EUROPEAN FUSION DEVELOPMENT AGREEMENT

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Development on JET of Advanced Tokamak Operations for ITER

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ABSTRACT.

Recent research on Advanced Tokamak in JET has focused on scenarii with both monotonic and reversed shear q profiles having plasma parameters as relevant as possible for extrapolation to ITER. Wide ITBs, R ~ 3.7m, are formed at ITER relevant triangularity $\delta \sim 0.45$, with $n_e/n_G \sim 60\%$ and ELMs moderated by Ne injection. At higher current ($I_P \leq 3.5$MA, $\delta \sim 0.25$) wide ITBs sitting at $R \geq 3.5$m (positive shear region) have been developed, generally MHD events terminate these barrier otherwise limited in strength by power availability. ITBs with core density close to Greenwald value are obtained with plasma target preformed by opportune timing of LHCD, pellet injection and small amount of NBI power. ITB start with toroidal rotation 4 times lower than the standard NBI heated ITBs. Full CD is achieved in reversed shear ITBs at 3T/1.8MA, by using 10MW NBI, 5MW ICRH and 3MW LH. Wide ITBs located at R=3.6m, without impurity accumulation and type-III ELMs edge can be sustained for a time close to neo-classical resistive time. These discharges have been extended to the maximum duration allowed by subsystems (20s) with the JET record of injected energy: E ~ 330 MJ. Integrated control of pressure and current profiles is an essential feature used in these discharges. Central ICRF mode conversion electron heating, added to about 14MW NBI power, produced impressive ITBs with equivalent $Q_{DT} \sim 0.25$. Conversely ion ITBs are obtained with low torque injection, by ICRH ^{3}He minority heating of ions, on pure LHCD electron ITBs. Similarity experiments between JET and AUG have compared the dynamics of ITBs and have been the starting point of Hybrid Scenarios activity, then developed at ρ^* as low as $\rho^* \sim 3\times10^{-3}$. The development of hybrid regime with dominant electron heating has also started. Injection of trace of tritium and a mixture of Ar/Ne allowed studying fuel and impurities transport in many of the explored AT scenarios.

1. INTRODUCTION

JET programme is designed accordingly to priorities focused on ITER requirements. A large fraction of the experimental activity is devoted to study and develop Advanced Tokamak (AT) scenarios suitable for ITER operations. JET plays a key role in developing these regimes as, with its size and shape, it bridges the gap in parameters space between smaller experiments and ITER, thus providing a sounder basis for extrapolation. Since last IAEA the AT research at JET [1] has widened from Internal Transport Barrier (ITB), characterised by reversed magnetic shear profiles and more suitable for real steady state operation, to the so-called Hybrid regime with monotonic/flat q profiles thought to be a good candidate for high fluence long burn operation on ITER. Given the present power availability, JET AT strategy has been oriented to: i) development of scenarios with ITER relevant $\rho^*-\nu^*-\delta$, including scenarios with $T_e \sim T_i$ and low momentum input, ii) maximisation of JET contribution to AT database through dedicated similarity experiments, iii) integration of core-edge solutions to obtain wide barriers and increase performances, iv) Real Time Control (RTC) techniques. The latter has become a routine tool in AT experiments on JET since the first successful control of plasma current profile achieved using as actuator the Lower Hybrid Current Drive (LHCD) firstly in the low density prelude phase of the discharge then on the high power phase [2]. More recently a simultaneous control of plasma current and electron temperature profile has been achieved in ITB plasmas. Acting with LHCD, NBI, ICRH, the RTC has successfully reached both monotonic and reversed target q-profiles. At same time different ITB strengths and positions have been obtained controlling control the normalised electron temperature gradient. Detailed results on RTC at jet will be found in EX/P2-5. It is worth noting that RTC of q profile in the high power phase of the discharge is possible thanks to progress achieved in coupling LH waves in severe edge conditions [4, EX/P4-28]. Here we will report in the following section 2 an overview of the results obtained in different JET-ITB scenarios, while in section 3 a summary of fuel/impurity transport in the different scenarios will be reported.

2. AT SCENARIOS AT JET

Future experiments with 50%D-50%T would require plasmas with high fusion power, in particular for α particle studies, and duration longer than the α particle slowing down time [3]. This motivates the development of ‘steady-state’ ITB plasmas on JET with high magnetic field (BT) and plasma current (IP), to favour a high neutron yield. Additionally, a necessary condition for high fusion performance is to obtain an ITB at large radius (r/a >0.6), to maximise the volume confining the particles and energy, and to improve stability. Furthermore the scenario needs to be exported at ITER triangularity. Given the present power and operational constraints the different aspects have been addressed separately.

2.1. DEVELOPMENT OF ITBS AT HIGH TRIANGULARITY

Integrated optimisation of core and edge conditions has been key to the progress in the high triangularity scenario. ELM free or type I edge conditions are more favoured in high triangularity, this has been the limiting factor of ITB durations in past JET experiments [4]. Edge MHD activity mitigation by injection of D or light impurities allows triggering narrow core ITBs in deeply reversed current profile discharges ($q_{min} = 3$) that do not survive Hmode transition. Very wide ITBs (confining with edge pedestal as shown in fig.1) have been obtained at $\alpha \sim 0.45$ ($B_T = 3.45T$, $I_P = 1.5MA$). These barriers survive the H transition if total injected power is in excess of ~20MW and edge is moderate by Ne injection. These discharge have $H_{89}\beta_N$ ~ 3.5, linear averaged density around 60% of Greenwald value, last for ~10£nE and are only limited by the power pulse duration, results shown in EX/P3-11.

2.2. DEVELOPMENT OF ITBS IN HIGH CURRENT PLASMAS

Development of wide ITBs at high current ($I_P \leq 3.5MA$, $B_T = 3.4T$) has started from negative magnetic shear targets to allow triggering the barriers in the region of low magnetic shear at large radius. In the selected scenario, ITBs are triggered at relatively large radius (r/a > 0.5) when the minimum safety factor (qmin) reaches an integer value [5], with a relatively modest amount of power (P_{NBI} + P_{ICRH} ~15MW). This ‘outer’ ITB is situated in the positive magnetic shear region of the plasma, and can coexist with an ITB situated at a smaller radius, in the negative shear region. Three routes for pre-forming the q profile, before the high additional power (PADD) is applied, were compared:

fast ohmic current ramp, NBI preheat (relying on the bootstrap current for shaping the q profile) and LHCD preheat (relying on the external current drive). The first two routes led to weak negative shear, the third one, to weak or deep negative shear depending on the LH power. In all three scenarios, when P_{ADD}~15MW is applied, an "outer" ITB is triggered, when qmin reaches either 3 (NBI preheat and LHCD preheat scenarios) or 2 (fast ohmic ramp scenario). There is little difference in the 'outer' ITB location, indicating that it is not sensitive to the magnetic shear in the inner part of the plasma. At the additional power levels used in the experiments described above, the 'outer' ITB has a relatively weak pressure gradient, and does not lead to high neutron yield. Higher power is needed to obtain strong ITB at wide radius in plasmas with monotonic q profile in JET [6]. P_{ADD} > 18MW (NBI + ICRH) has been applied in plasmas with LHCD preheat in a limited number of shots. At that power level, large ELMs are triggered, which result in the termination of the ITB. Neon puffing was used to control the edge and maintain small ELMs throughout the high power phase. Figure 2a shows the time evolution of the ITBs obtained, and figure 2b, the additional powers and IP waveforms. The 'outer' ITB is triggered when qmin reaches 3, and moves outwards as the current is ramped. This is in addition to the ITB located in the region of negative magnetic shear, which exists already during the LHCD preheat and persists throughout the high power phase. The 'outer' ITB is terminated by a MHD event at 7.1s, which has been identified as a snake. Snakes have been linked to the presence of an integer q surface and a sharp pressure gradient, and are frequently observed in plasmas with ITB [7]. In the experiments described above, the 'outer' ITB is terminated by snakes in several pulses, typically at ~ 5.5s, or at ~7s. This is correlated to $n = 1$ edge MHD activity. The snake at ~5.5s can be prevented by keeping the NBI power low. A possible solution to avoid the snake at 7s would be to crop the current ramp before the edge MHD is reached. However, note that the 'outer' ITB remains weak (near the empirical threshold for an ITB in JET [8]) even with P_{ADD} > 20MW, and does not lead to the performance hoped. Likely this is due to the magnetic shear at the ITB location not low enough, which in turn indicates the need for a larger off-axis current contribution.

2.3. PELLET FUELLED HIGH DENSITY ITBS

Both NBI central fuelling and torque injection will be much lower or missing in ITER compared with present experiments. High additional current drive power will be needed to maintain an optimal magnetic shear profile to stabilise the turbulence. Pellet injection is a promising tool for creating steep density gradients that can contribute to turbulence stabilisation and to raising the central density. Experiments in JET have successfully started exploring this possibility [9]. The basic scenario makes use of LHCD applied at the very beginning of discharges ($B_T = 3.2$T, $I_P = 2.0$MA) to produce a reversed shear configuration which is maintained after a 1s gap used for pellet pre-fuelling. At the end of the gap, that is either ohmic or heated by low NBI power (4MW), main ICRH and NBI heating is switched on. A high density ITB is obtained at an initial toroidal rotational shear which is four times lower than in standard ITB discharges [10] with PLH/PNBI/PICRH=1.9/8.6/6.6 MW, see figure 3. In this way, current and density profiles are independently controlled and a variety of combinations have been produced. So far, it seems that both early LHCD pulse and pellet fuelling are needed to enter this regime, thus pointing to the synergetic role of density gradient and magnetic shear for turbulence quenching. This recipe has allowed producing barriers with core density beyond the Greenwald linear averaged value, which have equalised ion and electron temperatures and that last for more than 1s corresponding to 4-6 times the energy confinement time. The improved performance phase is typically terminated by MHD events and by the decay of the core density. First attempts were made to refuel the already formed barrier during the main heating. So far, barriers seem to survive only the injection of shallow pellets (80m/s), efficiently refuelling the edge. According to JETTO simulation [11], the density perturbation of deeper pellets (160m/s), reaches the barrier foot, reduce locally both the density gradient and the toroidal rotation shear with a negative impact on turbulence stabilization. Results of the simulation for the two cases are shown in figure 4. Analysis of particle deposition and transport done by JETTO code shows that ablation is in agreement with code prediction without any evident radial drift. During the gap between LHCD prelude and high power phase, the post pellet density evolution is in agreement with mixed Bohm/gyro-Bohm diffusion including an anomalous pinch velocity as usually observed in L-mode. During the main heating, the barrier formation and disappearance are well described by criterion taking into account the magnetic shear, the ExB rotation frequency and the ITG growth rate [12]. Magnetic islands with a $m/n = 3/1$ topology and double tearing features are destabilised after pellet injection which causes as well a braking of the edge rotation [10]. Further studies are planned for the future for better clarifying the separate role of density peaking and current profile in the barrier formation and for obtaining a more steady performance.

2.4. LONG PULSE

ITB experiments in JET have also attempted to extend ITB discharges to duration close or exceeding the current diffusion time [13]. In this scenario NBI power is split in two to be used sequentially. The first step has been to develop a wide ITB regime ($I_P \leq 18MA$, $B_T = 3T$) at the power available in these conditions ($P_{tot} \sim 18MW$). Wide ITB are required in order to increase the confinement significantly by their larger volume. This is achieved by a careful timing of the main heating power (as the minimum q value reaches 3. To generate a wide ITB in the positive shear region, the LH preheat phase is tuned so that to form a moderately reversed shear q profile in the plasma core. In this case, the ITB triggered at $q_{min} = 3$ then evolves in the positive shear region up to $r/a = 0.6$ and the central ITB in the negative shear region does not develop or vanishes.

Thanks to the combination of LH, NB and bootstrap current the q profile can be maintained above $q = 2$ for long time. Although this discharge is not fully noninductive and still has a β_N of 1.6, the ITB is sustained for more than 7s. The real time control of the ion temperature gradient by the NBI power has been used successfully to stabilise the ITB strength. The ITB strength is moderate ($\rho^* < 0.02$), and this could explain that no impurity accumulation is observed by soft X-ray signals. This type of discharge has been used as a target to experiment the new real time techniques for the simultaneous control of the current and pressure profile. Additional experiments have attempted to extend this ITB to times up to 20s i.e. significantly longer than the resistive time ~8s. Although the creation of wide ITB is quite reproducible, the worse machine conditions and higher impurity concentration made it difficult to maintain the ITB for long times due to continuous evolution of current profile as shown in the bottom trace of fig 5. However a record of 326MJ was injected in this discharge demonstrating that JET is capable of handling large amount of power for the purpose of long pulse discharges.

2.5. MODE CONVERSION ICRF HEATING ON ITBS

An ITB scenario, with concentrations of 3He minority up to 20% in deuterium plasma [14], has been developed at JET for using Ion Cyclotron Radio Frequency (ICRF) heating in Mode Conversion (MC). The MC power provides a well-localised source of electron heating thus allowing both to obtain high electron temperatures and to infer transport characteristics of the ITB [15] through the well-assessed modulation technique of the coupled power. The reference scenario makes use of discharges at $B_T = 3.2\text{-}3.6T$ and $I_P = 2.6\text{-}2.9MA$, the bracket values allow for localisation of the ICRF power outside/inside the ITB. Target plasmas, with deep reversed magnetic shear profiles. are obtained by applying 2-3MW of LHCD power in the early phase of the discharges. Barriers, sitting in the region of negative shear, are then triggered injecting up to 18MW of NBI power. 4 MW ICRF power, 50% amplitude modulated, are also coupled to these plasmas at different radial positions. The effect of the ICRF power is strongly enhanced by the good transport properties of the barrier when it is coupled in the core region. In fig. 6 the profiles of one of these discharges at BT = 3.6T, are reported, where a 12% 3He concentration generated a mixed minority-MC heating regime. In these conditions both minority heating (R = 3.31m) and MC (R = 3.06m) deposition locations are inside the barrier radius (R ~ 3.5m) producing $T_{e0} \geq 13keV$, $T_{i0} \sim 24keV$. This performance is significantly higher compared to similar shots where H minority or pure ^{3}He minority (^{3}He concentration~5%) schemes are used. The ITB strength in this discharge is further revealed by the hysteresis effect seen on the barrier when the main power is stepped down by the real time control for avoiding disruption induced by extreme pressure profile peaking. Neutron emission reaches its maximum 1 s (~3τ_E) after the NBI power has been reduced from 14 to 11MW and is still close to the maximum with barrier surviving 300ms after a further reduction to 8 MW. A TRANSP simulation of this discharge estimated a transient equivalent $Q_{DT} = 0.25$. From modulation analysis the barrier is seen behaving as a narrow layer of reduced diffusivity that strongly damps the heat wave. Detailed transport results deduced from detected heat waves moving inward when the power is deposited outside the ITB location or outward when centrally deposited are reported in EX/P6-18.

2.6. SIMILARITY EXPERIMENTS IN THE ITB AND HYBRID REGIME

The objective of this study is to compare the dynamics of the same type of ITB on JET and ASDEX Upgrade (AUG), using neutral beam heating in current ramp with low magnetic shear. The parameters for the two experiments are matched as far as possible, using the same, low triangularity ($\delta \sim 0.22$)

plasma shape, similar q-profiles (with $q_{min} \sim q_0 \sim 2$) and closely matched values of δ^*, ν^* and β for the target plasma, just before the start of the neutral beam heating, at similar line averaged densities, neutral beams have comparable power deposition profiles (see Table I, for more details). In this comparison, the target electron temperature in JET is too low without additional heating. The results of the experiments show that both devices generate an ion ITB at 7-10MW input power. Neither machine exhibit an electron ITB in this regime. Both experiments made transient ITBs, which collapsed coincident with the onset of large ELMs (always the case at AUG). This suggests similar ITB phenomenology in the two tokamaks. Differences between the experiments mainly result from the low target temperature in JET. Hence the neutral beams in JET begin mainly as an electron heater while the AUG beams heat ions dominantly from the outset. AUG achieves higher ratios of the ion temperature over the electron temperature, than the JET cases, throughout the main heating phase (including the ITB phase). In follow up discharges in JET, the scenario used weak LHCD heating in the prelude obtain higher target electron temperature, to overcome the mismatch between the experiments. Moreover, by effectively mitigating the edge MHD activity with Neon seeding, an ITB was sustained for 10 energy confinement times, with barriers both on ions and electrons. Similar mitigation techniques in ITB discharges on AUG were not successful so far.

Activity on hybrid scenarios started in 2003 at JET with the objective to develop the regime toward non-dimensional parameters achievable on ITER. Firstly the AUG regime was reproduced in an identity experiment where magnetic configuration, q profile, ρ^* and β were matched and performance verified up to $\beta_N = 2.8$ at $B_T = 1.7T$. Stationary conditions with $H_{89}\beta_N/q_{95} = 0.42$ have been achieved, then the scenario has been tested at high triangularity $\delta = 0.45$ and at ITER magnetic configuration before been developed at lower $\rho^* \sim 0.4\times10^{-2}$. Here all the signatures of the scenario have been reproduced, but the performances are limited by the available power. Detailed results of Hybrid research at JET will be reported in the companion paper EX/4-2.

More recently, in a low activation campaign, the development of the hybrid scenario with dominant ICRH and negligible momentum input has started [16]. In the same conditions, experiments to probe the ion confinement in presence of pure electron barrier have also been carried out. In these discharges ITBs on ion have been triggered with the evaluated E×B shearing rate always lower than the analytical evaluations of the turbulence growth rate. The results of this low power campaign will be reported in EX/P2-1.

3. FUEL AND IMPURITIES TRANSPORT IN AT IN JET PLASMAS

The control of plasma density, purity and fuel concentrations will be a key issue to optimise and maintain fusion performances in the next generation experiments. In particular the study of these issues has been addressed in advanced scenarios at JET as the presence of ITB could strongly affect the transport of fuel and impurities. The scenario described in sec 2.2 was used to study tritium transport and fuelling in ITB plasma [17]. By engineering the NBI and LHCD waveforms, plasmas with either a single ITB in the negative magnetic shear region of the plasma, or a double ITB with additionally an ‘outer’ ITB, were obtained. Trace amounts of tritium were injected either by gas puffing, or by neutral beam injection, in both types of ITB plasmas for comparison. The T evolution was monitored with collimated vertical and horizontal neutron cameras. The diffusion coefficient (DT) and convection velocity (vT) are determined by fitting the spatial and temporal of the neutron emissivity with the transport code UTC/SANCO, using the more complete DT neutron calculation by TRANSP [18]. This analysis has been done only for the single ITB plasma up to now and is reported in Fig.7. It shows that DT decreases to the neo-classical value in the region of the ITB, but remains higher inside. The inward convection of Tritium also decreases at the ITB location by about a factor 3, but remains higher than the neo-classical prediction.

In Hybrid regimes DT remains higher than neoclassical value on the whole minor radius while measured diffusion and convection of T in the edge show a strong correlation with q_{95}[18]. A new technique has been developed at JET that allows studying impurities transport virtually in all the discharges by injecting a calibrated mixture of Ar/Ne, [19]. Diffusivity and convection coefficients, both for Ar and Ne, have been found strongly anomalous in Hybrid regime discharges at fixed $q_{95} = 4$ and different ρ^*, while a change at plasma edge from outwards to inwards convection is found increasing δ. Preliminary analysis of impurity transport has been carried out in high current and long pulse ITB discharges, both with double barrier. The phenomenology is similar in the two cases although the barriers have different strength. Figure 8 shows the preliminary D and V for the neon in a long pulse discharge. The double barrier structure, though not very strong in this pulse, is clearly visible on the impurity transport. A strong outward convection is inferred at the outer barrier. A change to inward is observed in the inner part, but with values that remain always very close to the neoclassical ones. Diffusion remains higher than neoclassical value on all plasma section. These preliminary results represent the starting point of a wide campaign of analysis that will study the whole JET database thus allowing a systematic regression of transport coefficient with main scenario parameters.

4. CONCLUSION

Recently the research on advanced scenarios at JET has focused on scenarios development more than in performance achievement, accordingly with the evolution of power availability at JET. Different techniques (modulate RF power in Mode Conversion scheme, impurity injection, Tritium beam blip and gas puff) have been employed to infer transport characteristics of the ITB. In a low activation campaigns the development of scenarios with dominant RF heating, hence low momentum input and T_e close to T_i, has started. The development of RTC, up to the integrated control of q-profile and ITB strength, has allowed a better control of plasma core and allowed long pulse operations. Combining the core control with techniques of mitigation of edge MHD activity has allowed obtaining regimes with wide barriers that last in the H-mode phase both at high current and at ITER relevant triangularity. These regimes will be pushed at higher performance in term of the figure of merit $H^*\beta_N/q_{95}^2$ in an ITER relevant space parameter in the coming campaigns at JET following the on going power upgrade.

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	AUG No: 16147, t = 0.7s	JET No: 62175, t = 2.5s
B_T	3.0 T	1.8 T
I_P	0.78 MA	0.81 MA
q_{95}	6.8	7.6
$<n_e>$	$2.3\times10^{19}m^{-3}$	$1.1\times10^{19}m^{-3}$
$<T_e>$	1.2 keV	0.6 keV

Table 1: Discharge parameters for AUG-JET ITB comparisonI

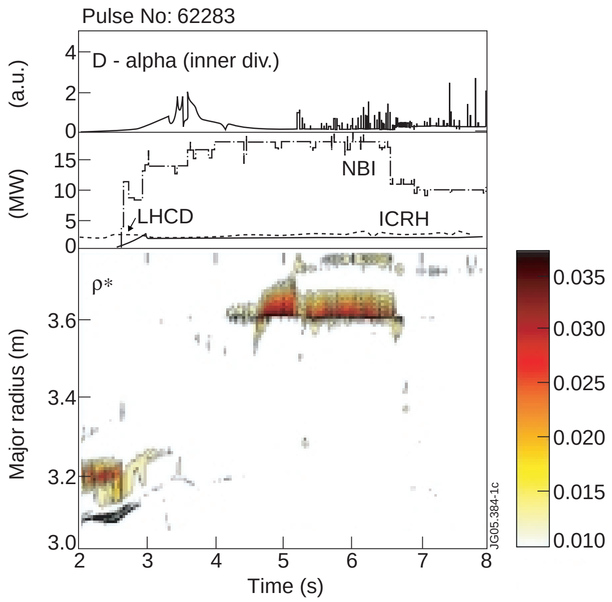

Figure 1: Contour plot of the strenght of a high tringularity. ITB, bottom trace), $D\alpha$, top) and power waveforms, mid trace). The dark area at $R \sim 3.7$ indicates the position of the barrier very close to H-mode pedestal.

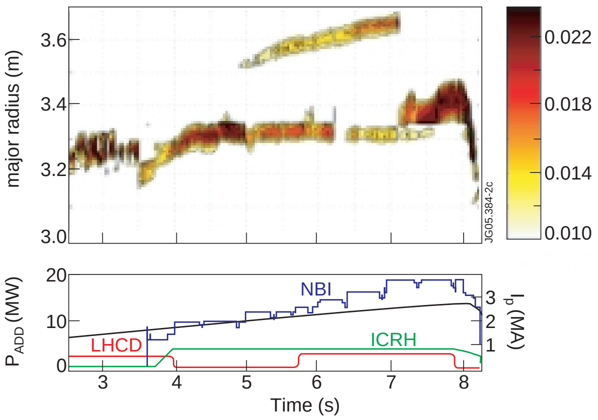

Figure 2: a) Location of the ITB as a function of time, b) power and I_P waveforms

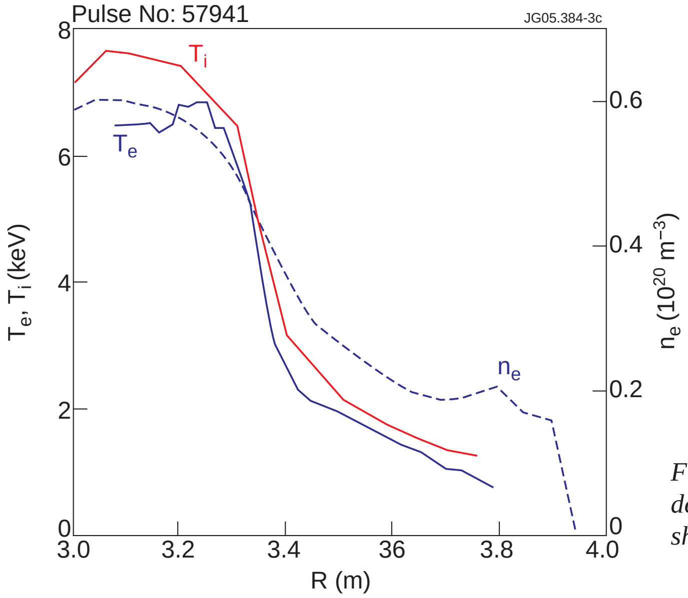

Figure 3: Density and temperatures profiles of a high density ITB after 1.1s high power and refuelling with shallow pellets.

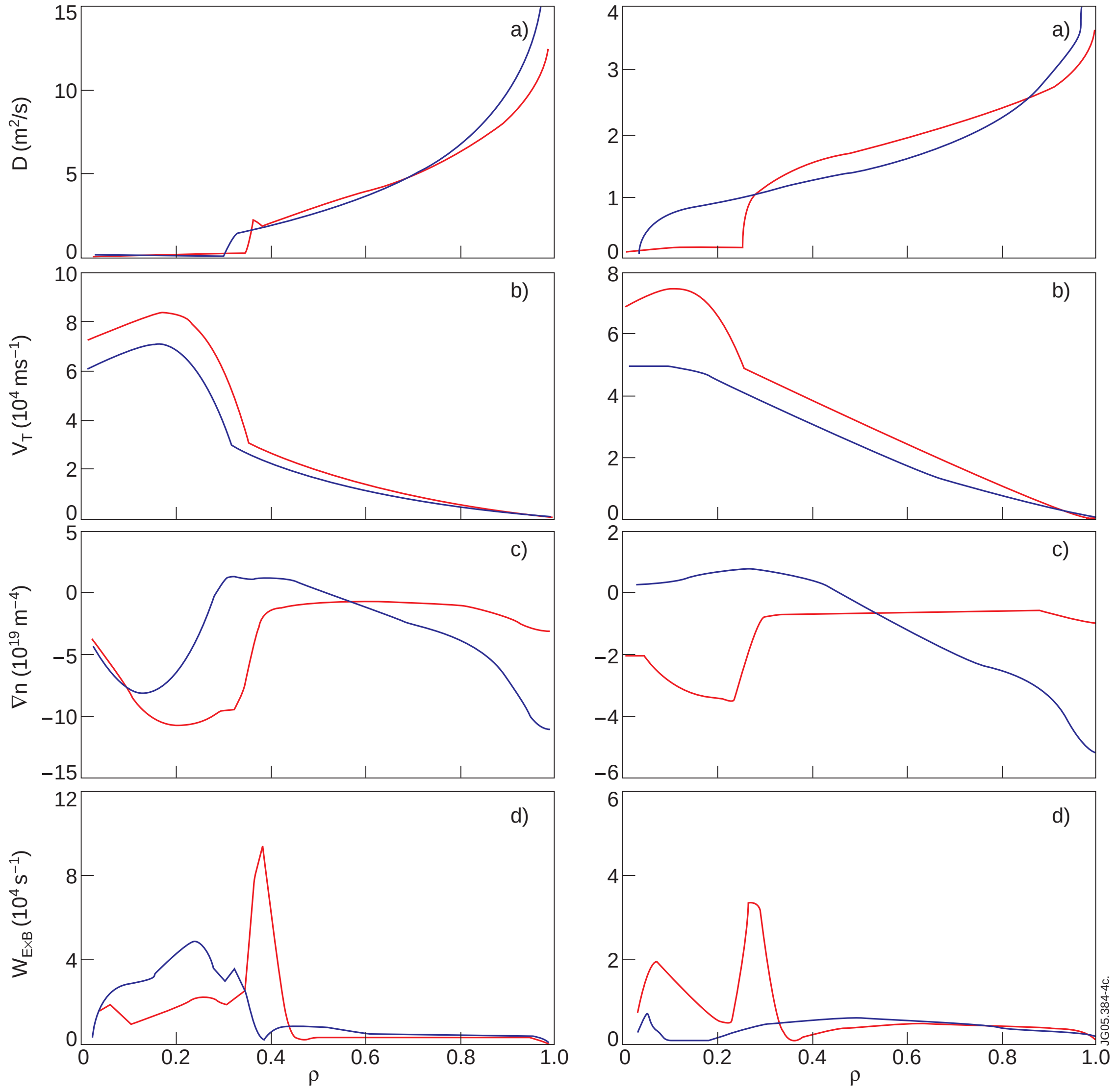

Figure 4: JETTO simulation: left) Pulse No's:57941 (shallow pellet), right) 55861 (pellet destroying the ITB). Red lines pre-pellet, blue lines post-pellet profiles. a) particle diffusion cofficient, b) plasma toroidal rotation velocity, c) density gradient, d) w_{ExB} shear

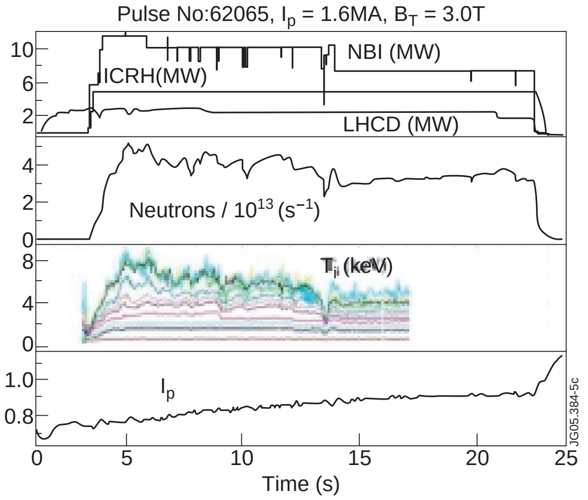

Figure 5: Time traces of Pulse No: 62065, I_P=1.6MA, B_T=3.0T. ITB end at 9s. E=326MJ inject energy

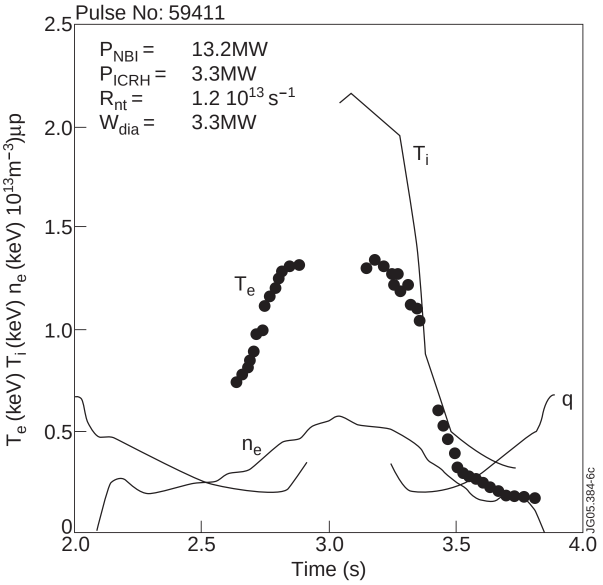

Figure 6: Temperatures, density and q profiles of a B_T = 3.6T ITB discharge. 12% ^{3}He concentration in D for core deposition of minority and MC ICRF power (33MHz)

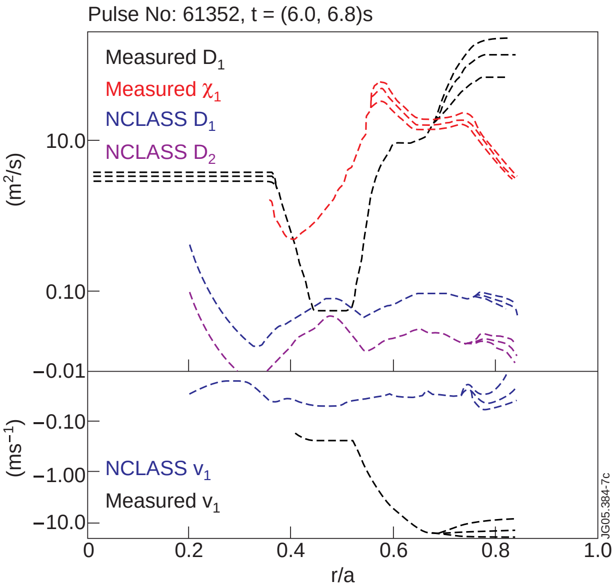

Figure 7: Measured DT and VT (negative inward) compared with neoclassical predictions. Also reported are effective diffusivity and neoclassical prediction for deuterium D.

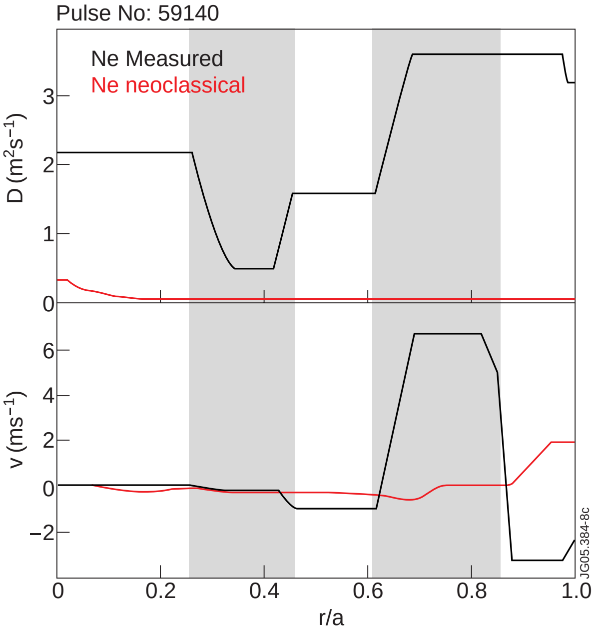

Figure 8: Measured D (top) and V (Bottom) for Neon in a double barrier. Computed neoclassical values (red lines) are also reported. Shadowed areas indicate localisation of barriers.