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ABSTRACT

Many tokamak plasma regimes have been developed which exhibit improved plasma stability and energy confinement compared with the ELMy H-mode which has been used for some time as the baseline for reactor design. In particular, transient high performance has been achieved in experiments with low or reversed magnetic shear (s=r/q(dq/sr)) and substantial progress is now being made to extend these plasmas towards steady-state. The achievements with regime in several tokamak devices are presented in this paper and outstanding issues for the further exploitation of this scenario are discussed.

I. INTRODUCTION

Since the first demonstration of an improved plasma energy confinement regime in a tokamak experiment, the so-called H-mode in ASDEX [1], a substantial effort had been devoted in almost all tokamak devices to the development of regimes with even higher confinement. There are two main reasons for high priority to be given to such research.

Firstly, high confinement regimes extend the capability of present tokamak experiments to produce high fusion yield and, even if they are only achieved transiently, allow a study of the limits of plasma operation due to magneto hydrodynamic (MHD) instabilities. Secondly, regimes capable of delivering high fusion yield with reduced plasma size and current compared with H-mode plasmas with Edge Localised Modes (ELMs), considered for the reference ITER [2] offer the potential for cost reduction as well as steady state operation in tokamak reactor design. In order to make progress towards such a reactor relevant regime it is necessary to demonstrate high confinement and fusion yield in plasmas with high poloidal β (β_p), where significant non-inductive current drive is provided by the bootstrap mechanism for steady state operation, and high normalised β (β_N) = βaB/I), which indicates the potential for good plasma stability with reduced machine parameters [3.].

Many plasma regimes have been developed which exhibit some of these features: hot-ion ELM-free H-modes in JET and DIII-D; supershots in TFTR; PEP modes in JET and C-MOD; low or reversed magnetic shear in TFTR, DIII-D, JT-60U, JET, Tore Supra and ASDEX Upgrade; VH-modes in DIII-D and JET; high plasma internal inductance modes in TFTR, DIII-D and Tore Supra; high β_p modes in JT-60U and JET; RI modes in Textor; EDA modes in C-MOD, etc.. The highest fusion yield (16MW) and first observation of alpha particle heating was achieved transiently in the hot-ion H-mode regime using deuterium-tritium (D-T) fuelled plasmas in JET [4] in contrast to 4MW of fusion power produced in steady ELMy H-mode for several seconds [5].

To review and compare all these regimes is beyond the scope of this paper. However, there are now a wide variety of experiments being performed using low or negative magnetic shear that are focused on the development of high fusion performance plasmas with the potential for steady state operation. These are characterised by significantly reduced heat and particle diffusivity within a region of the plasma interior. This phenomenon, called an Internal Transport Barrier (ITB), results in a peaked pressure profile which, with the use of substantial ion heating and fuelling, can result in plasmas with high fusion performance. These experiments are the subject of this topical review.

II. PLASMA OPERATION WITH MODIFIED MAGNETIC SHEAR

It has been proposed that plasma stability and energy confinement can be improved by modifying the plasma current profile. A flat or hollow current density profile produces a zero or negative value of the magnetic shear (s). This is predicted to allow the plasma to remain stable at higher plasma pressure than would be possible with positive shear and to stabilise toroidal drift modes such as trapped particle and ion temperature gradient instabilities [6]. Such an improvement has been observed in several tokamaks [7] [8] [9] [10] [11] [13]. This is illustrated in Figure 1 where the formation of an ITB in the core of a TFTR plasma is shown by the strong peaking of the plasma pressure within the region of reversed magnetic shear. A very strong reduction of the turbulence was also observed inside the barrier region [14]. The mechanism for transport reduction within the ITB is likely to be a combination of strong ExB shear, leading to decorrelation between density and velocity perturbations, and low or negative magnetic shear, stabilising or reducing the growth rate of various MHD modes [15][16][17]. Low magnetic shear also allows to decouple turbulent modes whose width scales as $s^{-1/2}$ as compared to the distance between modes which scales as s^{-1}. Synergy between ExB shear which either negative or low magnetic shear can be invoked to stabilize turbulence.

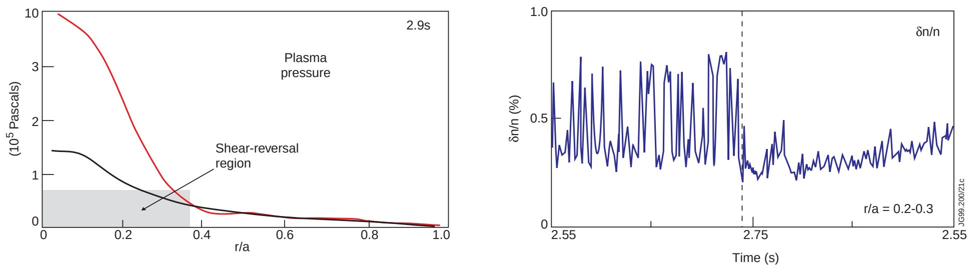

Fig.1: Strong plasma pressure peaking and reduction of turbulence in some reversed shear discharges in TFTR[7][4].

The methods used to produce the low or negative magnetic shear capable of producing ITBs are very similar in present experiments. Additional heating is used during the initial current ramp-up phase of the pulse in order to slow down the plasma current penetration. The techniques then vary as to the details of the heating power waveform and the use of different heating schemes. An example of a Neutral Beam (NB) heated plasma with no pre-heating phase in JT-60U is shown in Figure 2. The pulse shown in Figure 2 reached the highest fusion yield in JT-60U with a record value for Q, and Q_{DT} equivalent of 1.25. The ITB is formed close to the location of the q_{min}.

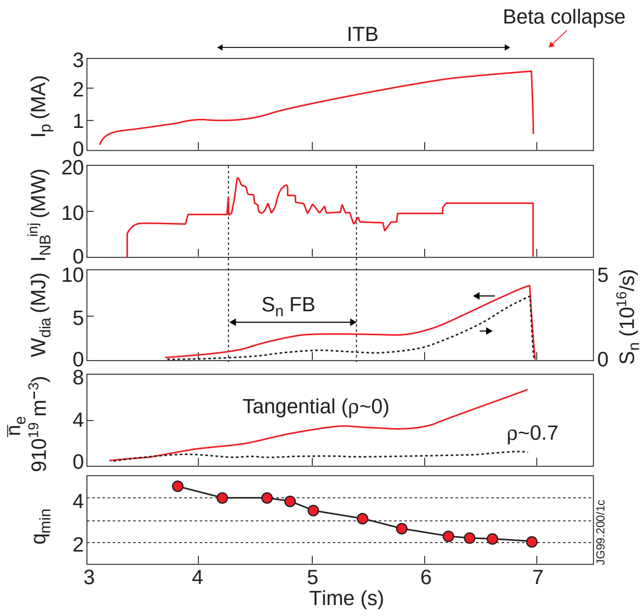

Fig.2: Waveforms of highest performance reversed shear plasma in JT-60U. NB power is applied very early when Ip is low and the current profile very hollow. Power is feedback controlled when 4 < q_{min} < 3 to avoid pressure driven disruptions. [13].

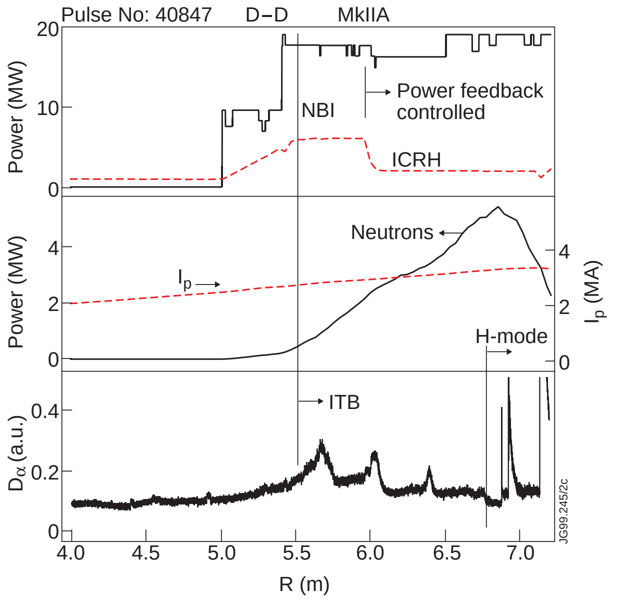

Fig.3: Optimised shear scenario in JET (Bt = 3.4T). Lower Hybrid Current Drive is used to assist in the plasma start-up phase and to provide a reproducible current profile. ICRH is then used at low power to raise the electron temperature. Additional heating power is controlled to avoid disruptions due to pressure profile peaking.

Figure 3 shows a pulse with an ITB which produced the highest D-D fusion yield so far achieved in JET. A single null X-point configuration is used with the location of the strike points allowing maximum pumping by the divertor cryopump to reduce the edge density [18]. In JET, the production of an ITB is very sensitive to the timing of the main heating phase [19]. ITBs are mainly produced when q_o is close to 2 with a very flat current profile [20] but barriers can also be obtained with $q_o \approx 3$. It appears that increasing the heating power level significantly enlarges the range of conditions where ITBs can be obtained and that centrally located power is important to trigger an ITB [21]. Scaling of ITBs is not well documented. A first attempt to scale the power needed to produce ITB with the magnetic field strength has been made at JET [22] as shown in Figure 4. The data has been obtained with similar target q profiles and the required power increases approximately linearly with the magnetic field. A study of the effect of the magnetic shear on the power required to produce ITBs remains to be done and could lead to a better understanding of the mechanisms responsible for turbulence stabilisation.

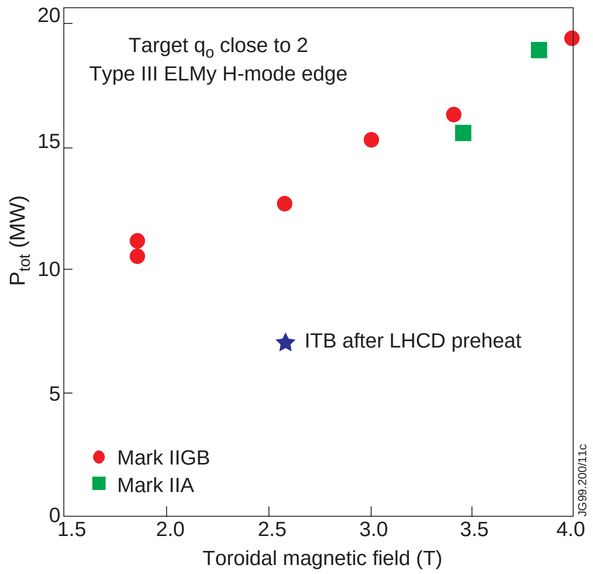

Fig.4: Power needed to trigger an ITB in JET as a function of B_t for similar target current profile density and q_{95} (~3).

ITBs can be produced with a wide variety of current profiles as exemplified in Figure 5 where examples are shown from JT-60U for a strongly reversed shear plasma and a low shear configuration in the so-called high β_p regime [23]. The ITBs are produced either close to the location of q_{min} in the reversed shear case and the q=2 surface (as in JET) in the high β_p example, and the resulting ion and electron temperature profiles are quite different. The large ∇Ti and ∇Te region is very narrow for the reversed shear configuration, similar to the ERS discharges in TFTR, indicating a localised improvement in transport. For the low shear plasma the high ∇Ti region is much larger and the confinement improvement extends to the plasma centre. This is illustrated in Figure 6 where the ion and electron diffusivities (χ_i and χ_e) are shown for a strong reversed shear plasma in JT-60U [22] and a low shear case in JET [24]. It should be noted that the reduction in χ_e tends to be spatially localised near the ITB whereas χi can often approach neo-classical values over the entire plasma core region [25]. In some experiments an improvement in χ_e is not even apparent [26]. The localised improvement in electron diffusivity has been correlated with reflectometer measurements of density fluctuations

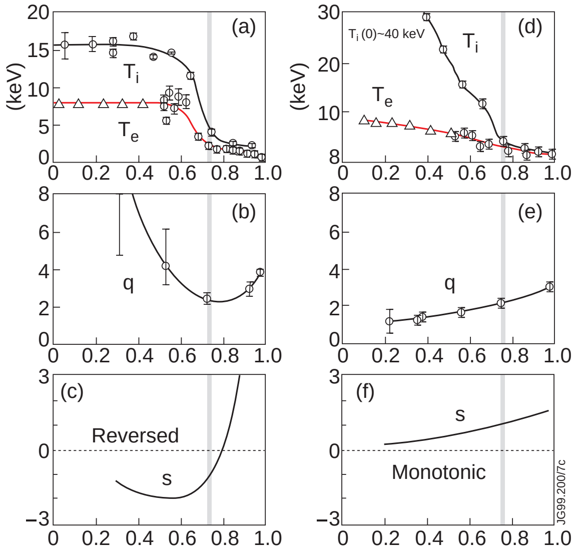

Fig.5: Profiles of ion and electron temperatures, of the safety factor and of the magnetic shear for JT-60U reversed shear and high β_p discharges (I_p, B_t, q_{95}) are similar. Characteristic ITB radius is given by a thick solid line [23].

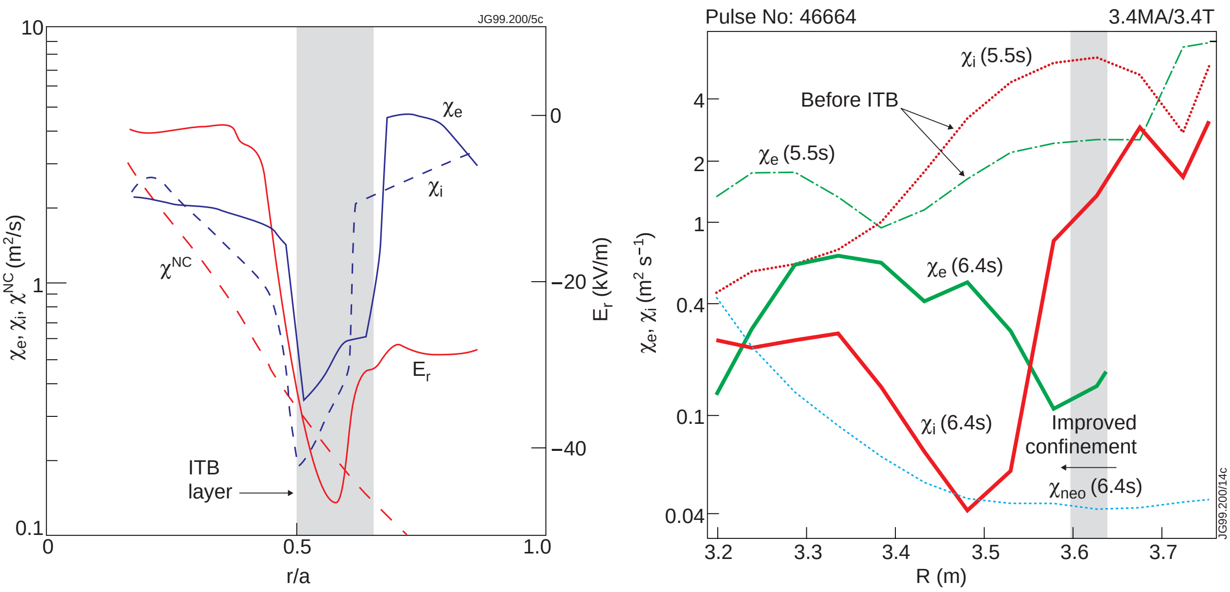

Fig.6: Radial profiles of ion and electron diffusivities for ITBs produced with a reversed shear configuration (JT-60U, fig.6a) and for a low shear configuration (JET, fig.6b). In JET, error bars are large for density profiles in the plasma periphery.

in JET [27] which show that short wave length turbulence is only stabilised completely in the region of reduced χ_e rather than the much larger region of low χ_i. This is in line with the expectation that long wavelength ITG and trapped electrons turbulence, mainly responsible for ion transport, is more easily stabilized than the short wavelength ETG modes which are responsible for electron electron transport.

The selection of hydrogen isotope for plasma fuelling does not appear to have any significant impact on ITB production in JET [25] as shown in Figure 7. Up to 8.2 MW of fusion power was produced in D-T experiments with a fusion triple product $n_{i0}T_{i0}\tau_E$ (central ion density x central ion temperature x energy confinement time) up to $1\text{x}10^{21}\text{m}^{-3}$keVs and very high ∇Ti and ∇Te in the plasma interior. The ion and electron diffusivities were quite similar in D-T and D-D plasmas as was the heating power required to form the ITB. This was in contrast to the TFTR experiments [28] where the production of ITBs in D-T plasmas required higher levels of additional heating power than comparable D-D experiments and did not achieve high fusion performance [29].

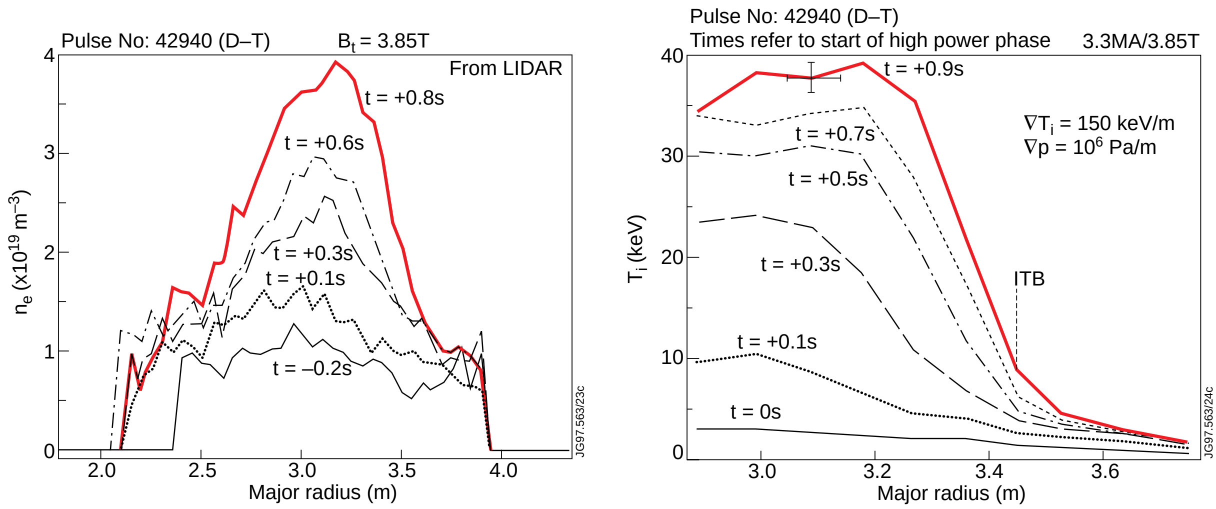

Fig.7: Evolution of density and ion temperature profiles for a JET D-T optimised shear discharge delivering 8.2MW of fusion power. [25]/

All the experiments discussed so far were transient in nature. Despite the presence of a transport barrier in the plasma interior the pressure gradients are typically small at the plasma edge which is characteristic of the, so-called, L-mode. In this case the pressure profile peaking becomes very large in high confinement, high fusion yield plasmas leading to pressure driven instabilities and plasma disruptions as seen in JET [30], TFTR and JT-60U. Two techniques have been developed to avoid this termination event: a reduction of the heating power level to control the pressure gradient directly, as in JET and JT-60U and a transition to H-mode where an edge pressure gradient develops and makes the pressure profile less peaked. The latter H-mode is typically ELM-free and the consequent very high edge pressure pedestal can lead to a further improvement in the fusion yield as observed in DIII-D and JET. However, the experience of high fusion performance regimes with high edge pedestals, such as the hot-ion H-mode and the

VH-mode, is that this phase cannot be extended indefinitely and is normally terminated by a giant ELM. In the next section, experiments specifically designed to maintain high fusion performance ITBs will be discussed.

III. HIGH PERFORMANCE STEADY PLASMAS WITH INTERNAL TRANSPORT BARRIERS

Steady plasmas with an ITB and an L-mode edge (no H-mode edge pedestal) have been produced in several experiments (DIII-D, JT-60U, JET) and have shown that ITBs can be maintained in steady conditions [31] but only at relatively low fusion yield and β_N. Higher performance plasmas have been achieved in the so-called double barrier mode where an ITB can be maintained together with an H-mode edge with type III ELMs allowing the edge pedestal to remain low. Such modes were observed in JET D-D and D-T plasmas where up to 7MW of fusion power was produced in such a mode after only some optimisation [32]**.** With tritium, the H-mode was achieved more easily due to the favourable scaling of the H-mode power threshold with hydrogenic isotope [5]. The loss power from the plasma is also increased with respect to the H-mode threshold level in cases where the core confinement due to the ITB is poor.

High performance steady plasmas have been achieved in the high β_p mode of operation in JT-60U [12] with the new W-shaped divertor and a plasma triangularity of δ = 0. A $Q_{DT}{}^{eq}$ of 0.16 was maintained for 5 sec. The achieved β_N of 2 is lower than the values transiently achieved (3.2). To maintain strongly reversed shear discharges in JT-60U was more difficult. An ELMy H-mode was triggered either by modifying the target q profile or by stepping down the NBI power to produce a weaker ITB [12]**.** Plasmas with β_N = 1.5 - 1.8 and H_{89} = 1.8 - 2.5 were sustained for about 1.5s. Lower performance plasmas were maintained for 5.5s as shown in Figure 8. The limitation here was mainly due to the lack of off-axis current drive which resulted in a constantly evolving current profile. The location of the ITB also moved inward from ρ = 0.5 at t = 7.9 sec to ρ = 0.4 at t = 10 sec. Steady discharges have been also produced in DIII-D [31] and ASDEX Upgrade [33] (see Figures 9 and 10) with relatively weak barriers located at ρ = 0.3 for DIII-D and at ρ = 0.4 for ASDEX Upgrade . Both experiments used broad current profiles with central q close to 1. In ASDEX Upgrade, the current profile was maintained during the 5 second heating

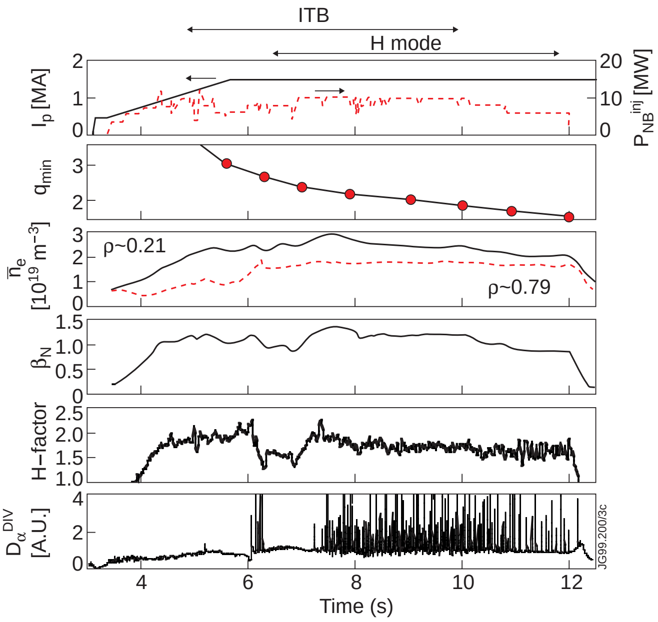

Fig.8: Waveforms of ELMy H reversed shear discharges in JT-60U were an ITB is sustained for 5.5s[12].

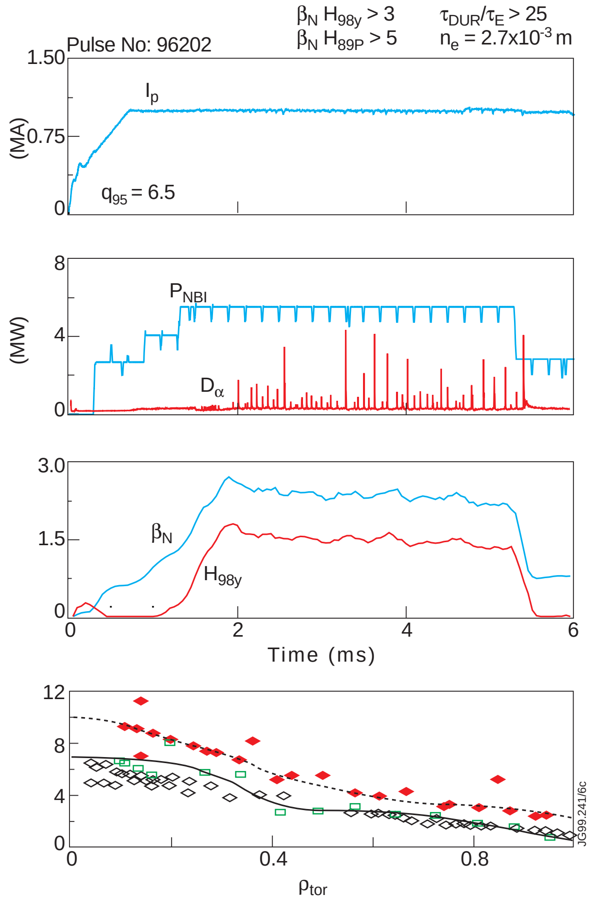

Fig.9: Waveforms of long pulse high performance plasma with core transport barrier (B_t = 1.9T, n_e = 2.7 $10^{19}m^3$ in DIII-D. The pulse was terminated when NBI power was turned down [26].

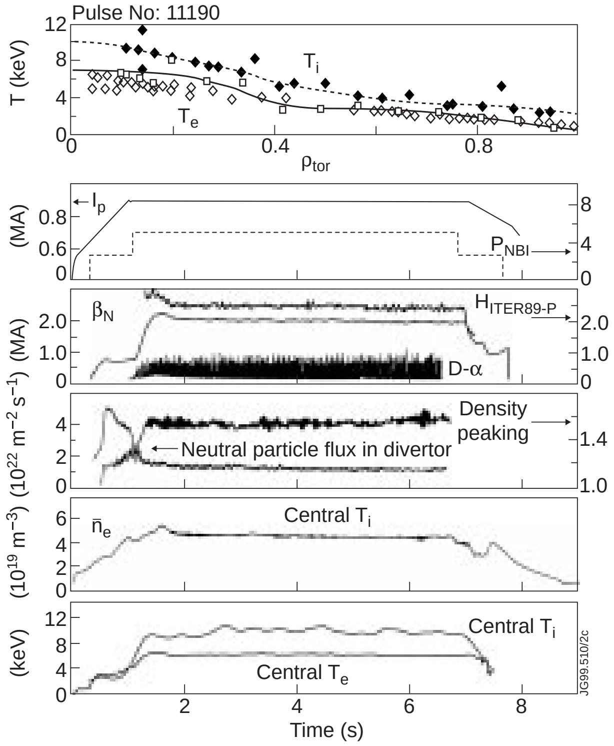

Fig.10: Waveforms of a stationary discharge with an ITB and an H-mode edge in ASDEX Upgrade (B_t = 2.5T) [33].

pulse by magnetic reconnection events due to MHD instabilities called “fishbones” [33]. The performance in both experiments was clearly limited by the onset of neo-classical tearing modes.

All of the steady experiments discussed so far have been performed at relatively low plasma current (up to 1.5MA) and q_{95} above 4. In JET with the new Gas Box divertor configuration, [34] an attempt has been made to produce steady high performance plasmas at high plasma current and with q_{95} close to 3 in order to produce high fusion yield. In this new divertor configuration, the H-mode power threshold has been found to be lower than in the more open MKIIA divertor in the conditions required to trigger an ITB, (e.g.. at low density). Consequently, ITBs have only been produced in the double barrier mode. It should be noted that the evolution of the current profile is affected by the edge pressure pedestal in H-mode plasmas and that, in particular, the current penetration can be arrested or even reversed by the bootstrap current and reduced resistivity in the plasma periphery.

Once an ITB has formed and disruptive MHD events avoided, “soft” MHD events can still limit the performance. An MHD instability called a “snake,” which is a non-linear magnetic perturbation localised at the q=2 magnetic flux surface can cause roll-over in fusion performance

[36]. Within the snake region (r = 10 to 20cm) the ITB is rapidly eroded resulting in an extra power loss to the plasma periphery. If the resulting increase in ELM activity is not too large, a good ITB can be restored. This results in an increase in the size of the ELMs which, if large enough, can destroy the ITB and terminate the high performance phase. “Snakes” can occur in regions of low magnetic shear close to the q=2 magnetic surface and are commonly observed on JET Optimised Shear experiments. High n number (6-8) tearing modes are also often seen in JET high performance which grow and saturate at a rather low amplitude, typically $\delta B/B \sim 10^{-4}$. These modes do not appear to be neo-classical as is the case for the limiting modes in DIII-D and ASDEX Upgrade. Nevertheless, in JET these modes affect the confinement, primarily of the electrons [24]. n=2 fishbone and TAE activity is also observed in JET, notably during the early phase of optimised shear discharges when the ICRH power is large and the density is low. However, they do not appear to affect the performance and very often disappear during the high power phase.

Extending the time duration of JET optimised shear has been only possible so far by using impurity seeding, either krypton or argon, [22] as shown in Figure 11. One effect of the argon bleed is to modify the current profile by reducing the edge pedestal and the associated bootstrap current, and by increasing the resistivity and hence penetration of the peripheral current. As a result the q=2 magnetic surface expands and a large steady ITB can be produced. The use of impurity seeding also prevents the occurrence of large ELMs and so avoids one mechanism for ITB termination. An example of a steady high performance optimised shear plasma obtained using this technique is shown in Figure 12. The power was increased in steps in order to avoid excessive pressure profile peaking and allowing β_N of 1.95 and H_{89} of 2.3 to be maintained for several energy confinement times. The cause of the termination in this case is unclear but is not associated with any obvious MHD events. It could be due either to contact between the plasma and carbon surfaces in the closed divertor possibly linked to high β or by the total power being insufficient to maintain the shear flow required to stabilise turbulence. The evaluation of the ion temperature using charge exchange spectroscopy is very difficult by the presence of Argon line radiation in the observed spectrum [37] and there is a significant level of uncertainty in the region $r/a < 0.5$. Although the main radiation takes place outside the ITB, dilution of the hydrogenic plasma due to Argon is significant. The deuterium concentration (n_D/n_e) decreases rapidly when the ITB is building-up and then is approximately constant or slowly decreasing during the steady phase, down to a value of 70% compared to 80 to 90% without Argon. The neutron yield which corresponds to an equivalent D-T fusion power in the range of 10MW and Q_{DT}^{eq} f about 0.4, could be increased by 25% to 40% if dilution from Argon could be avoided. Although further optimisation of this discharge appears feasible, this technique of noble gas seeding for current profile control does not seem to offer a long term solution. However, it shows that, with a similar current profile, high performance steady ITBs can be produced. As seen in Figure 13 high

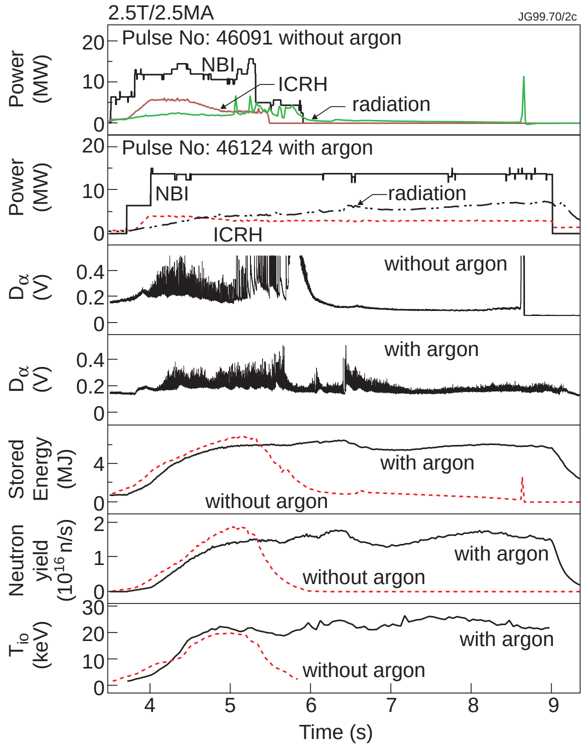

Fig.11: Waveforms of optimised shear discharges in JET with and without Argon bleed. NBI power was feedback controlled on neutron yield in order to prolong the discharge. Pulse length was the maximum available with large additional power.

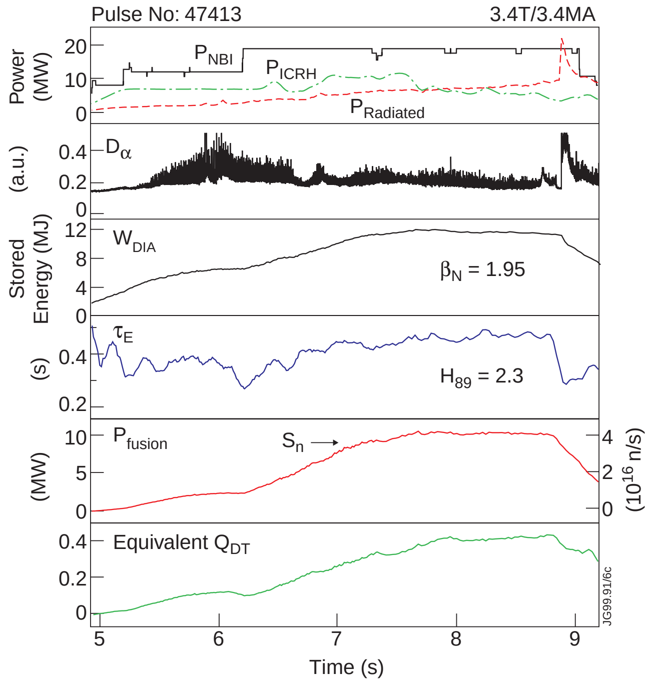

Fig.12: Waveforms and ion temperature profile for a high performance steady pulse in JET.

confinement and β_N values can be achieved simultaneously with high fusion yield especially with 2.5MA/2.5T plasmas. It is likely that the lower β_N values achieved at 3.5MA/3.45T are due to lack of additional heating power.

Finally, it is interesting to compare a standard ELMy H-mode [38]with an optimised shear plasma. as shown in Figure 14. For a similar additional heating power and density, the neutron yield in optimised shear discharges is twice that of the ELMy H-mode and, although the confinement and β_N are higher, this is mainly due to the higher ion temperature. It should be noted that both discharges are capable for further optimisation.

IV. SUMMARY AND CONCLUSIONS

The high performance regimes with internal transport barriers are now well developed. They can be achieved in either reversed magnetic shear or low magnetic shear configurations. Transient high neutron yield and high confinement and stability have been achieved in TFTR, DIII-D, JT-60U and JET including an equivalent Q_{DT}^{eq} of 1.25 in JT-60U. These scenarios have been validated by D-T plasmas in JET with a fusion yield of 8.2MW with optimisation.

Substantial progress has been made towards the extension of these high performance plasmas to steady-state. The present route uses the so-called double barrier mode where an ITB is maintained together with a type III ELMy H-mode edge. Steady scenarios with ITBs have

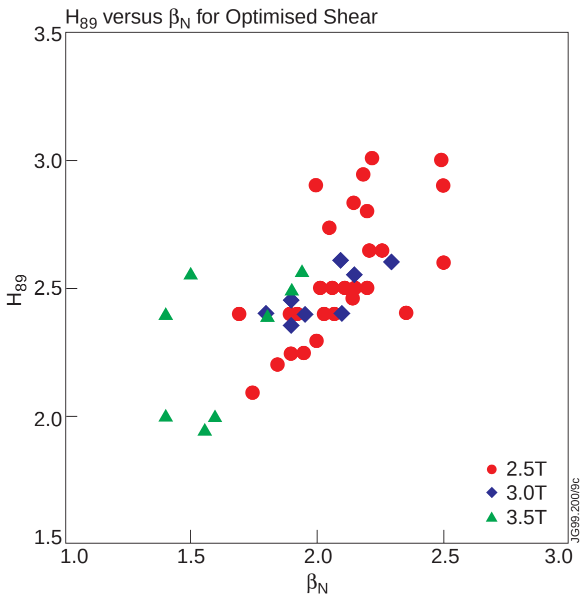

Fig.13: H_{89} versus β_N in JET for steady optimised shear high performance plasmas. Performances have been maintained for $4 < t < 10\tau_E$ The bootstrap current fraction is 30 to 40%. β_p optimisation would require to operate at $q_{95} > 3$.

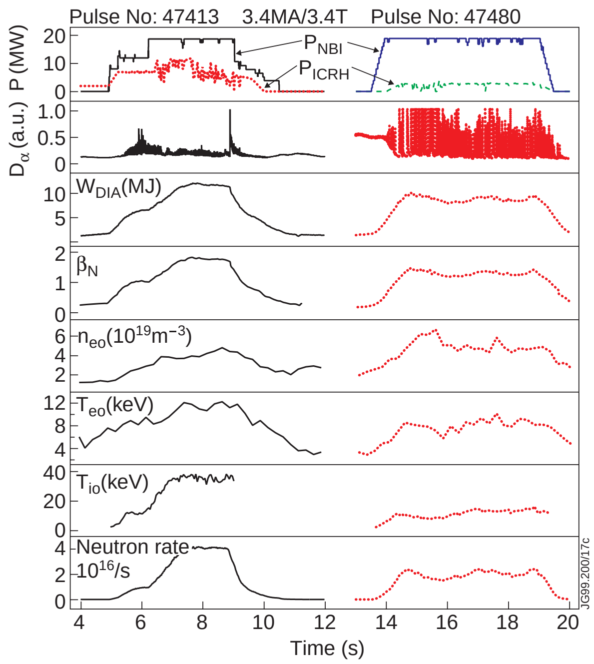

Fig.14: Comparison between waveforms of record D-D yield steady optimised shear and ELMy H-mode discharges in the JET MKIIGB configuration.

been developed in most machines, JT-60U, DIII-D, Upgrade , but with lower β_N, than can be achieved transiently. In JET high central pressure and high fusion yield (T_i = 30keV, T_e = 12keV, β_N = 1.95, H_{89} = 2.3, $P_{Fusion}{}^{eq}$~ 10MW, $Q_{DT}{}^{eq}$ ~ 0.4) have been produced for several energy confinement times using impurity seeding the key role of which is to modify the current profile.

MHD stability in the presence of ITB and the resulting large pressure gradients is still the main challenge. β_N in excess of 2.5, as would be needed for Advanced tokamak reactors, has not been produced in steady conditions, particularly at high plasma current. In order to progress further, the development of specific control tools is required to:

- actively control the plasma current profile;
- stabilise pressure driven MHD modes and neo-classical tearing modes;
- fuel the plasma.

In present experiments, high performance scenarios with modified shear have produced higher steady fusion yield than the conventional ELMy H-mode. They have yielded insight into transport and MHD phenomena and offer the prospect of interesting routes for fusion research, but a substantial development remains necessary before the performance achieved in today's experiments can be extrapolated to a tokamak reactor.

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