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The "Hybrid" Scenario in JET: Towards its Validation for ITER.

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E. Joffrin¹, A.C.C. Sips², J. F. Artaud¹, A. Becoulet¹, R. Budny³, P. Buratti⁴,
P. Belo⁵, C.D. Challis⁶, F. Crisanti⁴, M. de Baar⁷, P. de Vries⁶, C. Gormezano⁴,
C. Giroud⁶, O. Gruber², G.T.A. Huysmans¹, F. Imbeaux¹, A. Isayama⁸,
X. Litaudon¹, P.J. Lomas⁶, D.C. McDonald⁶, Y.S. Na⁹, S.D. Pinches²,
A. Staebler², T. Tala¹⁰, A. Tuccillo⁴, K.-D. Zastrow⁶, and JET-EFDA contributors*

¹Association Euratom-CEA, DSM/DRFC, Cadarache, F-13108, France.
 ²Max-Planck-Institut fur Plasmaphysik, Euratom Association, 85748, Garching Germany.
 ³Plasma Physics Laboratory, Pinceton University, Princeton USA.
 ⁴Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Frascati, Italy.
 ⁵Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.
 ⁶Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK.
 ⁷FOM-Rijnhuizen, Ass. Euratom-FOM, TEC, PO Box 1207, 3430 BE Nieuwegein, NL.
 ⁸Japan Atomic Research Institute, Naka-machi, Naka-gun, Ibaraki-ken 311-0193, Japan
 ⁹Korean Basic Science Institute, 52 Yeoeun-Dong, Yusung-Gu, Daejeon,305-333, Korea
 ¹⁰Association EURATOM-TEKES, VTT Processes, P.O. Box 1608, FIN-02044 VTT, Finland.

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ABSTRACT.

In 2003, the performance of the "hybrid" regime has 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 fusion figure of merit (H_{89} . β_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 has 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 $\beta_N < 2$) by the triggering of Neo-classical Tearing Modes (NTM) driven by the sawtooth m=1 n=1 activity. To get maximum confinement for reaching fusion gain of 10, this regime looks feasible when operating the machine close to its operating limit and in particular at high plasma current (i.e. $I_p=15MA$ and $B_T=5.3T$ for $q_{95}=3$).

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 fusion figures of merit (G=H₈₉. $\beta_N/q_{95}^2 \sim 0.4$ to 0.6) in stationary conditions at reduced plasma current (for q₉₅ around 4). Fusion performance at this lower current is maintained by operation at β_N up to 3. 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 with dimensionless variables ρ^* , β , and υ^* as [4]:

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

where Bo is the toroidal field at major radius R, M the average ion mass, $\varepsilon = a/R$ the inverse aspect ratio and κ the elongation. The relative dependency upon β and υ^* is still a matter of research, but the dependencies upon the magnetic configuration and the parameters q and ρ^* are much stronger, and therefore they play 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 if necessary.

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 0.5 to 1.5MW of 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 Fig.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 as plasma pressure increases. Heated too early the q profile in the plasma core is too high above 1 and the q=2 surface becomes unstable. Similarly, without the LH power assistance, sawteeth are occurring in the NBI power phase of the pulse and can trigger an n=1, m=2 NTMs leading to the termination of the discharge. All this suggests that the target q profile is an important parameter in the creation of this scenario.

The pulse is then heated in two power steps controlled by the reference β_N waveform. The first phase at $\beta_N = 2$ 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 $n_G = Ip/(\pi.a^2)$. This level of power is held for another 4.5s at $\beta_N = 2.8$ which is 95% of the no-wall limit estimated by 4 x li. The confinement time compared to the ITER-89P scaling [4] is 2.1. This gives a common fusion figure of merit $G = H_{89} \cdot \beta_N / q_{95}^2$ of 0.39 in steady state conditions for a q_{95} of 3.9. This is in line with the results from ASDEX Upgrade [5] and also DIII-D [6] at similar q_{95} . This pulse 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%. On the other hand, for the same ρ^* at this density, 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 fusion figure of merit G=0.4. As observed in ASDEX Upgrade, high triangularity pulses 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 (Fig.2). 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 fusion 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 in shape to those observed in hybrid ASDEX Upgrade pulses.

A summary of the hybrid discharges achieved in JET is illustrated in an β_N versus ρ^* diagram

(Fig.3). 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 [7]. Provided that more power is available, future experiments are planning to explore the low ρ^* and high β_N region and demonstrate the hybrid regime for ρ^* reachable by ITER at low field.

MHD STABILITY ANALYSIS

The stability of the hybrid regime is the most attractive feature of this regime. For all toroidal field strength and triangularity, hybrid discharges show low level of magnetic fluctuations. Like in ASDEX Upgrade, low amplitude n=2, m=3 MHD activity is also recorded as confirmed by the mode analysis using poloidal and toroidal arrays of magnetic sensors the presence (Fig.4). There are often intermittent n=1, m=1 fishbones confirming that the q profile is close to 1 in the plasma core. The 3/2 mode is often accompanied by a 4/3 NTM destabilised by toroidal coupling as suggested by the opposite evolution of their amplitudes [8]. The relative confinement reduction due to the 3/2 mode is modest and does not exceed a few percent [9]. The small island size of NTMs (~2 to 4cm 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. This is supported by the dependence of the mode amplitude evolution with the plasma pressure (β_p) .

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 equivalent 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 [10] 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.5). Small variations of the central q profile from its initial value predict that the ideal kink instability would 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). The sensitivity of the ideal kink growth rate to the proximity of the q=1 surface, 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 using real time control tools [11].

CURRENT BALANCE ANALYSIS

The presence of the 3/2 and 4/3 surfaces without sawteeth relaxation does confirm that the core (r/a<0.3) q profile and q_{min} lie between 1 and 1.3 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 Pulse No:58323 (see Fig.1) with the integrated modelling code CRONOS [12]. 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.6(a)) shows that q stays close to unity for about 2 resistive time throughout the pulse indicating that the non-inductive current sources are sufficient to maintain a steady state q profile at β_N =2.8 consistently with the experiment. This is in contrast to current diffusion calculations for ASDEX Upgrade [5], as their measurements cannot be matched using non-inductive sources alone. In recent ECRH stabilisation experiment in DIII-D, it has been shown that the 3/2 NTM is acting on the current penetration towards the plasma core [6]. This effect could also play a role in JET, but would need discharge duration in excess of several resistive time to be observed. During the 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 (Fig.6(b)). With this level of non-inductive current (typically 50 to 60%), it would be possible to produce pulses 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 =2.3, see Fig.2) shows on the contrary that q_0 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} . β_N this also suggests that the hybrid regime requires a minimum β_N to reach steady state current density profile and avoid the onset of sawteeth.

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 7 is showing

the thermal confinement for a large variety of magnetic configurations and input power operated in JET at high β_N and B_T =1.7T. 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 [3] improved confinement with respect to this scaling law has also been observed for the hybrid regime.

However recent dedicated studies [13,14] 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:

$$W_{ESGB} = 0.028.P^{0.45}B_0^{0.07}Ip^{0.83}\kappa^{0.75}ne^{-0.49}a^{0.3}R^{1.81}M^{0.14}$$

without β dependence appears to give a reasonable fit to the database of JET and DIII-D. The two scaling applied to JET hybrid discharges with NBI only are bracketing the experimental thermal energy content (Fig.7). This suggests that the higher confinement observed for the hybrid regime could be related to the β negative dependence ($\beta^{-0.9}$) of the IPB98y2 scaling law, meaning that this scaling is underestimating confinement for high β_N regimes.

In past JET experiments attempting to produce flat q profile just above unity, an Internal Transport Barrier (ITB) had been observed close to the q=1 rational surface [15]. In contrast, in the present identity hybrid scenario experiment with ASDEX Upgrade, there is no obvious sign of ITB on both ion and electron temperature profiles.

The possibility of Ion Temperature Gradient (ITG) turbulence stabilisation has been investigated by comparing the critical gradients for hybrid scenario to those of JET standard sawtothing ELMy H-mode and ITBs pulses with reversed q profiles. In Fig.8, the experimental normalised ion temperature gradient R/L_{Ti} is plotted versus the critical gradient prediction for ITG modes from asymptotic formulae [16] for magnetic shear above 0.2 and R/L_n typically less than 2. From this analysis, we conclude that hybrid scenario behaves in the same way as the standard ELMy Hmode. Pulses with ITBs, on the other hand are clearly showing normalised ion temperature gradients well above the critical gradient of ITGs for ELMy H-modes. 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 pulse. Calculations with the GLF23 model [17] suggest that ExB shearing rate stabilises marginally the turbulence in the gradient region (r=0.3-0.7). This is consistent with similar calculations for hybrid discharges in ASDEX Upgrade and DIII-D. However, it is possible that the same effect also occurs in the standard H-mode pulses. Therefore, it is not possible to conclude from GLF23 calculation that the hybrid scenario has an improved core confinement with respect to the standard ELMy H-mode.

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 pulses 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 nineteen channel neutron profile monitor. D, V and influx from the wall and divertor are inferred from these data by least square fitting techniques [18]. For hybrid regimes, tritium diffusion is higher than its neo-classical levels (Fig.9) 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 [19].

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 Neon 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 [20] (Fig.10). 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).

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 fusion figure 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 [13] 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:

$$\chi \sim q^2/B^2 . \nabla P/n_e . \sqrt{T}$$

for both ions and electrons. The global confinement time 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 pulses i.e. HH=1. The pedestal height is given by scaling inferred from the pedestal database [21, 22] 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 contributes only to the plasma thermal energy, i.e. no effect of fast ions is assumed.

In the first place, this model has been validated on JET pulse 58323 shown in Fig.1 using IPB98y2 scaling law to normalise the global confinement and density from the experiment. As illustrated by Fig.11 the model reproduces reasonably well the experimental electron and ions temperature data.

Then the calculation with CRONOS has been made using the same hypothesis as the ITER Plasma Performance Assessment [23] for the hybrid scenario, i.e. 85% of the Greenwald density, q_{95} =3.3 and Ip=13.8MA. This comparison (Table 1, 2 first lines) shows that the CRONOS simulation yields a higher fusion power P_{fus} (by 30%). This difference could 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.

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 b_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 q₉₅ and higher density.

CONCLUSIONS

The hybrid scenario has been successfully achieved in JET, by the mean of an identity experiment. The maximisation of confinement and stability does provide to this regime a good probability for achieving high fusion gain at reduced current (typically 13MA) for more than 2000s. The operation of ITER at lower plasma current with Q close to 10 is beneficial in reducing the mechanical stresses in case of disruption. In addition, it also provides a promising route for high neutron fluence in stationary conditions.

Stability is probably the main attraction of the hybrid regime. Sawtooth-less operation or with small sawteeth prevents the development of Neo-classical tearing modes which are the main drawback of the standard advanced scenario. In the JET hybrid scenario, the 3/2 NTM looks fairly benign and the 2/1 NTM could be avoided if the q profile is controlled in the initial phase of the q profile formation. The hybrid regime in JET has been operated up to β_N =2.8. However, working at high plasma pressure above the ideal limit has still not been demonstrated in JET. It is foreseen that operation above q of unity will require fine plasma control of the current density profile by external means.

In contrast to DIII-D and ASDEX Upgrade, the observed q profile evolution can be explained by the non-inductive current components inferred from TRANSP and the evolution code CRONOS. However this has been achieved in JET on relatively short discharges with respect to the resistive time. Longer duration pulses would give more insight on the behaviour of the current diffusion processes, particularly in relation with the 3/2 mode as it has been demonstrated in the DIII-D hybrid regime. The evolution of the plasma current would be also probably different in a burning plasma with dominant electron heating and this aspect also deserves attention.

The transport in the hybrid regime looks the same as in standard ELMy H-mode. Systematic comparisons of the two regimes remain to be done to assess the differences in terms of core versus pedestal transport. In JET, the operation of the hybrid regime at high β_N supports the recent works on the dependence of global scaling laws upon b suggesting that the global confinement time scaling law has a weaker negative dependence in β than the standard H98y2 scaling.

To confirm the relevance of this scenario as a burning operating regime for ITER, the parameter space has also to be investigated more thoroughly in terms of q_{95} , plasma density and power. Low ρ^* and high β_N operation in JET will give to this regime an increased probability to produce in ITER a high fluence and safe Q=10 regime.

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	P	Paux	β _N	Density peaking	Q _{fus}	q95	lq
Scaling used (H = 1)	(MW)	(MW)					(MA)
IPB98y2 (PPA)	400	73	1.9	ne _o =ne _{ped}	5.4	3.3	13.8
IPB98y2 (CRONOS)	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	4.0	11.3
Pure Gyro-Bohm	285	73	2.25	ne _o =ne _{ped}	3.9	4.0	11.3
Pure Gyro Bohm	337	73	2.4	ne _o = 1.5 x ne _{ped}	4.6	4.0	11.3
Pure Gyro-Bohm	600	50	2.85	ne _o = 1.5 x ne _{ped}	12.0	3.5	13.0

Table1:

ITER projections for the hybrid scenario using the 1D code CRONOS. Lines 1 and 2 are showing the difference between the model used in the projection from ref [23]. The next three lines are showing projections at $q_{95}=4$ and $n/n_{Greenwald}=0.7$ with the IBP98y2 scaling, the pure Gyro-Bohm scaling and with density peaking. The last line gives a case at a slightly lower q_{95} of 3.5.





Figure 1: Hybrid scenario achieved in JET from the JET - ASDEX Upgrade identity experiment. LH power is used in the plasma ramp up to broaden the target q profile above unity before the beam power is launched. This pulse reaches β_N of 2.8 and a fusion figure of merit of 0.4 with low MHD activity.

Figure 2: Hybrid scenario achieved in JET at lower ρ^* (2.4T). This pulse reaches β_N of 2.3 and a fusion figure of merit of 0.36. Three sawteeth can be observed before the end of the NBI heating pulse.



Figure 3: Summary of the hybrid regime experiments in JET (open symbols) in comparison with the ASDEX Upgrade « improved H-mode» r egime [2] (filled symbols) and the hybrid regime in DIII-D (orange filled diamond) from the ITPA database. JET – ASDEX Upgrade identity hybrid pulses are achieved in for $\rho^*\sim0.007$ and $\beta_N\sim2.5$. JET has extended the regime to lower values of ρ^* (i.e. $B_T=2.4T$, green symbols) and ITER-like triangularity (open triangles). The oblique stripes indicate the overlap in the (ρ^* , β_N) space between ITER and JET on one hand, and JET and ASDEX Upgrade on the other. Also, note that DIII-D and ASDEX Upgrade have reached the ideal MHD limit as symbolised by the box on the top right. JET experiments have not yet reached that the ideal limit due to power limitations.



Figure 4: Typical spectrogram observed during an hybrid pulse in JET. A continuous 3/2 mode is visible at 15kHz accompanied by a coupled 4/3 mode at 28kHz. 1/1 fishbones are also visible as well as the ELM activity that modulates the 3/2 mode amplitude.



Figure 5: Linear growth rate λ^2 for the n=1 ideal kink mode computed by the MISHKA code for different values of central q as function of β_p indicative of the plasma pressure. This calculation shows the sensitivity of the growth rate to the central q value. For q_o =1.07 the growth rate is computed both with and without the wall. The dotted line indicates the values for Pulse No: 58323 (Fig.1).



Figure 6(a): Non-inductive current components in the JET hybrid regime from TRANSP for Pulse No: 58323 (figure 1). The beam current accounts for 35% of the total current and the boostrap current for 25%.



Figure 6(b): q profile simulation from the CRONOS code [12] using TRANSP kinetic data. For $b_N=2.8$, (t=8.5s to 13.5s) non-inductive currents are maintaining stationary conditions above q=1 for 2 resistive times consistently with the experiment.



Figure 7: Comparison of the experimental thermal energy with it prediction from IPB98y2 scaling law (circles) with the pure gyro-Bohm scaling law (crosses) for JET hybrid discharges above β_N of 2 at different triangularity.



Figure 8: Comparison of the experimental maximum normalised ion temperature gradient with the critical gradient from theory [16] for ITB regimes (triangles), hybrid regimes (circles) and standard ELMy H-modes (squares). This graph is made for a limited dataset of pulses with magnetic shear greater than 0.2 and normalised density gradient length below 2.



Figure 9: Diffusion and convection coefficients for tritium in a hybrid discharge at JET determined from trace tritium experiment. The dashed lines indicate the error bar on D as determined by the fitting technique with the transport model for tritium. Diffusion and convection of tritium are dominated by turbulent transport.

Figure 10: Diffusion and convection coefficients for neon in two hybrid discharge with different triangularity at JET determined from Neon puff experiments. Diffusion of neon is dominated by turbulent transport in the plasma core and is affected by triangularity at the edge.



Figure 11: Comparison of ion and electron temperature from the CRONOS code predictive simulation using scaling law normalisation for JET Pulse No: 58323 (see Fig.1) with experimental charge exchange data (ion temperature) and Thomson scattering data (electron temperature)