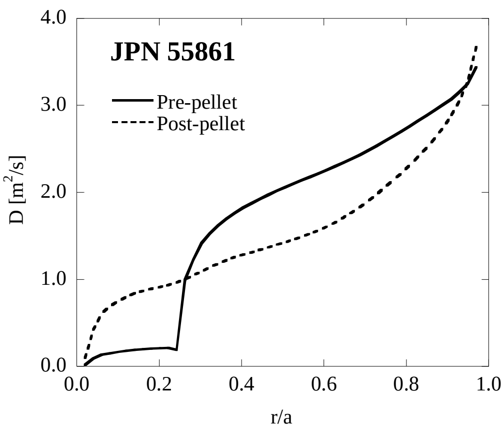
Simulation results

To perform the simulations one particular pellet was chosen for each shot. We considered the second pellet of the main heating phase injected at 45.20 s for shot 57941 and the first pellet of the main heating phase injected at 44.935 s for shot 55861.

JETTO

Fully predictive transport simulations have been performed with the JETTO code using the semi-empirical mixed Bohm/gyro-Bohm transport model [5]. To describe pellet injection, JETTO has been equipped with a module based on a neutral gas and plasma shield (NGPS) ablation model [6]. This module gives the pellet ablation profile and does not take into account the possible effect of a drift of the ablated material towards the low field side of the tokamak. However, at least for this kind of shots, this phenomenon seems to be negligible [2]. To simulate the barrier formation in JETTO, the particle and energy transport coefficients D and χ can be reduced according to a criterion which takes into account the magnetic shear s and the ratio $\omega_{E\times B}/\gamma_{ITG}$ between the shear of the E×B velocity and the growth rate of the ITG modes. Indeed, it has been observed on a statistical basis that in general a barrier is formed where the condition $z=-0.14+s-1.47\omega_{E\times B}/\gamma_{ITG}<0$ is satisfied [7]. Therefore the Bohm diffusion term in the mixed Bohm/gyro-Bohm transport model is multiplied by $\Theta(z)$, where Θ is the Heaviside step function. Since the scope of these simulations was to investigate the reaction of the barrier to the pellet injection we concentrate more on the simulation of the barrier dynamics than on the exact reproduction of the plasma density and temperature profiles.

The results of the simulation are shown in figure 2. We show D as given by the mixed Bohm/gyro-Bohm model before and after pellet injection for shot 55861. It can be seen that, in agreement with the experiment, D increases up to the Bohm level after pellet injection for the deep pellet shot. This is due to a reduction in $\omega_{E\times B}$ induced by a decrease of both density gradient and toroidal velocity when the density pulse reaches the foot of the ITB. On the other hand, in the shallow pellet case (shot 57941), the density pulse is too peripheral to modify the density gradient and the toroidal velocity near the foot of the barrier. Therefore the s-$\omega_{E\times B}/\gamma_{ITG}$ criterion is

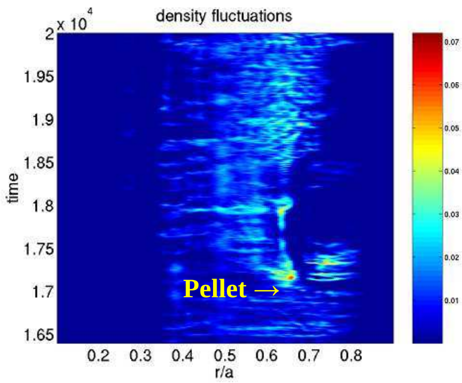


<u>Figure 2:</u> particle diffusion coefficient calculated by JETTO according to the mixed Bohm/gyro-Bohm model for shot 55861.

working and D and χ are suppressed during all the time interval considered. It is also worth noting that to simulate the density decay after pellet injection the diffusion coefficient has to be increased by a factor of about 3 in the zone interested by the pellet deposition. This is consistent with simulations of pellet injection in other experimental scenarios done with JETTO.

TRB

TRB is a full torus, electrostatic, fixed flux code solving fluid equations for ITG and TE modes. The equations considered are for electron density and pressure, vorticity, parallel ion velocity and ion pressure. The q profile is taken from the experiment and does not evolve during the simulation. All TRB runs are done with 256 radial mesh points, 70 poloidal and 10 toroidal harmonics (toroidal harmonics range between 4 and 40 with a spacing of 4, i. e. n= 4, 8, 12, …, 40). To simulate the pellet injection a source describing the pellet ablation is switched on. The shape of the source is gaussian. Centre and width are inferred from the interferometer profile and the duration of the time window during which the source is active is deduced from the duration of the H_α emission. For shot 57941 the source was located at 10 cm inside the separatrix and its width was estimated 10 cm. For shot 55861 the barycentre of the source was located at 30 cm inside the separatrix and the width was 25 cm. For both shots the duration is 4 ms and the intensity has been kept constant and equal to $5\cdot10^{23}$ atom/s corresponding to a total pellet particle inventory of $2\cdot10^{21}$ atoms. The simulations done for both shots show the formation of barriers both on density and on electron and ion temperature profiles. In both cases the ITB survives the pellet injection. This is in agreement with the experiment for the shallow pellet but not for the deep pellet shot. Figure 3 shows the propagation of the density pulse after pellet injection for shot 57941. It can be seen that the intensity of the density fluctuations increases, the turbulence burst propagates inward and stops at the foot of the ITB. An enhanced turbulent activity is in agreement with what is needed in JETTO to model the fast relaxation of the post pellet profile and may explain the fast propagation of the density pulse.



<u>Figure 3:</u> propagation of density fluctuations for shot 57941 (shallow pellet) given by TRB. The ITB foot is located at r/a≈0.4. Time is in units of a/c_s and the total duration of the simulation is 46 ms.

CUTIE

CUTIE is a global electromagnetic fluid turbulence code. It solves the evolution equations for the fluctuating electron density, electron and ion temperature, velocity, potential and magnetic field. CUTIE co-evolves the q-profile, density and temperature profiles self-consistently with the turbulence and calculates the zonal flows and dynamo currents taking account of specified external sources [8]. The particle and energy sources (in particular the pellet source) are implemented exactly as in TRB. All runs are done on a radial mesh of 100 points and using 64 poloidal and 16 toroidal harmonics. In order to highlight the effect of the pellet two CUTIE runs were performed for each shot, one with and the other without pellet injection. The main result of the simulations is shown in figure 4 where the evolution of the relative difference $(n_{e,pellet}-n_{e,no\ pellet})/n_{e,no\ pellet}$ between the density profiles in the two runs is shown. It its clearly seen that for shot 57941 the density pulse stops at the barrier and the barrier survives, whereas for shot 55861 the barrier is weakened by the pellet and the density pulse reaches the plasma centre, in good agreement with the experimental observation. The same is true for the cold pulse on the electron and ion temperature profiles. Apart from the

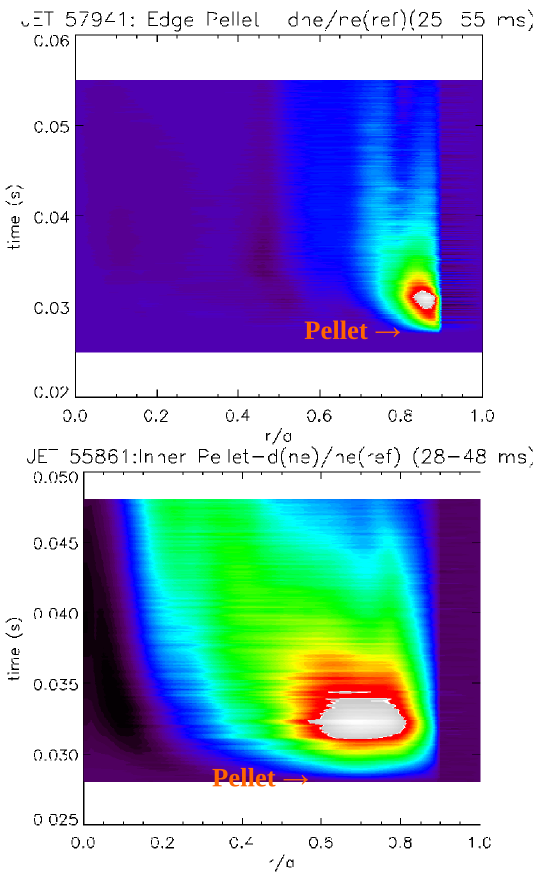


Figure 4: propagation of the density perturbation given by CUTIE for shot 57941 (shallow pellet, top frame) and 55861 (deep pellet, bottom frame).

pellet penetration length, the main difference between the two shots regards the behaviour of the zonal flows. In shot 57941 they are maintained in the barrier zone even after the pellet ablation, whereas they are strongly reduced in shot 55861. CUTIE simulations indicate therefore that the main reason for the barrier disappearance observed in association with deeper pellet injection is the damping of the zonal flows and the reduction of their stabilising effect on ITG turbulence in the barrier zone [9]. This is a first principle mechanism and it is different from the one at work in JETTO.

Conclusions

Experiments have been performed at JET to fuel by means of pellets high density ITB plasmas. It is seen experimentally that shallow pellets maintain the ITB but do not fuel the plasma core and deeper pellets produce a density pulse that reaches the plasma centre but destroys the ITB. Different simulation approaches have been attempted to analyse the dynamics of ITBs when pellet injection is performed. A transport code (JETTO) and two fluid turbulence codes (TRB and CUTIE) have been used. For the shallow pellet case all codes reproduce the general features of the experiment. For the deep pellet case, there are differences in the degree of agreement between the codes and the experiment. In particular JETTO seems to confirm the validity of the s-$\omega_{E\times B}/\gamma_{ITG}$ criterion. TRB simulates well the increased turbulence and associated diffusivity following pellet injection, but it is not able to reproduce the loss of the ITB observed in the case of deeper pellet injection. CUTIE simulates reasonably well most of the experimental features. In particular it shows that the reduction of the zonal flows after pellet injection can explain the different reaction of the barrier to the pellet and the loss of the ITB when penetration is too deep. The reasons for the difference between TRB and CUTIE results could be the different excitation and damping mechanisms of the zonal flows in the two codes and the different role they have in triggering and sustaining the ITB. This issue is still open at the moment and needs further investigation.

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