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Pellet Injection and High Density ITB Formation in JET Advanced Tokamak Plasmas

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ABSTRACT.
High density Internal Transport Barriers (ITB) with peaked density profiles have been produced at JET by optimising the pellet fuelling, heating power, current drive and plasma start-up. The scenario was developed with moderate momentum input and comparable ion and electron temperatures. Both features aim at matching the conditions envisaged for a burning plasma regime. Current and density profiles, which both appear to influence transport barrier formation, were independently controlled. The optimisation recipe included early Lower Hybrid Current Drive (LHCD) followed by an Ohmic or Neutral Beam heated pellet fuelling gap. The internal transport barrier was then formed at the start of a high power additionally heated phase. Typical plasmas were at a toroidal field of 3T and plasma current of 2MA, corresponding to a peripheral safety factor $q_{95} \approx 5$. Particle and energy transport were analysed by a 1.5 dimensional code including a pellet ablation module and a criterion for the barrier formation. Results of turbulence simulations with global electrostatic and electromagnetic fluid codes and a description of the observed magnetohydrodynamic instabilities are also reported.

1. INTRODUCTION
The injection of solid pellets of frozen fuel in a wide velocity range (50-3000m/s) has proven to be an efficient method for raising the density of Tokamak plasmas. The peaked density profiles thus obtained are often associated with improved core energy confinement, which has been observed on several machines (1-6). In general, the particle deposition due to the pellet injection has a combined effect both on the electron density and on the plasma current density profile. The latter is due to the sudden change of the plasma resistivity, due to the effect of the pellet fuelling on the electron temperature, and/or due to the neoclassical bootstrap current driven by steep pressure gradients [7]. In some cases the improved confinement has been due to the creation of a transient Internal Transport Barrier (ITB) of the kind being investigated for application to the so-called Advanced Tokamak (AT) regime [8-16]. These AT scenarios are especially studied for their potential of operating in steady-state. Due to the improved confinement with respect to the standard H-mode, an AT power plant would have the potential to operate at a reduced plasma current, which could be mostly driven by the bootstrap mechanism. Control of the density profile would be highly advantageous in such regimes as this strongly influences the bootstrap current drive. Additionally, it is important to demonstrate the possibility to fuel AT plasmas effectively and operate them at high density, i.e. at a large fraction of the Greenwald density [17].

In recent years the JET ITB regimes have typically been accessed using current profile control at low density. Experiments have been performed with the aim of raising the electron density, at the start of the main heating phase of such a regime, by gas fuelling [18], but these proved challenging due to the reduced plasma electron temperature, allowing the current density profile to relax more rapidly away from the optimum shape for stabilising turbulence. The use of pellet fuelling, on the other hand, can generate steep internal electron density gradients that can substantially contribute to the turbulence stabilization both reducing the instability growth rate and driving the off-axis bootstrap current that keeps the core magnetic shear small or negative [19, 20].
The injection of a series of frozen fuel pellets before the main heating phase, in the 100m/s velocity range, turned out to be an efficient tool for creating peaked density profiles in JET, even when penetration of the initial pellet was not very deep. It proved possible to maintain an optimised q-profile shape during this fuelling phase, thus allowing controlled investigation of the formation of ITBs in negative shear plasma at high density. This paper is based on the experimental data presented in various posters at the 30th EPS Conference on Controlled Fusion and Plasma Physics at St. Petersburg in 2003 [21-24] with the addition of more detailed data analysis, new code simulations and further physical interpretation. The paper is organised as follows: section 2 describes the experimental set-up including the machine configuration, the pellet injection system, the relevant diagnostics and the data analysis tools; section 3 illustrates the main macroscopic observations; transport analysis is discussed in section 4; magnetohydrodynamic (MHD) behaviour is briefly described in section 5 and conclusions are drawn in section 6.

2. EXPERIMENTAL SET-UP

In the reported campaigns, JET (http://www.jet.efda.org) was operated with an open divertor (MkII-SRP) obtained from the previous ‘Gas Box’ divertor (MkII-GB) after removal of the septum during the 2001 shutdown. In a typical discharge from the investigations discussed in this paper the D-shaped lower single-null plasma had a lower and upper triangularity of 0.25 and 0.15 respectively and strike points placed near the corners of the divertor target structure [Fig.1]. The on-axis toroidal magnetic field was $B_T \approx 3$T and the plasma current $I_p \approx 2$MA corresponding to an edge safety factor of about $q_{95} \approx 5$. Neutral Beam Injection (NBI), Ion Cyclotron Resonant Heating (ICRH) and Lower Hybrid Current Drive (LHCD) were used in addition to the basic Ohmic input power. The Neutral beams were injected in the same direction as the plasma current (co-injection) at voltages typically in the range 80-130kV and power levels up to about 9MW. About 6 MW of ICRH power in fundamental hydrogen minority mode were also applied during the main heating phase while 2MW of LHCD were applied during the current ramp up.

Deuterium pellets were delivered by a centrifuge injector capable of working at a maximum repetition rate of 10Hz in the velocity range of 80-600 m/s. Pellets had a cubical shape with a linear dimension of about 4mm corresponding to a content of the order of $4 \times 10^{21}$ atoms: such a size could be reduced to one half when lower fuelling or penetration was required. The pellet velocity was derived from the centrifuge rotation frequency which was fixed in each shot. Pellets were detected at the centrifuge output by a microwave cavity whose output signal was proportional to their mass. The number of particles actually injected into the plasma and the resultant deposition profile were estimated from the electron density profile modification observed on a timescale much shorter than typical particle confinement time. For this purpose, measurement from the eight chord interferometer, employing a deuterium cyanide Laser (DCN, $\lambda=195\mu m$), and those from the LIDAR Thomson scattering system were used. The former was used to yield a profile every 5ms by inversion of the line integral data,
after the correction of fringe jumps caused by pellet injection. This was obtained by a cross-check with the LIDAR profiles, consisting of 50 points along a horizontal chord taken at 4Hz repetition rate, which allowed a recalibration of the DCN data whenever a LIDAR pulse was present between two successive pellets. It was estimated that the local density obtained by this inversion method, was affected by an error of +/- 25%. The electron temperature was measured by the LIDAR and by the ECE radiometer: the latter was often affected by cut-off problems immediately after pellet injection making it unavailable in the very high density phases. Plasma rotation was estimated from Carbon rotation velocities measured by Charge Exchange Spectroscopy (CXS). Three different injection trajectories were available (Fig.1): one from the Low Field Side (LFS) crossing the plasma horizontally below the midplane at a normalized impact parameter \( r_{\text{imp}}/a = 0.2-0.3 \) and another one from the High Field Side (HFS) with \( r_{\text{imp}}/a = 0.6-0.7 \) at 44° with respect to the midplane. The third one had a high field side top-down vertical path (VHFS) with \( r_{\text{imp}}/a = 0.3-0.4 \) and an inclination of 74°.

It is well known that low or negative magnetic shear can be advantageous for the formation of ITBs in tokamak plasmas [8-16]. This is routinely achieved in JET by applying the LHCD early in the discharge to provide off-axis non-inductive current and high core electron temperature, both of which impede current diffusion towards the plasma centre. The same technique was used in pellet experiments although, in this case, the LHCD pulse was terminated about one second before the beginning of the main heating phase in order to allow effective pellet pre-fuelling. This avoided excessive ablation of the pellet mass by the LHCD driven fast electrons before the pellet could penetrate beyond the plasma edge. The pellet ‘gap’ (i.e. the time interval between the end of the LH prelude and the beginning of the main heating phase) was either Ohmic or additionally heated with a moderate amount of NBI power (≈4MW). The latter option provided extra fuelling and, by raising the electron temperature, helped to delay the current penetration. As a result the current density profile remained hollow during NB gaps even after the injection of several pellets, as will be shown later. In the way outlined above, many different combinations of current density and electron density profiles were produced, thus demonstrating a significant progress with respect to the former Pellet Enhanced Performance (PEP) scenario at JET [7, 25] where the two features could not be independently controlled. Such a technique, which has not been fully exploited yet, is potentially useful for investigating the separate roles of the magnetic shear and density gradient in barrier formation. All the available pellet tracks were used although not yet in a systematic way. In the experiments tested so far the particle deposition was in reasonable agreement with ablation code predictions [24].

During the main heating phase, comparable amounts of NBI and ICRH power were injected into the plasma in order to produce similar ion and electron temperatures, as envisaged for burning plasma devices. Pellet injection was also performed during this phase, after the ITB had been formed. In an initial experiment, it was found that shallow pellets were able to refuel the plasma edge while, in the experiments performed so far, pellets capable of deeper penetration tended to
destroy the internal barrier. It should be noted that deep injection coincided with weak barriers in the present database. Further investigation will be needed to establish whether more robust ITBs can survive core pellet fuelling.

3. MACROSCOPIC OBSERVATIONS

The formation of an ITB is usually identified by the divergence of temperature time traces corresponding to fixed adjacent major radii (Fig.2, Top). This is the most direct evidence for the local increase in the temperature gradient usually associated with the suppression of anomalous transport processes. A more objective criterion was proposed for detecting such an event on JET [26]. According to this criterion, an internal transport barrier is formed when the condition $\rho T^* > 0.014$ is met, $\rho T^*$ being the ion Larmor radius (evaluated at the ion sound velocity) normalized to the electron temperature profile scale length $L_T = d/dr(lnT)$ (see Fig.2, Bottom). All the ingredients described in the previous section were essential to trigger an ITB in this high density, moderate NBI power scenario. The LHCD was required to prepare the non-monotonic q-profile and pellets were used to create steep density gradients. Figure 3 shows a direct comparison of three shots with a similar main heating phase. Only the discharge having both LHCD during the early phase and pellets during the ‘gap’ (Pulse No: 55860) developed an internal barrier. This is clearly demonstrated by the larger amount of neutrons due to the enhanced core pressure and the higher $\rho T^*$ value. In the other two discharges either the LHCD pulse was missing (Pulse No: 55891) or the pellets were omitted (Pulse No: 55875). This suggests a possible synergy, in triggering the barrier, between the magnetic shear, kept low or negative by LHCD, and the density gradient, made steeper by the pellet injection.

As anticipated in the previous section, several different combinations of the electron density and q-profile were produced. The q-profile was varied using LHCD prelude and the duration or heating method during the pellet ‘gap’, while the density profile was influenced by the pellet series. Figure 4 shows some of these profiles at the start of the main heating phase following different LHCD and ‘gap’ sequences. Figure 5 shows main waveforms of Pulse No: 57941, which forms an ITB with $T_e \approx T_i$ and core density close to the Greenwald density. Electron density and temperature profiles, measured during the ITB phase, are plotted in figure 6. At the end of the early LHCD pulse, the q-profile was strongly reversed with a current hole at the magnetic axis, as clearly shown by the EFIT equilibrium reconstruction constrained by the MSE measurements (Fig.7). The shear reversal in this case, although partially smoothed out, survived the injection of 2 pellets during the ‘gap’. The pre-fuelling ‘gap’ was, in this case, heated with 4MW of NBI power. Pellets were injected at 5Hz repetition rate with a velocity of 80m/s and a typical particle content of $1-2 \times 10^{21}$ D atoms. Initially, during the ‘gap’, the HFS track was used and then, at the start of the main heating phase, pellets were diverted along the new VHFS trajectory.

Pulse No: 55860 is an example of an Ohmic pellet ‘gap’, in which pellets with same mass and frequency as above were injected at 160m/s from the LFS during the ‘gap’ and then switched to the HFS track when the main heating started. Waveforms and profiles are shown in figures 8 and 9. The
MSE data were not collected in this pulse before the end of the ‘gap’ as this diagnostic relies on the NBI to make its measurement. However, the q-profile generated by the early application of LHCD in this plasma configuration is reproducible in JET and it is reasonable to assume that it was similar to that of Pulse No: 57941. At the end of the pellet ‘gap’ in Pulse No: 55860 the magnetic shear was low and perhaps slightly negative in the core (Fig.4), in contrast to the strongly negative shear in Pulse No: 57941. This different evolution was related to the different temperature in the Ohmic and NBI ‘gaps’, which affected the current diffusion times. A comparison of the expected difference in the q-profile evolution during the ‘gap’ for the cases of Ohmic and NBI heating has been made using the JETTO heating and transport simulation code [27]. The results, shown in Fig.10, are in qualitative agreement with the observed difference. In both cases the internal barriers lasted more than one second and ended as the current progressively diffused towards the plasma centre and the density profile flattened due to the lack of deep pellet fuelling during the main heating phase. Figure 11 illustrates such an evolution in terms of increasing internal inductance and decreasing density peaking factor for Pulse No: 57941. A similar behaviour was observed in Pulse No: 55860. It is also interesting to note the impurity behaviour during this type of discharges. The effective charge, measured using charge-exchange spectroscopy and therefore representative of the contribution from carbon impurities, was seen to increase while the ITB was being formed, but then to decrease as the barrier evolved (Fig.12).

4. TRANSPORT ANALYSIS

The main tool employed to analyse pellet ITB discharges, was the JETTO 1.5 dimensional transport code, run in both fully predictive and interpretative modes. In predictive simulations the semi-empirical mixed Bohm/gyro-Bohm transport model was used [28]. To analyse the experiments described above JETTO had also been equipped with a pellet injection module based on a Neutral Gas and Plasma Shield (NGPS) ablation model [29] and with a criterion to trigger the formation of an ITB. This criterion takes into account the stabilising effect of both the magnetic shear and of the $E \times B$ velocity shear on the Ion Temperature Gradient [ITG] driven modes [30].

4.1. PELLET ABLATION AND PARTICLE TRANSPORT DURING THE PRE-FUELLING ‘GAP’

The transport study was conducted separately for the pellet ‘gap’ and for the main heating phase. The first issue addressed was the characterisation of the pellet particle deposition profile. In particular the analysis was used to establish whether there was a fast $\nabla B$-drift of the pellet cloud (plasmoid) affecting the ablation profile, as has been reported for ASDEX Upgrade [31], and whether the Low Field Side (LFS) and High Field Side (HFS, VHFS) injection produced different effects. Secondly, the density profile evolution was analysed on a slower timescale (~100ms) to study the transport mechanisms leading to the observed peaking of the density profile. Finally, the role of the LHCD prelude and its effect on the subsequent current distribution was addressed.

The effective pellet deposition profile was determined by the modification of the electron density
profile following the injection of a single pellet. Using both the Interferometer and the LIDAR signals, as described in section 2, it was possible to obtain the density perturbation with a time resolution of 5-10ms, which was short compared with typical transport timescales. Such an experimental deposition profile was then compared with the ablation profile given by the NGPS module installed in the JETTO code. The results show that the deposition profile was wider than the expected ablation profile but the radial location of their peaks was the same (Fig.13). This indicates that the radial diffusion of the pellet particles was fast and that no significant radial drift was present. Similar results were obtained for HFS injection. It was then concluded that, in these discharges, the NB-drift did not play a significant role in the effective particle deposition.

The density profile evolution on a longer time scale is shown in figure 14. The ablated material, which was initially deposited in the periphery, diffused towards the centre eventually producing a rather peaked density profile. It is estimated that, in a similar ITER discharge, assuming a cubic temperature profile with $T_{e0} = 10\text{keV}$ ($T_{ped} = 1.5\text{keV}$) and a flat target density profile with $<n> = 10^{20} \text{m}^{-3}$, a pellet of 3.5km/s and $10^{23}$ atoms would produce a similar effect on the density. The transport analysis showed that the profile evolution was compatible with a Bohm/gyro-Bohm particle diffusion coefficient ($D_{BgB}$) plus a pinch velocity of the form $V = -c_q D_{BgB} \nabla q/q$ with $c_q = 0.75-1.0$.

It was necessary to enhance the diffusion coefficient by a factor of 3-4 in the ablation region during the pellet transient in order to explain the observed fast particle redistribution. Figure 15 shows the results of such an analysis during an Ohmic pellet ‘gap’. The electron density profiles at different times (top box) were simulated with an analytical expression for the particle diffusivity ($D_{\text{analytical}}$) and pinch velocity ($V_{\text{analytical}}$) previously deduced from an interpretative analysis of the experimental data [24]. As shown in figure 15 (bottom box) both $D_{\text{analytical}}$ and the $V_{\text{analytical}}$ were close to the values given by the mixed Bohm-gyro-Bohm transport model. Similar results were found in a ‘gap’ heated with a moderate amount of NBI (4MW). This picture is consistent with observations previously made in pellet fuelled L-mode plasmas [32]. However, it is worth noting that the necessity to increase the diffusivity in order to simulate the transient following the pellet injection might indicate that the assumption that $D$ depends only on the normalised minor radius ($r$) is too simplistic and that other dependencies (for example on $\nabla n$) may also play a role. The above transport model was able to simulate situations with LFS and HFS injection, with and without an LHCD prelude. This indicates that, before the barrier is formed, particle transport properties were insensitive to the injection geometry and the current profile evolution during the initial phase of the discharge. On the other hand the discharge without LHCD prelude did not form an ITB during the following main heating phase. In this case the $q$-profile was monotonic at the beginning of the main heating phase, compared with low or weakly negative magnetic shear when the LHCD prelude was included. This suggests that magnetic shear may have played a role in the suppression of anomalous heat transport during the main heating phase, but did not significantly affect the particle transport through the $\nabla q/q$ particle pinch velocity during the pellet injection ‘gap’. 
4.2 PARTICLE AND ENERGY TRANSPORT DURING THE MAIN HEATING PHASE

As noted above, a criterion to simulate the barrier formation was introduced in JETTO, which took into account the magnetic shear \( s \) and the ratio \( \omega_{E\times B/ITG} \) between the shear of the \( E\times B \) velocity and the growth rate of the ITG modes. It had already been observed on a statistical basis that in general a barrier was formed in JET when the condition \( z = -0.14 + s - 1.47 \omega_{E\times B/ITG} < 0 \) was satisfied [30]. Therefore the Bohm particle and thermal diffusion term in the mixed Bohm/gyro-Bohm transport model was multiplied by \( q(z) \), where \( q \) is the Heaviside step function.

A typical result of the energy transport analysis is shown in figure 16. The experimental and simulated density and temperature profiles are plotted together with the corresponding diffusivities, derived both from the experimental data and from the Bohm/gyro-Bohm model. For the ions, the predicted neoclassical value is also illustrated. It can be seen that the experimental diffusivity profiles, i.e. those given by the power and particle balance equations, are reasonably well reproduced by the model, especially with regard to the level of transport inside the barrier and at the location of the ‘foot’, or outer edge, of the barrier region (Fig.16).

Regarding pellet injection during the main heating phase, after the ITB had been formed, it was experimentally observed that a strong ITB (i.e. with \( \rho_T^* > 0.014 \)) could survive the perturbation induced by relatively slow pellets (80m/s), whereas weak ITBs were destroyed by faster pellets (160m/s) (Fig.17). Simulations showed, in the latter case, that the density gradient and the toroidal rotation were substantially reduced in the barrier region thus provoking a decrease of the stabilising \( w_{E\times B} \) term. As a consequence the ITB criterion was no longer satisfied and the transport was returned to the Bohm/gyro-Bohm level (see also Fig.17). This might explain the observed collapse of the barrier. Unfortunately, shots with a ‘strong’ barrier and fast pellets are not present in the experimental database, and so the possibility of a robust barrier surviving core pellet fuelling has not yet been assessed. A simulation of the injection of faster pellets into the ‘strong’ ITB case mentioned above, predicts the survival of the barrier, stressing the value of performing further experiments to clarify this point.

Significant edge fuelling was achieved in those shots with shallow pellets that neither reached nor destroyed the barrier (Fig.18). This is also an interesting result demonstrating the possibility of increasing the edge density of ITB plasmas according to plasma-wall interaction requirements in next step devices [33].

5. TURBULENCE

In addition to the JETTO transport simulations, other simulation approaches were used to analyse the dynamics of the ITBs observed during the pellet injection experiments [34]. In particular two fluid turbulence codes were employed: TRB [35] and CUTIE [36]. TRB is a full torus electrostatic fixed-flux code solving the fluid equations for ITG and Trapped Electron Modes (TEM). CUTIE is a global electromagnetic fluid turbulence code which self consistently solves the evolution equations for the densities, temperatures, velocities and magnetic fields. In both codes pellet injection was simulated as a Gaussian particle source switched on instantly at the injection time. For the case of shallow pellet
injection \((v_p = 80\text{m/s})\) in the presence of an ITB both codes reproduced the general features of the experiment. For the deep pellet injection case \((v_p = 160\text{m/s})\) there were differences in the level of agreement between each code and the experiment. TRB simulated well the increased turbulence and the associated diffusivity following pellet injection, but was not able to reproduce the loss of the ITB observed in the case of deeper pellet injection. CUTIE, on the other hand, simulated reasonably well both of these experimental features. In particular it showed that the reduction of the zonal flows and their shearing rate after pellet injection could explain the different response of the barrier to the pellet deposition profile and the loss of the ITB when pellet injection was deep. The difference between the TRB and CUTIE results could be due to 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. More details about this item can be found in ref. 34.

6. MHD ACTIVITY AND PLASMA ROTATION

Observations of MHD instabilities confirmed the presence in these discharges of non-monotonic q-profiles [23]. Upward frequency sweeping Alfvén Cascade modes [37], which indicate the presence of negative magnetic shear, appeared as soon as ICRH heating was applied producing the fast particles which drive these modes. A multiple frequency spectrum called Grand Cascade, indicating the simultaneous destabilisation of different toroidal mode numbers, was observed when the minimum q-value crossed integer values of 3 and 2. A growing low frequency \(n = 1\) mode activity was observed during the main heating phase following the arrival of a \(q = 3\) magnetic surface in the plasma. Cross correlation of magnetic probe signals displaced in the poloidal and toroidal directions indicated a mode number \(m/n = 3/1\), confirming the link with the \(q = 3\) surface. The analysis of the electron temperature profile, determined from ECE emission, identified these modes as magnetic islands. Double tearing magnetic islands with poloidal/toroidal wave number \(m/n = 3/1\) formed around the \(q = 3\) surface and rotated at a frequency of a few kHz, much smaller than the typical 10-20kHz observed in other ITB discharges heated by a similar amount of NBI power \(P_{NBI} = 8-10\text{MW}\). When the ratio \(P_{NBI}/n_e\) was high, these modes tended to decouple, leaving higher order modes which were eventually stabilised. Decoupling was more difficult at high density and mode locking could be observed with the consequent growth of the island width. Larger amounts of NBI power \((\sim 13\text{MW})\) enabled the decoupling to be achieved and reduced the mode amplitude (Fig.19).

Hollow toroidal rotation profiles were observed at the beginning of the main heating pulse when tearing modes were coupled. At lower density, when modes were decoupled, the rotation profile became peaked. However the toroidal rotational shear, at the start of ITB formation, was significantly smaller than in typical ITB experiments without pellet injection (Fig.20). Since the rotational shear is thought to play a role in the suppression of anomalous transport, this might indicate that, in the barrier formation phase, the density peaking acted to compensate for the reduced toroidal flow shear.
CONCLUSION
Internal transport barriers with core density close to the Greenwald density and $T_e \sim T_i$ have been formed at JET using pellet fuelling. In these pulses, the toroidal rotation was low due to the high density and the moderate neutral beam power used. This feature is relevant to the requirements of burning plasma devices, such as ITER. Both the low or negative magnetic shear obtained by LHCD prelude and the steep density gradients produced by pellet injection were needed to access this regime. The new scenario represents significant progress with respect to the former PEP regime, as it allows the independent control of the current density and electron density profiles, opening the possibility to gain a better understanding of the underlying physics of internal transport barriers. Attempts to re-fuel the plasma during the main, high power heating phase showed that barriers could survive if shallow pellets were injected. Clear edge fuelling was observed in these cases, showing the possibility to modify the edge density to satisfy first wall power load requirements. The MHD analysis confirmed the existence of hollow current density profiles when the internal barrier was triggered. The observed pellet ablation and particle deposition was in agreement with a standard NGPS pellet ablation code. Particle and energy transport was consistent with a Bohm-gyro/Bohm model with an anomalous particle pinch being responsible for the density peaking. The appearance of the internal transport barrier was modelled satisfactorily using a criterion for the suppression of the Bohm term based on a combination of the magnetic shear and/or the ExB rotational shear. The viability of core re-fuelling, once the ITB is fully established, remains an important issue that could be addressed by further experiments, perhaps using deep pellet fuelling.

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Figure 1: a) Poloidal cross section of JET magnetic surfaces (Pulse No: 57941 t=4.6s) with pellet injection lines b) Divertor region c) Divertor components

Figure 2: Pulse No:55860 barrier formation following pellet injection. Top: time evolution of the electron temperature at various radii. Bottom: evolution of constant $\rho_T^*$ contours.
Figure 3: Left: barrier formation ($\rho_T > 0.014$) in Pulse No:55860 where both LH preheat and pellets were present. Comparison with two similar shots missing either LH (Pulse No: 55891) or pellets (Pulse No:55875). $N_e$ is the central line integrated density and $T_e$ is the central electron temperature. Right: heating power waveforms.

Figure 4: Different $q$ (top) and $n$ (bottom) profiles at the end of the pellet gap (Equilib.+MSE, Lidar). Pulse No’s:55860 (LH+Ohmic gap+ Pellets), 57942 (LH + NBI Gap + Pellets), 55875 (LH only), 55891 (Pellets only).

Figure 5: Typical waveforms of an ITB pellet fuelled scenario (Pulse No: 57941, top: line integrated densities from interferometer, bottom: heating powers). Pre fuelling pellets are injected during a NBI heated gap between the LH pulse and the main heating phase starting at $t=4$ s. In this shot, pellets were also injected during the main heating phase.
Figure 6: Density and temperature profiles during the ITB (Pulse No: 57941). The core density is at the Greenwald density limit ($0.6 \times 10^{20} \text{m}^{-3}$) and the electron and ion temperatures are close to each other. KK3: ECE radiometer. CXFM: charge exchange spectroscopy.

Figure 7: $q$-profiles at the beginning of the pellet gap (solid line) and 0.7 s later (dashed line). Pulse No: 57941 with NBI Gap (Equilib+MSE).

Figure 8: Main waveforms of a pellet fuelled ITB with an Ohmic pellet gap (Pulse No: 55860, top: line integrated densities from interferometer, bottom: heating powers).

Figure 9: $T_e$, $T_i$, $n_e$ profiles during ITB for Pulse No: 55860 (Ohmic pellet gap; $t=4.65s$).
Figure 10: Direct comparison of the q-profile evolution during an Ohmic (dashed) and a NBI (solid) pellet Gap. (JETTO simulation).

Figure 11: Top: Li from equilibrium only (EFIT) and constrained by MSE data (EFTM). Bottom: density peaking factor $N_{eo}/<N>_{vol}$ from the Lidar. (Pulse No: 57941).
Figure 12. Top: $Z_{\text{eff}}$ profiles taken at the start of the barrier. Bottom: time evolution of average $Z_{\text{eff}}$. Horizontal lines indicate the barrier duration, vertical dashed ones indicate times at which the profiles have been taken. The data are from charge exchange spectroscopy and the main contributing species is carbon.

Figure 13. Comparison of ablation code prediction and particle deposition for Pulse No: 55849: LFS injection at 160m/s during an Ohmic gap.

Figure 14: Density profile evolution after pellet injection during a NBI heated (left) and an Ohmic (right) gap. Deposited particles diffuse to the centre on a timescale of 100-200ms. (Interferometer inverted data).
Figure 15: simulated density evolution during the Ohmic gap of Pulse No: 55850 (from 3.13s to 3.88s). Pellets are injected at 3.19s, 3.40s and 3.61s. The calculated density profiles are compared, at different times, with the interferometer measurements (Top). The analytical $D$ and $V$ used in the simulation are compared with the prediction of the mixed Bohm/gyro-Bohm model enhanced by a factor of 3-4 in the pellet perturbed region (Bottom). (ref 14).

Figure 16: Density and temperature profiles and related transport coefficients during the barrier (Pulse No: 57941). From experimental data (dashed) and Bohm/gyro-Bohm simulation (solid). The ion neoclassical conductivity is also shown for comparison in the bottom right frame.
Figure 17: Pellet injection on a formed barrier: \( \rho^* T \) contour plot. Top: Pulse No: 55861, weak barrier, deep pellets. Bottom: Pulse No: 57941, strong barrier, shallow pellets. The vertical lines mark the pellet times.

Figure 18: Control of the edge density during the main heating phase. \( H_n \) measurement and NGS code simulation indicate pellet ablation peak at \( R=3.62 \)m and \( R=3.73 \)m respectively (Pulse No: 57942).
Figure 19: MHD behaviour in the $n_e/P_{NBI}$ domain. Red: coupled modes. Blue: others (ref. 13).

Figure 20: Density profiles (Lidar) and Toroidal rotation frequency (CXS) for a pellet ITB (Pulse No: 55860) as compared to conventional ITBs (Pulse Nos: 51573 and 51619). Profiles are taken at the beginning of the ITB formation.