The "hybrid" scenario in JET: towards its validation for ITER

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Abstract: In 2003, the performance of the "hybrid" regime have been successfully validated in JET up to β_N=2.8 at low toroidal field (1.7T), with plasma triangularity and normalised Larmor radius (ρ^*) corresponding to identical ASDEX Upgrade discharges. Stationary conditions have been achieved with the figure of merit for fusion gain ($H_{89}.\beta_N/q_{95}^2$) reaching 0.42 at q_{95}=3.9. The JET discharges are showing similar MHD, edge and current profile behaviour than in ASDEX Upgrade. In addition, the JET experiments have extended the hybrid scenario operation at higher toroidal field 2.4T and lower ρ^* towards projected ITER values. Using this database, transport and confinement properties are characterised with respect to the standard H-mode regime. Moreover, trace tritium have been injected to assess the diffusion and convective coefficients of the fusion fuel. The maximisation of confinement and stability properties provides to this scenario a good probability for achieving high fusion gain at reduced plasma current for duration up to 2000s in ITER.

1- Introduction

To achieve burning plasma conditions for long periods of time, operating regime in a fusion reactor will have to comply with a number of challenging conditions. By combining high fusion gain and steady state operation [1] the Advanced Tokamak research effort has the objectives to provide long pulse operation in ITER with sufficient fusion gain (Q>5). To reach that goal, it would be necessary to decrease the plasma current and increase plasma pressure while optimising external current drive sources. In this process, present days experiments are faced with the onset of plasma instabilities at high β and plasma current profile control with reversed shear in the plasma core to increase confinement by the means of turbulence stabilisation. More development is therefore required to make this concept a reliable candidate for producing high fusion gain in the next step device. The ELMing H-mode has been so far the reference regime for ITER design. Numerous experimental and theoretical validation of the physics basis have established that this scenario would indeed meet the goal of fusion gain of Q=10 at β_N=1.8 for a few hundred seconds. However this performance is limited at moderate plasma pressure (typically for β_N <2) by the triggering of neo-classical tearing modes (NTM) driven by the sawtooth m=1 n=1 activity.

In this context, new series of experiments have successfully eliminated the deleterious effect of sawteeth and reduce NTMs triggering by establishing a current profile in stationary state with q above unity. Originally operated in ASDEX Upgrade [2] and DIII-D [3], these discharges have produced high figures of merit ($G=H_{89}.\beta_N/q_{95}^2$~0.4 to 0.6) in stationary conditions at reduced plasma current (for q_{95} around 4). Plasma performance at this lower current is maintained by operation at β_N up to 3. Preparation and This scenario also named "hybrid scenario" provides a promising route to ITER operation with reduced flux consumption, high fluence and lower potential damage associated with disruptions.

In the last two or three years, this regime has received considerable interest in D-shaped machines. In the recent 2003 campaigns, JET has started the detailed study of the hybrid regime. With its size JET has the unique opportunity to bridge the gap between machine such as DIII-D and ASDEX Upgrade on one side and ITER on the other. The portability and physics validation (confinement, stability and transport) of scenarios can therefore be investigated in detail. The study of this scenario on JET, which is capable of achieving non-dimensional parameters close to ITER, is therefore essential.

In this paper, the experimental procedure to reproduce the ASDEX Upgrade hybrid regime is first described. With this technique, identity experiments have been achieved and are demonstrating the portability of this new scenario to larger size devices. The following sections examine the confinement and transport properties of this regime including tritium transport. The last section gives fusion power projections for ITER using this new scenario under various assumptions.

2- Overview of the JET hybrid regime.

JET experiments first focused on reproducing the hybrid regime achieved in ASDEX Upgrade. For confinement and transport comparison, an identity experiment has been designed using a dimensionless parameter ordering approach. The making of an identity experiment requires several elements in its design. In the first place, new plasma magnetic configurations have been developed to match those used by ASDEX Upgrade. Two ASDEX Upgrade magnetic configurations at low triangularity (~0.2) and double null high triangularity (~0.45) have been devised and validated in JET. In addition, to investigate the portability of the hybrid scenario to ITER, an ITER-like magnetic configuration has also been used in JET. All three configurations have the outer strike point close to the pumping throat of the divertor to ensure optimum pumping. To complete this work the normalised current I_N=Ip / a.B_T has also been matched to that of ASDEX Upgrade.

Then, for heat and particle transport comparison, the choice is made to match the normalised Larmor radius ρ^*. The currently recommended ELMy H-mode energy confinement time scaling (IPB98y2) can be expressed in dimensionless form as [4]:

$$Bo\ \tau_{IPB98(y,2)}\ \alpha\ \rho^{*-2.70}\ \beta^{-0.90}\ \upsilon^{*-0.01}\ q^{-3.0}\ \varepsilon^{0.73}\ \kappa^{3.3}$$

The relative dependency upon β and υ^* is still a matter of research, but the magnetic configuration, q and ρ^* have the strongest dependence and therefore plays the dominant role in an identity experiment. Matching ASDEX- Upgrade ρ^* in JET means operating JET at low field, typically around 1.7T. A match in β can be obtained by varying the input power whereas υ^* has a small impact on confinement but can be adjusted by varying gas fuelling.

The other key element in achieving stationary discharge is a controlled q profile above unity stable to sawteeth as obtained in ASDEX Upgrade. Given the much longer resistive time constant in JET (typically 5 times longer than in ASDEX Upgrade) this is achieved in JET using current profile tailoring in the current ramp with lower hybrid (LH) power. With this tools the q profile could be tuned with low magnetic shear close to q=1 almost independently from the machine start-up conditions. For the pressure profile, the β_N is increased and held constant by feedback control of the neutral beam injection power.

A typical identity discharge of this type is shown figure 1 for the low triangularity configuration. The current ramp up phase in L-mode is used to establish the target magnetic configuration and q profile. The main heating power (NBI) is launched when the q profile approaches q=1 in the plasma centre. For these regimes, the time of the NBI heating is a crucial parameter in JET. Heated too late, sawteeth can occur and induce 3/2 or 2/1 NTM. Heated too early the q profile in the plasma core is too high above 1 and the q=2 surface becomes unstable. This suggests that the target q profile is an important parameter in the creation of this scenario. The discharge is then heated in two power steps controlled by the

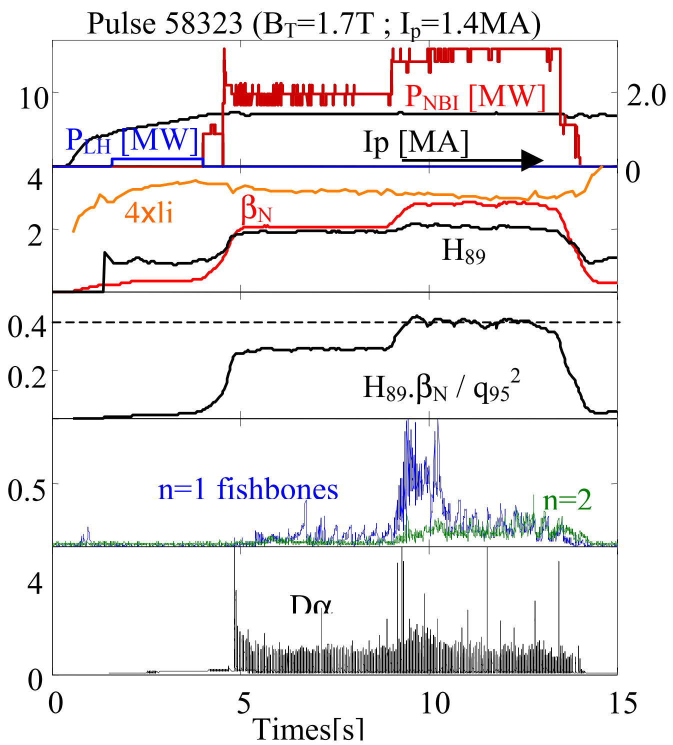

Figure 1 *: Hybrid scenario achieved in JET from the identity to ASDEX Upgrade.*

reference β_N waveform. The first phase at β_N =2 helps in landing the hybrid q profile just above q=1 with the beam power, after which it is safe to increase β_N further. After 4.5s the request in β_N is increased to 2.8 with 15MW of neutral beam injection (NBI) obtaining Tio=11keV, Teo=5keV and 50% of the Greenwald density n_G=Ip/(π.a^2). This level of power is held for another 4.5s at β_N =2.8 which is 95% of the no-wall limit estimated by 4xli. The confinement time compared to the ITER-89P scaling [4] is 2.1. This gives a common figure of merit G=$H_{89}.\beta_N/q_{95}^2$ of 0.39 in steady state conditions for a q_{95} of 3.9. This is in line with the results from ASDEX Upgrade and also DIII-D at similar q_{95}. This discharge reproduces most of the features observed in ASDEX Upgrade in the so-called "improved H-mode' in terms of β_N, H-factor, ρ^*, q profiles and β. Most of the dimensionless parameters including H_{98}(y,2) are identical within less than 10%. However, for the same ρ^*, JET υ^* is 0.08 and 0.15 for ASDEX Upgrade. On the other hand, for the same ρ^*, JET υ^* is 0.08 whereas it is 0.15 in ASDEX Upgrade.

The hybrid regime has also been reproduced using an ITER-like magnetic configuration at both 1.7 and 2.4T. At 1.7T, β_N=2.7 has been reached and a figure of merit G=0.4. As observed in ASDEX Upgrade, high triangularity discharges are showing higher pedestal densities compared to low triangularity ones. Dedicated similarity experiments have also extended the hybrid regime operations in JET at higher toroidal field strength (B_T=2.4T) thus decreasing the normalised Larmor radius ρ^* towards projected ITER values. At this toroidal field strength, the hybrid regime has been produced up to β_N of 2.3 at the maximum available beam power reaching a figure of merit G=0.36. For both identity (B_T=1.7T) and similarity (B_T=2.4T) experiments, electron density and ion temperature profiles are similar to those

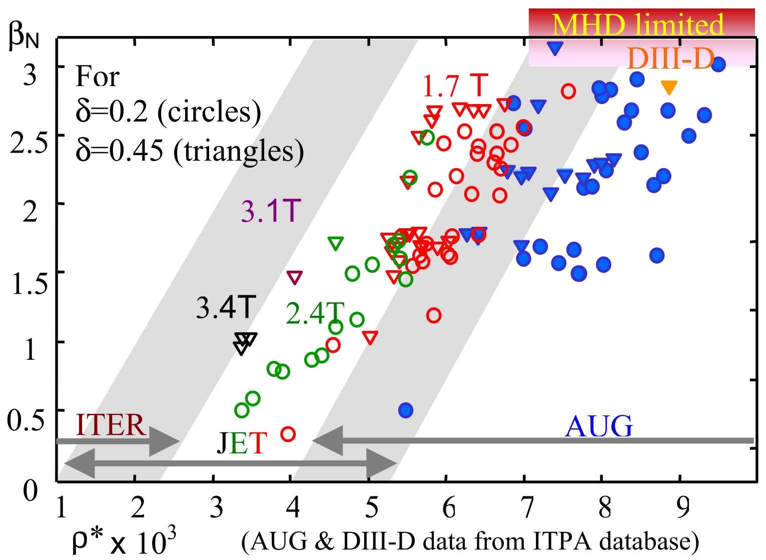

Figure 2 *: Summary of the hybrid regime experiments in JET in comparison with the ASDEX Upgrade « improved H-mode » regime [2]*

of ASDEX Upgrade and no internal transport barrier (ITB) is observed in contrast to previous JET experiments [5].

A summary of the hybrid discharges achieved in JET is illustrated in an β_N versus ρ^* diagram (fig 2). It shows how JET can bridge the gap in ρ^* between devices like ASDEX Upgrade and DIII-D on one side and ITER on the other. The hybrid regime has also been attempted at higher toroidal field strength (3.1T and 3.4T) and with dominant ICRH heating [6]. Provided that more power is available, future experiments are planning to explore the low ρ^* region and demonstrate the hybrid regime for ρ^* reachable by ITER at low field.

MHD stability analysis

For all toroidal field strength and triangularity, hybrid discharges show low level of magnetic fluctuations. There are often intermittent 1/1 fishbones confirming that the q profile is close to 1 in the plasma core. Low level of n=2 activity (fig 1) is also recorded like in ASDEX Upgrade. The mode analysis using poloidal and toroidal arrays of magnetic sensors confirms the presence of a 3/2 NTM mode. This mode is often accompanied by a 4/3 NTM destabilised by toroidal coupling as suggested by the opposite evolution of their amplitudes. The relative confinement reduction due to the 3/2 mode is modest and does not exceed 10% [7]. The small island size of NTMs (~2 to 4 cm in JET), its core location (at about 30 to 40cm from the magnetic centre) and the lack of obvious triggering mechanism could explain this behaviour. The modest amount of bootstrap current is also a possible reason for this small size. The 3/2 NTM occurs in the L-mode phase prior to the main heating. In this phase the bootstrap current is small and the 3/2 mode can only be current driven. It is therefore probably triggered when the stability parameter Δ' becomes positive in the q profile formation phase. In the H-mode phase the 3/2 mode becomes an NTM as the bootstrap current becomes significant.

The ELM activity affects the 3/2 mode NTM amplitude and resembles closely that of ASDEX Upgrade for both identity and similarity experiments. It is characterised by high frequency (~40Hz) type I ELMs. The loss of energy per ELM does not look better than for typical ELMy H-mode and therefore would be unacceptable for ITER. In future experiments, ELM mitigation techniques would be required to alleviate this problem.

Since the hybrid scenario can operate at high β_N, the ideal beta limit is the next stability limit to be investigated. Both DIII-D and ASDEX Upgrade did reach the ideal limit in this regime. In JET, the hybrid regime has been operated with small NTM islands up to a value of β_N (~2.8) reaching only 95% of the estimated ideal kink limit 4xli. The ideal kink instability growth rate has been computed for JET using the MISHKA code [8] and input data from the TRANSP code. From the linear stability calculations, it is not possible to decide when a mode leads to a sawtooth like event or leads to a disruption. The instabilities are mostly internal and are becoming more global as beta increases. Although this calculation cannot predict the exact stability boundary, it does indicate the strong increase of the growth rate as plasma pressure increases (fig 3). Small variations of the central q profile from its initial value predict that the ideal kink instability would

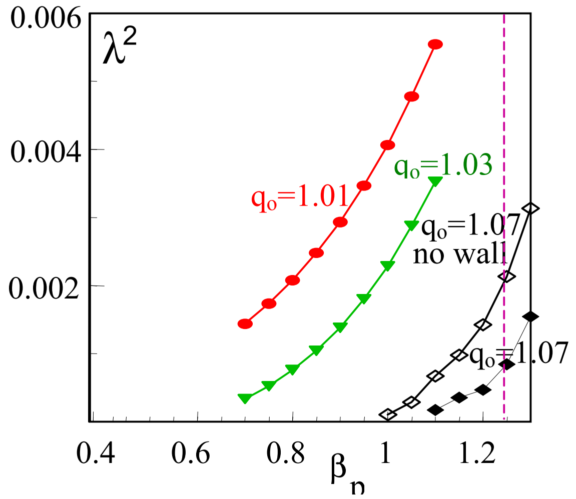

Figure 3: *Growth rate λ^2 of n=1 ideal kink mode for different values of central q . The no wall limit for qo=1.07 is also indicated. The dotted line indicates the values for 58323 (fig 1).*

be significantly enhanced as q in the plasma core is decreased towards q=1. Note that for JET, the difference between the wall and no-wall limits is relatively small due to the large distance between the plasma and the wall in JET, the moderate peaking of the pressure profile and the central location of the mode (r/a~0.3). This calculation also implies that in the experiment central q profile control would be required to keep the core q profile away from the q=1 surface.

Current balance analysis

The presence of the 3/2 and 4/3 surfaces without sawteeth relaxation confirms that the q profile lies between 1 and 1.3 in the plasma core when the main heating is applied. This is also in agreement with current profile measurement with the Motional Stark effect diagnostic. In the first power step the q profile broadens and reaches steady state during the second power phase.

The steady state property is demonstrated by the simulation of the current evolution for discharge 58323 (see figure 1) with the integrated modeling code CRONOS [9]. This simulation uses the resistivity and bootstrap current source from the neo-classical code NCLASS and TRANSP for the neutral beam current drive. The resultant profile evolution (fig 4) shows that q stays close to unity throughout the discharge indicating that the non-inductive current sources are sufficient to maintain a steady state q profile at β_N=2.8. This is in contrast to current diffusion calculations for ASDEX Upgrade [10] as their measurements cannot be matched using non-inductive sources alone. During this steady state phase of the hybrid regime beam and bootstrap non-inductive currents are contributing for about 35% and 25% respectively as computed independently by TRANSP. With this level of non-inductive current (typically 50 to 60%), it would be possible to produce discharges with duration in excess of 2000s in ITER. The same current diffusion calculation for a hybrid scenario at higher toroidal field strength of 2.4T and a plasma current of 2MA (β_N=2.2) shows on the contrary that q_o drifts steadily towards 1 and crosses it in the middle of the maximum power. This is consistent with the occurrence of sawteeth observed at the end of the pulse suggesting that the bootstrap current is not strong enough to maintain stationary conditions and keep q above the q=1 surface at this level of plasma pressure (β_p=1.05). Since the fraction of bootstrap current is roughly proportional to $q_{95}.\beta_N$ this also suggests that the hybrid regime requires a minimum β_N to reach steady state and avoid the onset of sawteeth.

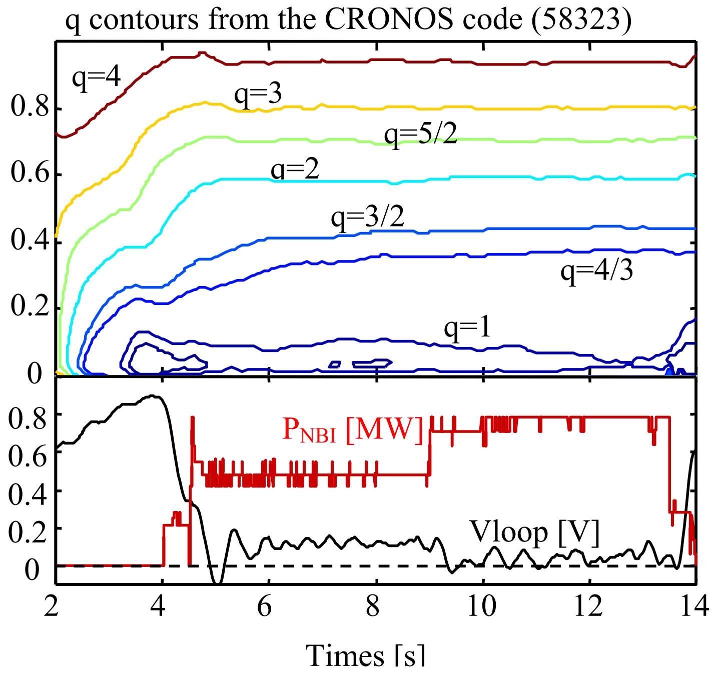

***Figure 4** : q profile simulation from the CRONOS code using TRANSP kinetic data. At β_N=2.8, (t=8.5s to 13.5s) non-inductive currents are maintaining stationary conditions.*

3- Confinement and transport analysis

Although the physics of this regime is still not fully established, the extent of the database with different configurations provides a good basis for confinement and transport characterisation. Figure 5 is showing the thermal confinement for a large variety of magnetic configurations, toroidal field strength and power operated in JET. It appears that the confinement can be up 20 to 30% higher than the scaling for ELMy H-mode IPB98y2 [4]. In both ASDEX Upgrade [2] and DIII-D [11] improved confinement with respect to this scaling law has also been observed for the hybrid regime. However recent dedicated studies [12,13] have shown that confinement has a weaker negative dependence on β than suggested by IPB98(y,2) for β_N greater than 2. According to these studies, the electrostatic Gyro-Bohm model ($W_{ESGB}=0.028.P^{0.45}B_o^{0.07}Ip^{0.83}\kappa^{0.75}ne^{-0.49}a^{0.3}R^{1.81}M^{0.14}$) without β dependence appears to give a reasonable fit to the database of JET and DIII-D. The two scalings applied to JET hybrid discharges with NBI only are bracketing the experimental thermal energy content (fig 5). This suggests that the higher confinement observed for the hybrid regime could be related to the β negative dependence in $\beta^{-0.9}$ of the IPB98y2 scaling law.

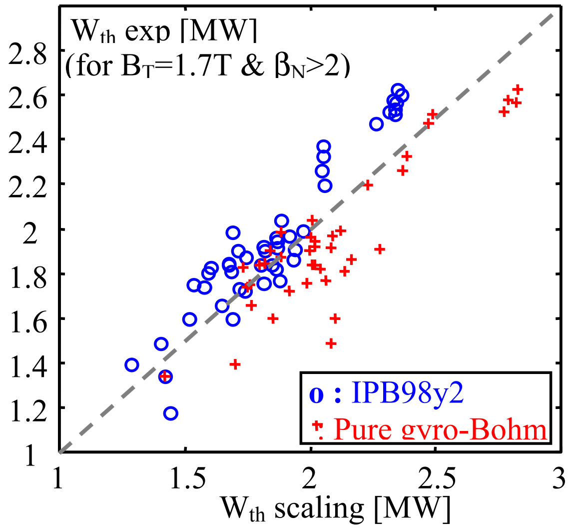

Figure 5 : *Comparison of the IPB98y2 scaling with the pure gyro-Bohm scaling for JET hybrid discharges above β_N of 2.*

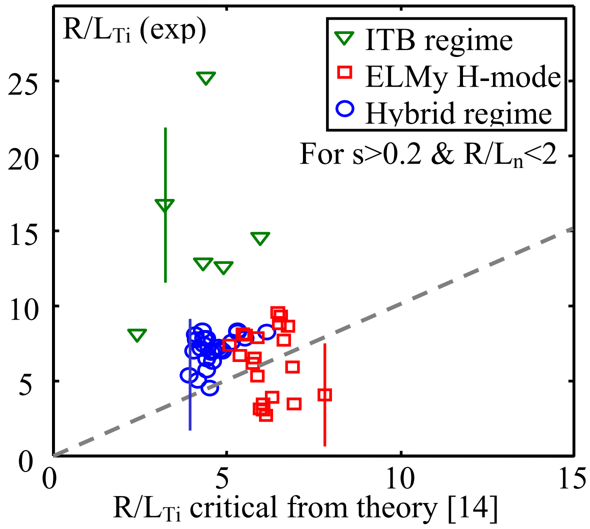

Figure 6 : *Comparison of the experimental normalised ion temperature gradient with the critical gradient from theory [14].*

The possibility of ion temperature gradient (ITG) turbulence stabilisation has also been investigated by comparing the critical gradients for hybrid scenario to those of JET ELMy H-mode and ITB discharges. In figure 6, the experimental normalised ion temperature gradient R/L_{Ti} is plotted versus the critical prediction from asymptotic formulae inferred by Jenko et al [14] for magnetic shear above 0.2 and R/L_n less than 2. From this analysis, we conclude that hybrid scenario behaves in the same way as the standard ELMy H-mode. The discharges with ITBs, on the other hand are clearly showing gradients well above the critical gradient of ITGs. This analysis is supported by turbulence spectrum measurements recorded by the JET reflectometer which level does not show any significant differences from standard ELMy H-mode discharge. Calculations with the GLF23 model [15] suggest that ExB shearing rate stabilises marginally the turbulence in the gradient region (r=0.3-0.7). However, it possible that the same effect also occurs in the standard H-mode discharges.

Although systematic experimental comparison of the hybrid with ELMy H-mode is not presently available at JET, these analyses of confinement and ITG stability suggest that there is no obvious sign of improved core confinement in hybrid discharges with respect to the standard ELMy H-mode regime.

Tritium fuel and impurity transport

For the different toroidal fields strength and magnetic configuration, tritium fuelling and impurity transport properties of the hybrid regime have been characterised during the 2003 JET trace tritium campaign. For the determination of tritium diffusivity D and convection term V short edge gas injections (~100ms) of tritium and on axis tritium beam injections have been used to constraint the analysis. The decay rate of thermalised tritium is measured by the JET neutron profile monitor and D, V and influx from the wall and divertor inferred from these data by least square fitting techniques [16]. For hybrid regimes, tritium diffusion is higher than its neo-classical levels (fig 7) showing that diffusion is dominated by turbulent transport. Convection is directed inward and negligible in the plasma core. In contrast to heat transport, there are also indications that D has an inverse β dependence [17].

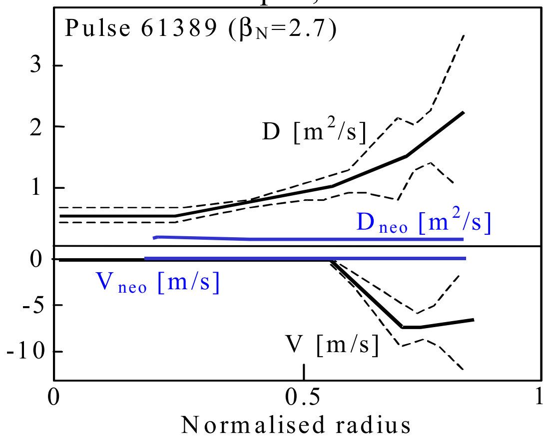

***Figure 7:** Diffusion and convection terms for tritium in a hybrid discharge at JET. Both coefficients are well above their neo-classical values.*

In the same way, impurity transport coefficients have been documented using short puff of Argon/Neon. The time evolution of the gas puff is monitored by three independent spectroscopic measurements namely, VUV, X-ray and charge exchange diagnostics. The Argon impurity transport coefficients D and V are inferred from a least square fit of the modelled line intensities with the 1 1/2D transport model code UTC SANCO [18]. Hybrid discharges at same q_{95} and different ρ* have been analysed by this method. Inferred diffusivities coefficients D and convection V are in general strongly anomalous for both Argon and Neon. The edge barrier appears to play a strong role in the impurity transport. In particular a change from outward to inward convection is observed when increasing triangularity for both low ρ* (B_T=2.4T) and high ρ* (B_T=1.7T). The ELM frequency could also explain this difference.

4- Fusion performance projections of the hybrid regime in ITER

By working close to the ITER normalised parameters, JET has enhanced the prospect of achieving the hybrid regime in ITER with factor of merit G up to 0.4 at reduced plasma current. However, this parameter provides only a rough indication of the fusion performance. A more complete computation of the fusion performance using the predictive 1D code CRONOS [9] has been made to verify the relevance of the hybrid scenario for ITER and define more accurately the operating space parameter in future JET experiments.

For this projection, a typical ITER magnetic configuration with q_{95}=4 is used with a toroidal field strength of 5.3T. The heat diffusion coefficients have a gyro-Bohm form as: $\chi = q^2/B^2.\nabla P/n_e.\sqrt{T}$ for both ions and electrons. The global confinement is normalised to two different scaling laws: IPB98y2 and the pure gyro-Bohm, as described in section 3. As stated above, this last scaling has no dependence on β whereas the first scaling has a negative dependence as $\beta^{-0.9}$. The H factor multiplier is set relative to the achieved JET discharges i.e. HH=1. The pedestal height is given by scaling inferred from the pedestal database [19, 20] and their dependence upon β is chosen consistently with that of the global scaling. Plasma density is given in terms of its peaking factor ne_o/ne_{ped} (where ne_o and ne_{ped} are the central and pedestal density respectively). In the calculations, it is set to 1 (flat density profile) or matched to JET experiments (=1.5). The absolute density value is set at 70% of the Greenwald density as in JET experiments at high triangularity. Helium ash concentration is 3% and the effective charge Z_{eff}=1.85. The auxiliary power is limited to the ITER design values (i.e. 33MW NBI and 40MW RF) and input thermally meaning that no effect of fast ions is assumed.

First of all, a calculation with CRONOS has been made using the same hypothesis as the ITER Plasma Performance Assessment [21] for the hybrid scenario, i.e. 85% of the Greenwald density, q_{95}=3.3 and Ip=13.8MA. This comparison (table I, 2 first lines) shows that the CRONOS simulation yields a higher fusion power P_{fus} (by 30%). This difference can be accounted for by the high sensitivity of P_{fus} to the volume average ion temperature which is higher by 10% in the CRONOS case as a result of the different transport model used.

Table I Scaling used (H=1)	P_{fus} [MW]	P_{aux} [MW]	β_N	Density peaking	Q_{fus}	q_{95}	Ip [MA]
IPB98y2 (PPA)	400	73	1.9	$ne_o = ne_{ped}$	5.4	3.3	13.8
IPB98y2	570	73	2.1	$ne_o = ne_{ped}$	7.8	3.3	13.8
IPB98y2	160	73	1.6	$ne_o = ne_{ped}$	2.2	4	11.3
Pure Gyro-Bohm	285	73	2.25	$ne_o = ne_{ped}$	3.9	4	11.3
Pure Gyro-Bohm	337	73	2.4	$ne_o = 1.5 \times ne_{ped}$	4.6	4	11.3
Pure Gyro-Bohm	600	50	2.85	$ne_o = 1.5 \times ne_{ped}$	12	3.5	13

The next lines 3 to 6 of table I are showing the predictions from CRONOS under various assumptions and 70% of the Greenwald density as in JET experiments. It seems that the hybrid regime does not reach the required β_N for producing stationary conditions with the standard IPB98y2 scaling. Using the pure Gyro-Bohm scaling and peaked density increases Q up to a value close to 5 but β_N is still limited to 2.4. A small increase of the total plasma current from 11.3 to 13MA is required to increase the confinement and reach higher β_N and fusion yield. Although the sensitivity of the scaling laws is quite large, this set of predictions suggests that this regime would achieve its objectives (Q=10 at reduced current) for q_{95} = 3.5 with the planned installed power and an H factor of 1. For this case, the CRONOS code also indicates that the burning phase would last more than 2000s with a loop voltage of 25mV.

Running ITER at a reduced current of 13MA is already an important step towards safer operation at Q above 10 provided that the fusion and auxiliary power are sufficient to reach high β_N and the total non-inductive current drive able to maintain the central q profile above unity. For future experiments, this is also a strong incentive for JET to demonstrate the viability of the hybrid regime at lower q_{95} and higher density.

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