JET PROGRESS TOWARDS AN ADVANCED MODE OF ITER OPERATION WITH CURRENT PROFILE CONTROL.

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Abstract

The recent progress of the EFDA-JET facility in the Advanced Tokamak scenario research are reviewed, emphasizing their relevance for the advanced mode of ITER operation. In particular, the key role played by the current density profile from the low performance prelude phase, to trigger an internal transport barrier (ITB), to the high-performance steady-state, to maintain the regime, is illustrated by the recent results obtained on JET on reversed magnetic shear targets. The mitigated ELMy edge behaviour, as well as the neoclassical nature of the particle transport in highly non inductive ITB discharges are also reported and discussed. Finally, the first demonstrations of real time profile controls of ITB discharges open the way towards high performance steady-state Advanced Tokamak discharges, provided that current density and pressure profiles are controlled.

1. Introduction

In the framework of the EFDA-JET facility, a significant effort is devoted to the study of Advanced Tokamak (AT) regimes, with the aim of developing such scenarios for operation in a next step burning plasma. AT regimes are desirable for high performance operation because they exhibit higher confinement with

respect to the reference ELMy H-mode. This would allow, for the same performance level, a reduction of the operating plasma current, thereby opening the route towards steady-state regimes with full non-inductive current drive. In addition, AT regimes are characterised by an intimate link between the plasma current profile and the energy transport properties, through the key role played by the self-sustained bootstrap current. In present day experiments, most of the recent works on AT regime development has focussed on the study of so-called internal transport barriers (ITBs), which are typically associated with local flattening and/or reversal of the plasma magnetic shear ($s = (r/q)dq/dr$, where *q* is the safety factor, and r the minor radius) in the plasma core and large flow shear, inducing stabilisation of turbulence. In this paper the progress achieved on JET (EFDA-JET campaigns 2000 and 2001) in this domain is reported, underlining the relevance of recent experiments for an integrated AT scenario in a burning plasma. The main remaining open issues, which form the basis for the mid-term workprogramme, are highlighted. In the paper the schematic time history of a plasma discharge is followed, from the breakdown to a steady-state phase, and the specificity brought to it by the AT regime is analysed in details. The present understanding of the assets and drawbacks of ITBs as candidates for an AT regime in large devices is then summarized.

2. The prelude phase : towards the target plasma

In large tokamaks, tailoring of the current profile towards flat and/or hollow profiles can only be carried out during a low-performance phase, which will be referred to as the “prelude”. The reason is the strong dependence of the plasma current resistive diffusion time τ_R upon the electron temperature and plasma size, leading to unacceptably long transients in the current profile if not tailored

in a low-performance phase. Let's note that τ_R, which reaches radial averaged values of tens of seconds on a performant JET discharge, will overcome several minutes in a burning ITER. On the other hand the long resistive diffusion times also imply that, once the desired current profile is achieved by pre-tailoring, it stays almost « frozen » in the high performance phase of a large tokamak. This allows real time current profile control to be envisaged, with long feedback times.

The most effective way of shaping remains the ohmic drive during the plasma current ramp-up phase. The plasma current then diffuses from the edge towards the centre, scanning in time a full series of current profile shapes from deeply hollow to monotonic. Let us add that the overall MHD stability is also more favourable in that case, compared to a procedure which would reverse the current density profile from a monotonic situation.

Experimentally, pre-shaping of the ohmic current profile depends on many parameters, and first of all on the plasma breakdown, strongly machine dependent. Particular attention was devoted in JET to improve the reproducibility of a low-voltage type of breakdown, in which a full-board single-null X-point plasma configuration can be achieved within less than 1 second, when the plasma current profile is still hollow. The breakdown scheme employed for Advanced Tokamak scenarios in JET is constrained to low loop voltage for technical reasons and as a result the plasma current profile obtained has tended to be sensitive to factors such as wall conditions. Control improvements have led to an increased reproducibility of the avalanche phase itself, of the rate of rise of plasma current and thus of the plasma current profile at early stage of the discharge. Then several other externally controllable

parameters influence the ohmic current penetration. In particular, the simplest way to maintain a significant degree of current profile hollowness is to maximize the current ramp rate at low plasma density. Unfortunately the achievable current ramp rate is limited both by MHD instabilities and by machine operation constraints; at the same time coupling of additional heating power during the prelude phase generally requires high plasma density. Such considerations restrict the range of target q-profiles accessible through this method. Typically in JET flat to slightly reversed q-profiles (q_{min}~$q_0 \leq q_{95}$) can be obtained with current ramp rates of the order of 0.4-0.6 MA/s at a line averaged density of the order of $10^{19}m^{-3}$. A machine like ITER will have further operating constraints on its current ramp rate, due to the super conducting nature of the poloidal coil system, and on the minimum target density to allow the negative neutral beam injection (NNBI) safely.

The availability of an additional heating and current drive (H/CD) system during this prelude phase is thus highly desirable to expand the range of target current profiles. In this context, the theoretical merits of the various existing H/CD systems are reviewed for JET conditions in [Tala01]. The use of either off-axis ion cyclotron resonant heating (ICRH) in D(H) minority scheme, or lower hybrid current drive (LHCD) power has allowed JET to reach, at the end of a 3-4 second long prelude phase, hollow ($q_{min}<q_0 \leq q_{95}$) to deeply hollow ($q_{min}<q_{95}<q_0$) current profiles. In addition, in high power LHCD cases ($2<P_{LH}(MW)<3$) there are strong indications of total absence of plasma current inside the core region ($1/q_{min}$ ->0 for $\rho < 0.2$-0.25, where ρ is the normalized minor radius) [Hawkes01]. The combination of a reproducible breakdown and LHCD power injection thus provides in JET a reproducible reversed shear (RS) target plasma. The

transposition to an ITER-like plasma would require, in the absence of an LHCD system, either a very localised off-axis electron heating scheme, like Electron Cyclotron Resonance Heating (ECRH), or a combined H/CD effect by NNBI. Quantitative simulations of such a prelude scenario in ITER need to be carried out; in the meantime, an experimental simulation may be available in JET once a multi-megawatt ECRH system, planned for the JET-EP phase, is installed and operational. Finally, the bootstrap current itself can be used in a high density prelude phase. This means optimising the prelude operation at the highest poloidal beta, by carefully shaping the power and gas injection waveforms, in particular through dedicated feedback loops. This will be investigated in the coming JET campaigns.

3. Accessing an ITB regime

The flexibility in the choice of the target current profile is important for the ITB regime for two main reasons: firstly it has a strong influence on the conditions to access a plasma with an ITB and secondly, as discussed in the next section, on the nature of the ITB itself. The dependence of the access power to ITB regime on the target current profile is clearly illustrated in figure 1. A low (positive) central magnetic shear target (LS) requires on JET (q_{95}~3.3) between 10 and 20 MW of additional power, usually a mixture of positive NBI and ICRH, with an additional dependence upon the magnetic field and/or the plasma current. On the contrary RS target plasmas with LHCD during the prelude allow ITBs to develop, in similar plasma current, magnetic field and density conditions, with typically half this power and with a much less obvious dependence from the magnetic field.

Quantifying such an effect requires a more careful analysis of the key factors in the ITB triggering processes. We have first investigated, for two given target current profiles, a LS and a RS target, with identical plasma current (2.2MA), magnetic field (2.6T) and target density (n_{e0}~$1.5x10^{19}m^{-3}$), the influence of the heating scheme on the ITB access power. As reported in [Challis01], the ITB access power in JET is lower when NBI heating is dominant; interestingly, the ITB access power does not appear to be strongly sensitive to variations in the injected torque. It has to be recalled, in this context, that in JET NBI provides more bulk ion heating than ICRH, in addition to significant fuelling. It is also worth noting that ITBs are often triggered, although in the electron temperature channel only, even during the LHCD prelude phase: in these cases the access LHCD power level (~2MW) seems to correspond to the power required to obtain a vanishing current density in the core. These electron ITBs are then located in the vicinity of the minimum (negative) magnetic shear [Hawkes01] [Hogeweij01] [Hellsten01] [Conway01].

Although tailoring of the magnetic shear profile appears to be crucial in determining the access power level, it doesn't fully control either the time or the location of the ITB growth event. A careful analysis of both LS and RS cases [Joffrin00] clearly shows the key role played by the q-profile itself, and in particular by the presence of low rational (q=…, 3, 2, 1) surfaces in the plasma core. More specifically, a local breaking of the plasma rotation, under the influence of MHD coupled modes, seems to be the mechanism favouring the bifurcation towards the ITB in its immediate vicinity. Attempts to produce similar modification by external means (shallow pellet injection, laser ablation, saddle

coils, …) and thus trigger ITBs independently from the q-profile have obtained mixed results, as reported in [Gorini01].

The electron ITB itself, when triggered in the prelude phase, usually develops into a general (electron and ion temperature-density-rotation) ITB once high power (NBI or NBI+ICRH) is applied. The subsequent time history of the ITBs then depends on the time evolution of the q-profile : transitions to very high performance ITBs have been observed when q_{min} reaches 2 or 3, and will be discussed in the next section.

Our studies also confirm that it is essential that the right pressure, rotation, and density profile conditions are present for an ITB to occur and to be sustained. The quantitative analysis [Esposito01] of recent JET ITBs further confirms, both in LS and RS targets, that the rotation shear locally exceeds the linear growth rate of the ion temperature gradient (ITG) modes [Hahm], provided that the calculation of this growth rate includes the shear dependence [Waltz]. This condition can sometimes be satisfied twice along the plasma radius; correspondingly, double ITBs have been observed. Results from perturbative transport experiments probing ITBs with cold pulses seem also consistent with this picture [Mantica01]. It is however still impossible to track experimentally the causality between the occurrence of the ITB and the local increase in the ratio between rotation shear and ITG growth rate. Note that the observed link between the rational q-surfaces and the triggering of ITBs, not included in the former approaches, is supported by recent modelling [Garbet], involving the specific role played by those surfaces in the turbulence decorrelation process.

4. Transition to a high performance plasma

In a burning tokamak experiment or a reactor, the operational window in which an ITB is triggered might be sufficiently constraining to justify a specific phase devoted to the set-up of the steady-state AT regime. A key question is then raised: under which time sequence should the ITB triggering and the achievement of break-even and Q>1 occur ? The answer is obviously strongly linked to the AT regime access condition, compared to the H/CD capability of the machine. Since the ultimate goal of an AT regime is ignition at reduced parameters, and in particular at reduced plasma current, burning experiments like ITER may require developing experimental scenarios where the triggering of the AT performance occurs prior to Q=1. This implies that an operational path has to be found where the plasma profiles are tailored to enter a low-current (q_{95}~4-5) AT regime which then drives the plasma above Q=1. If this first route is chosen, the AT regime may have to survive a major transition in the heating/torque/fuelling conditions. The opposite path, where the fusion alpha particle power is used to enter the AT regime, would require sustainment of the plasma current profile in an optimised shape during a high plasma current (q_{95}<3) phase, ensuring a Q>1 ELMy H-mode regime which then would transit into an AT state. Subsequently, the plasma current would be slowly decreased towards its steady-state value. This second route, probably more demanding in the prelude phase and with much longer transients, is worth investigating in super conducting tokamaks (Tore Supra, KSTAR, JT60-SC, …), where the pulse duration can significantly exceed the resistive time. The Tore Supra long pulse database contains examples of hot electron core regime triggered after one minute in LHCD almost fully sustained plasmas [LHEP]. In such cases,

experimental simulation of alpha particle heating, for instance by ICRH minority heating, would also be required.

The route presently followed by JET is the first one, where the ITB is triggered and then used to access the high power phase, under current profile conditions « frozen » and as close as possible to the current profile envisaged for the steady-state phase. Some of the recent experiments have concentrated on the study the strength of the ITB, and thus of the corresponding performance and bootstrap current fraction, as function of the target current density profile. It was found [Challis01] that a RS target discharge in which q_{min} reaches an integer value (namely 2 or 3) develops ITBs similar in width to LS targets in equivalent conditions, but with steeper pressure gradients, more localised in the barrier vicinity. Note also that, within the experimental uncertainties, ITBs are detected simultaneously and at the same location on electron and ion temperatures (T_e and T_i), on density and on plasma rotation. In optimised conditions, and particularly with broad current profile, maximum heating power and fuelling, RS discharges at Ip=2.5MA, B=3.45T and q_{95}=4.5, e.g. #51976, have reached simultaneously a neutron rate of $4.1 \times 10^{16} s^{-1}$, $H_{IPB98(y,2)}$=2, and β_N=2.4. A simplified extrapolation from DD suggests that these discharges would approach Q_{DT}^{eq}~0.5. This type of ITBs seems to provide relevant conditions for driving a tokamak plasma towards break-even, below the parameters required by the conventional ELMy H-mode, and/or by LS target ITBs (figure 2). The total energy content analysis in terms of pedestal plus core energy shows that above the ITB access power the core energy increases almost linearly with the additional power, thus breaking the usual confinement time degradation with power [Challis01]. The RS target ITBs even give some bonus to that respect,

due to stronger and more localised barriers, favouring core conditions (density and temperature) close to the requested fusion conditions : for example #51976 has ion temperature of roughly 25keV and $n_e > 4x10^{19}m^{-3}$ inside ρ=0.5. Further increases of the JET additional power capability, as planned for the near future and for the longer term in JET-EP, will help approaching the relevant Q_{DT}^{eq} conditions. Nevertheless it has to be stressed that the results presented here are obtained with a dominant fraction of positive NBI (mixture of 80 and 140 keV beams), i.e. with a significant bulk ion heating and fuelling signature. The specific H/CD mixture foreseen for ITER will demand a careful adaptation of the scheme, as in particular it is foreseen to provide a more balanced bulk ion/electron heating, with reduced torque and central fuelling. The particular problem of reaching a satisfactory operating density under such conditions remains an open issue [Lomas01].

As mentioned above, in a next-step AT scenario once the ITB is triggered the plasma will then enter a burning phase, which means a significant rearrangement of the heating sources from additional (NNBI, ICRH, …) to fusion alpha particles. For the ITB sustainement, this basically implies a dominant bulk electron heating driven by very energetic ions, low fuelling and no injected torque. The high density in a burning plasma will also imply a strong equipartition between the bulk ion and electron species (and thus T_i~T_e). Although the composition of the JET H/CD system prevents us from demonstrating the viability of high performance ITBs under such conditions, the JET experimental database now contains a significant number of ITB discharges obtained by balancing the power transferred to the bulk ion and electron species and showing T_i~T_e~10keV. It is these discharges that at

moderate plasma current, q_{95}~5-6, form the basis for the long-term sustainement of the regime, as described in the following section.

Here again, the significant increase of the ICRH power capability of JET in the coming years will help us improving progressively the operation of high performance ITBs with balanced heating (JET-EP project, ITER-like ICRH antenna).

The remaining point to be discussed in this section concerns the optimisation of the target current density profile with respect to the confinement of the trajectories of the fusion-born alpha particles, as well as to the various performance-limiting instabilities to which they may couple in the Alfven range of frequency. Both aspects certainly claim for the presence of a significant plasma current density in the hot core region. This implies that a deep shear reversal is not compatible with a steady-state burning plasma at high Q-value [Jaun] and it suggests that deeply hollow current density profiles may be envisaged only during the prelude phase and/or up to the burn-up phase of the discharge. The current profile must then aim towards a flat to slightly hollow shape compatible with an AT regime sustained by a large fraction of alpha particle power.

5. The steady-state

As mentioned in the introduction, an AT regime is ultimately fully justified only by its steady-state capability. This means that the current density profile should rely only transiently on its ohmic component ; furthermore a significant bootstrap current fraction must be generated and the additional low-efficiency current drive systems must provide additional current to align the overall current density to the desired stable profile.

Significant progress has been made in this field in the last JET campaign, in particular with the demonstration that a steady-state current profile leads to a steady-state AT regime. For such experiment [Litaudon01], the plasma parameters of B=3.45T, Ip~2MA were chosen as to give at the same time good plasma confinement and, given the available additional heating power, a significant value of poloidal beta ($1<\beta_p<1.6$). The resulting bootstrap current fraction is estimated to be of the order of 35-40% of the total plasma current, with the remaining part of the non inductive current provided by tangential NBI (co-current) and LHCD. The plasma loop voltage was close to zero during all the main heating phase and the estimations of the non inductive current fraction reach about 80%. More in detail, this type of discharges, e.g. #53521, was carried out as a RS target, with 2.8MW LHCD prelude: subsequently, a combined T_i-T_e-density-rotation ITB was maintained with 15MW of NBI, 4MW of ICRH and 2.8MW of LHCD for the entire 8 seconds of the pre-programmed high power phase, corresponding to about 27 energy confinement times. The T_e barrier itself was triggered during the prelude phase and lasted throughout the 11 seconds of the discharge. In these plasma the resistive time, either estimated at the foot point of the ITB or averaged over the plasma cross-section, is about 10 seconds. This breakthrough experiment is relevant to several crucial issues of the steady-state AT regime. First of all, the ITB initially expands from the prelude electron ITB; its radius is then frozen around ρ=0.4 and does not show any further expansion, shrinking or bifurcation behaviour. The q_{min}-radius is frozen as well around ρ=0.5. This reproducible observation confirms that the control of the current density profile is the key factor in the ITB width control: the « open loop » control by NBI+LHCD+bootstrap used in this

discharge, although not realistically applicable to an ITER AT operation, provides the indispensable proof of principle. In this framework, it is worth noting that some of the high performance discharges discussed in section 4 [Challis01] are also relevant to this issue as their very strong ITB drives up to 60% bootstrap current fraction, though not stationary nor controlled.

A second reason why discharges of the type #53521 are relevant to the steady-state lies in their edge behaviour. In JET, as in other divertor machines, high performance ITB discharges occur typically at power levels well above the L to H-mode transition, and even above the type III to type I ELM transition. This leads inevitably to the triggering of giant ELMs and usually results in the destruction of the ITB itself and, in the worst cases, in a major plasma disruption. For example, the termination of the high performance ITB on JET pulse #51976 falls into this category. Peripheral injection of high-Z gases (Argon, Krypton, …) has been demonstrated to have a mitigating effect on the ELM activity through edge radiative cooling. This solution is, however, non desirable for steady-state operation because it is susceptible to impurity accumulation. In fact, highly non inductive ITB discharges as #53521 do not show any strong ELM activity for the duration of the discharge [BécouletM01]. Detailed investigation of this feature, through dedicated experiments, highlights the possible role played by the edge plasma current and/or magnetic shear in the type III to type I ELM transition. It is important to underline here that the « edge » current in question is the « broad range » edge current, influenced by the overall plasma current density profile shaping process. These discharges in fact show steady-state low internal inductance (l_i~0.7-0.8), and/or low edge shear (s_{95}~ 2.5). The broadening of the plasma current density profile requested

by the AT regime itself thus seems to also have a beneficial effect on the ELMy edge behaviour. This issue will be further investigated in the forthcoming JET campaigns, when the modifications to the divertor geometry will allow operation with plasma equilibria closer to the high triangularity configurations envisaged for ITER.

Finally, a third reason why discharges of the type #53521 are extremely important in the progress of steady-state AT regime is the possibility to study quantitatively how particle transport and impurity accumulation are influenced by the presence of an ITB. Such studies, in fact, require that the regime is established on time durations at least of the order of the particle confinement times, which are several times larger than the energy confinement time. The analysis detailed in [Dux01][Giroud01][Litaudon01] clearly shows that the particle confinement is strongly influenced by the expected neo-classical effects due to density and temperature gradients, and dependent on particle charge Z. Steep density gradients, in particular, provide an unacceptable accumulation of high-Z impurities in the plasma core, with a dilution effect detectable on the neutron rate. In the case of discharge #53521, the high-Z impurity accumulation leads, 4-5 seconds into the high power phase, to a radiative collapse of the core ($\rho<0.2$) in which energy and density are expelled (figure 3). It is interesting to note, however, that the ITB regime recovers from this collapse. The screening effect expected from the ion temperature gradient is either too localised and/or not strong enough to prevent the accumulation. Similar analyses on ITBs with weaker gradients and/or multiple barrier cases show weaker impurity accumulation. The observation of strong high-Z impurity accumulation is strongly related to the measured coincidence between temperature and density.

A large effort must be devoted to investigate whether AT operation in burning plasma conditions, including higher collisionality, absence of core fuelling, relevant pumping conditions, …, would favour flatter density profiles, thus slowing down the impurity accumulation process. Let us finally note that very recent data, obtained with Helium-beam injection, on fast Helium behaviour in ITBs are now available on JET. Analysis of these experiments, fundamental for understanding the influence of the regime on the alpha particle and ashes confinement, is in progress and results will be reported later. An alternative way to alleviate phenomena like impurity accumulation on long pulses would be to base the steady-state scenario on a periodic (MHD) relaxation/instability, thus ensuring a periodic and controlled loss of confinement. A similar behaviour has been experimentally found, initially in ASDEX-U [AUG], in the LS target scenario with $q_0 \sim q_{min}=1$. In this type of AT discharges a fishbone m=n=1 MHD activity is observed, which maintains the central q value in the vicinity of q=1 and prevents too strong profile peaking in the core. In ASDEX-U such regime was sustained for about 6s without evidence of ITB; recently JET reproduced this regime, on a 1s timescale [Joffrin01] in presence of a narrow ITB correlated to the q=1 surface. Further optimisation is still needed to extrapolate this regime to high performance, but it could contain in principle an interesting solution to the problem of impurity accumulation, provided the fast fusion products are not too strongly affected.

Progress towards steady-state operation obviously also means understanding and avoidance of the various operating limits. A comparison (LS vs RS) of the MHD limits encountered in high performance ITB discharges on JET is given in [Hennequin01]. Beyond the specific aspect of « soft » or « hard » limits

generated by the MHD activity of the AT regime, already discussed on many occasions, this raises the important issue of control of such regimes. It is certain that the sustainement of AT regimes, relying on tailoring of a certain numbers of profiles, requires active feedback controls. These controls might then also include the MHD limit aspects by carefully keeping the discharge in a stable domain. A decisive effort has been made on JET to set up the first closed feedback loop on local profile control during ITB discharges [Mazon01]. The 48 channels of the ECE radiometer are now treated in real time to derive, following the criterion discussed in [Tresset01], the occurrence, the location, the strength and the width of an electron ITB in the discharge. This enables a close-loop feedback on local parameters to be carried. Several algorithms have been tested and optimised. The most promising in terms of stationarity consists in adding to an ITB scenario of the type #53521 (B=3.45T, Ip~1.8-2MA, LHCD during prelude and main power phases) a double control loop : the first one regulates the ITB strength through the ICRH power and the second one controls the total neutron rate by the NBI power. The resulting discharge #53697 shows a real improvement in its stationary behaviour (figure 4). One must underline here that in absence of LHCD during the high power phase, similar controls were possible but did not prevent the ITB radius from slowly shrinking in time as the current density profile evolves, thereby limiting the duration of the AT phase. The planned increase of measured plasma signals available in JET for real-time control allows us to envisage more advanced feedback control schemes involving, for example, ion temperature, density and current density profiles. This will also open the route to test new algorithms as for instance the link between the ITB radius dynamics and the LHCD power level, and/or spectrum.

It has to be emphasized, however, that developing control loops requires a large amount of dedicated experimental time and simulations in order to derive the relevant algorithms and test the actuators. Moreover, these types of controls always imply operating at somewhat reduced performance, in order to allow the actuators for substantial margin. This is true on JET as well as on any experiment.

6. Conclusions

Recent JET work on an advanced mode of operation for ITER has produced important results, in particular on the link between the current profile and the regime itself, and consequently on the steady-state characteristics and potentialities of an ITB-based AT discharge. The access to an ITB regime is strongly influenced by the target current density profile : it has been observed that Reverse Shear profiles yield lower access power than monotonic or zero shear target. In addition, rational-q surfaces have been found to play a determinant role in the initial growth event of the ITB. Though a quantitative extrapolation to ITER is not yet available, one can be reasonably confident to access an ITB regime at the end of a dedicated prelude phase in ITER, adjusting the current ramp rate, the operating density and the additional CD capability available, i.e. the target current density profile. Many models are already available, including 2D predictive self-consistent codes [Cronos], and will be used in the near future for this purpose. Although use of LHCD is not an absolute requisite, it remains nevertheless the best tool presently available for tailoring the current profile in the prelude and maintaining the desired profile during the ITB phase. In the planned q_{95} range of ITER AT operation the transition towards a very high performance phase with ITB and the break-even

is expected to be possible, though the present database is mostly supported by positive NBI power, i.e. by a high fuelling bulk ion heating scheme. A convincing and reactor-relevant demonstration of such a transition using a low fuelling bulk electron heating scheme, with a high level of equipartition and an independent edge fuelling system, like pellet injection, is clearly needed although it is unlikely to occur in the near future. The steady-state burning phase itself will require the current density profile to be flat and/or slightly hollow, to confine the fusion products, and the ion temperature barrier to be as wide as possible, with small density gradient, to minimize the high-Z impurity accumulation. Regimes with higher pedestal density are also to be developed for a better compatibility with the divertor. The broadening of the current density profile seems to be favourable for maintaining the edge in a type III ELMy H-mode, although this trend needs confirmation in a plasma shape closer to ITER. Edge issues will be further investigated on JET during 2002. To summarize, the Advanced Tokamak regime requires not only the full control of the pressure profile, but also of the current density profile, inside the MHD stability domain. The Advanced Tokamak studies for burning plasmas will continue on JET, integrating progressively all these aspects, under closed feedback loops.

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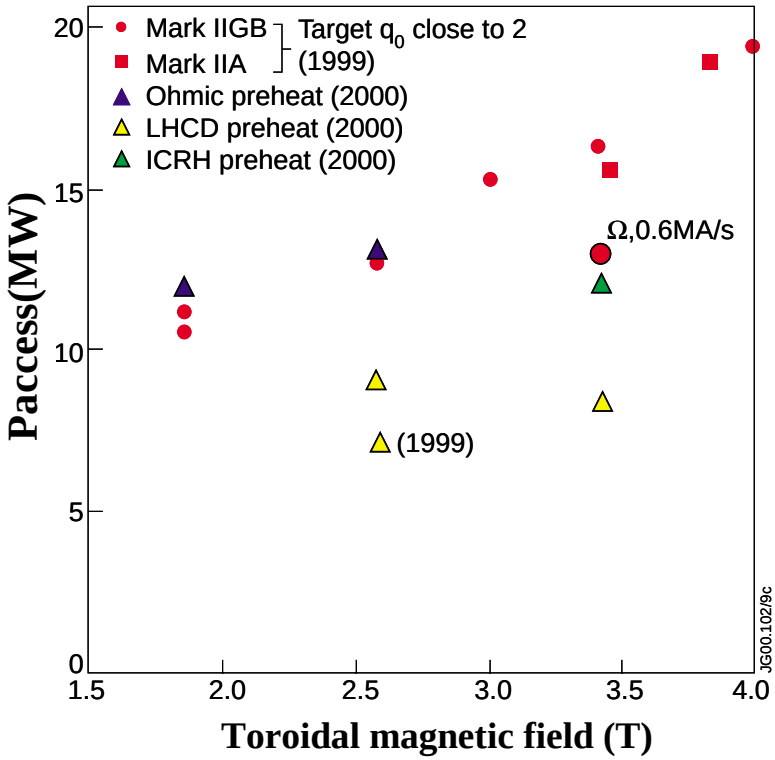

Figure 1 : *ITB access power versus magnetic field, for LS targets (red circles and squares, blue triangles), and RS targets (yellow and green triangles)*.

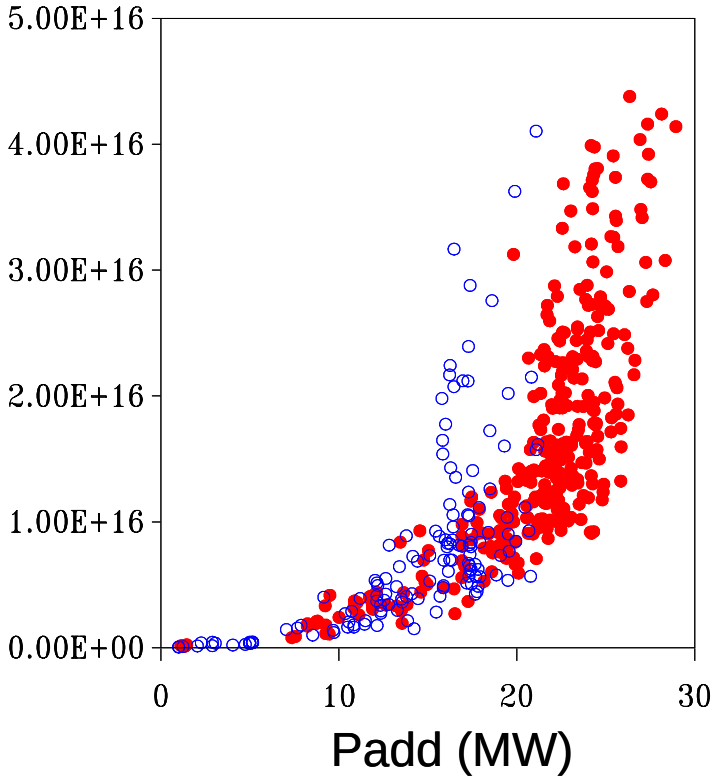

Figure 2 : *neutron rate versus maximum additional power, for all high performance recent JET discharges (ELMy-Hmode and LS ITBs 1998/99 (red full circles), RS ITBs 2000/01 (blue empty circles))*.

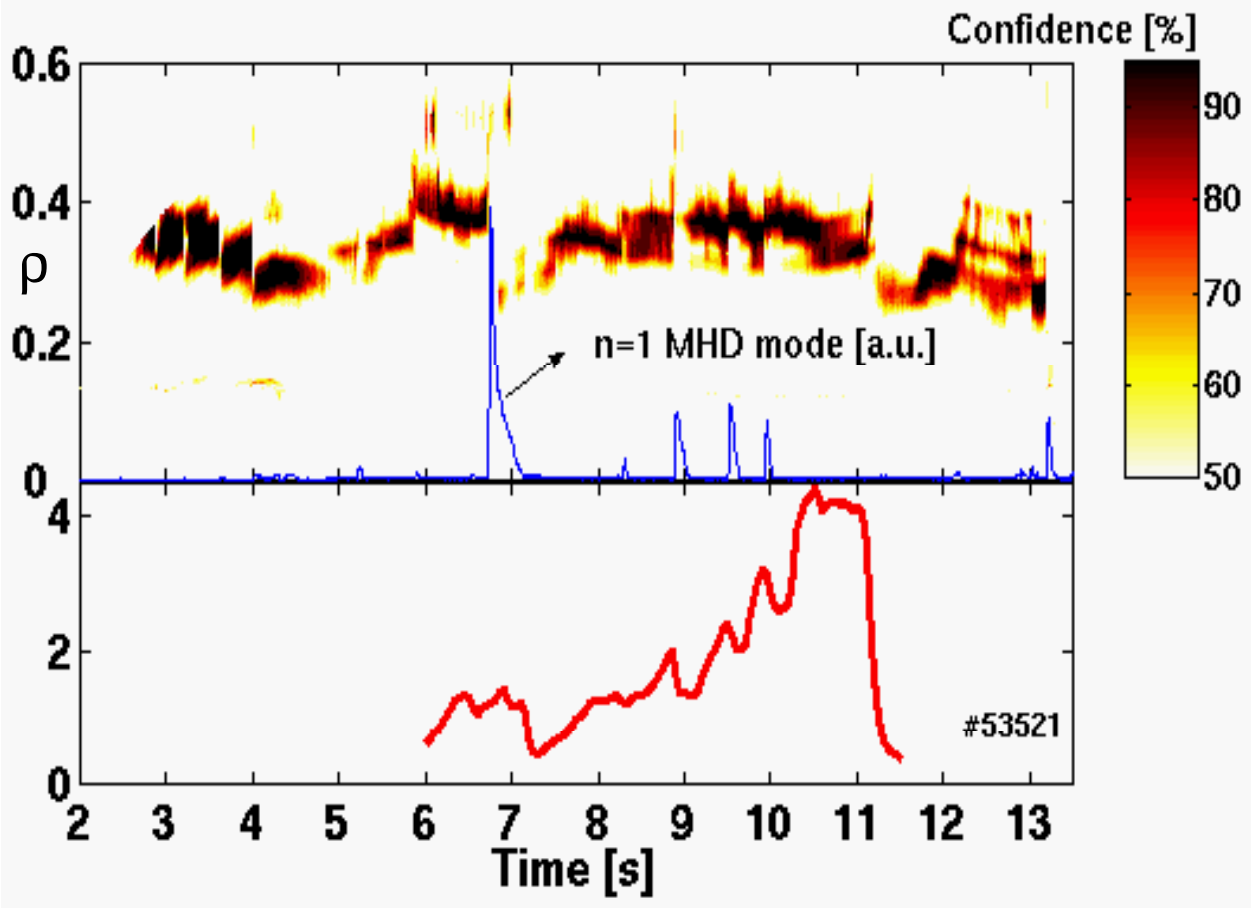

Figure 3 : *time evolution of the ITB radius (as determined by the criterion described in [Tresset01]), n=1 MHD activity, and of the Nickel core density for JET pulse 53521*.

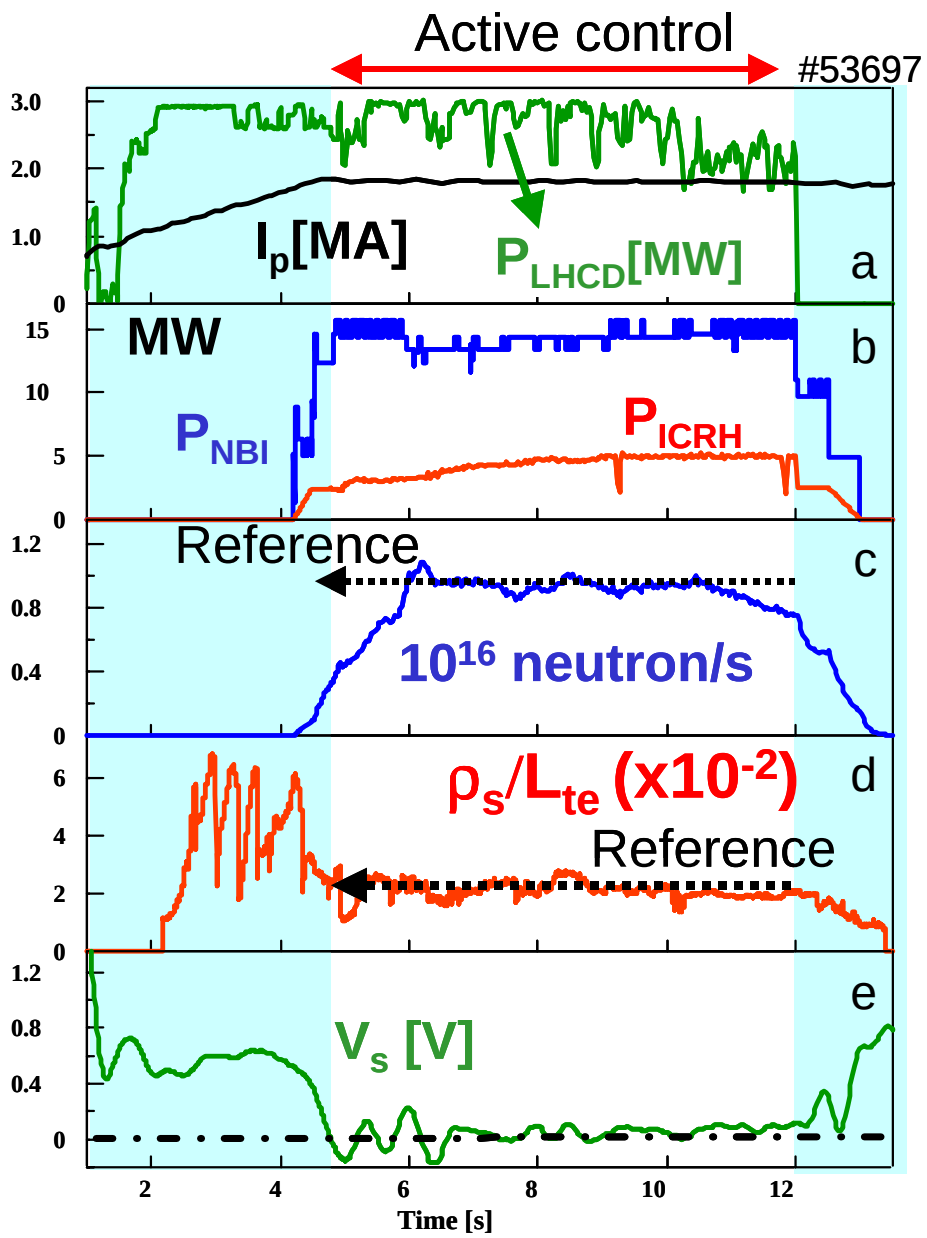

Figure 4 : *time evolution of (a) the plasma current and LHCD power, (b) the NBI and ICRH power, (c) the neutron rate and its prescribed reference, (d) the ITB criterion and its prescribed reference, and (e) the plasma loop voltage, for JET pulse 53697.*