Common and Distinct Features of Enhanced Confinement Regimes

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ABSTRACT

A large number of confinement regimes have been reported in recent years. An attempt has been made to identify the common and distinct features of auxiliary heated regimes. The various regimes naturally split into 3 main categories which are characterised by L-mode, Super Shot or H-mode like confinement, respectively. Within each category significant enhancements in confinement have been observed. Plausible reasons for the improvements in confinement have been suggested. However, the evidence in each case is still not conclusive.

1. INTRODUCTION

In the last 5-10 years various auxiliary heating methods have been used extensively in tokamaks in an attempt to reach as high plasma temperatures as possible. At the same time unfortunately the energy confinement time has been observed (with 1-2 exceptions) to degrade with increasing auxiliary heating power. This feature is independent of heating method. On each of the European tokamaks ASDEX, ASDEX-Upgrade, JET, TEXTOR and Tore Supra; the American tokamaks DIII-D, PBX-M and TFTR; and the Japanese tokamaks JFT-2M, JIPP T-IIU, JT-60 and JT-60U one or more of the following methods have been used to heat the plasma: Neutral Beam Injection (NB), Ion Cyclotron Waves (IC), Electron Cyclotron Waves (EC), Lower Hybrid Waves (LH) and Ion Bernstein Waves (IB). In this paper the results obtained on the above tokamaks with respect to energy confinement time will be compared and discussed. It is obvious that the confinement time not only depends on the main plasma parameters, see eq. (1), and this has lead to the definition of numerous confinement regimes. The most well known are the L-mode, Super shot and H-mode regimes. Other regimes with substantial improvement in the confinement time have been observed which have lead to different names describing in some way the source or reason for the enhancement. Here an attempt has been made to classify the results into 3 categories. In Section 2 the L-mode and improved L-mode regimes will be discussed, in Section 3 the Super shot regime and in Section 4 the H-mode and enhanced H-mode regimes. Finally the common features of the various enhanced regimes will be summarised in Section 5.

2. L-MODE REGIMES

The so-called low confinement mode (L-mode) is observed in all tokamaks using auxiliary heating. The dependencies of the energy confinement time τ_E on the main plasma parameters such as plasma current I, line average density n, toroidal magnetic field B, loss power $P_L = P_{tot} - dW/dt$ where P_{tot} is the total input power and W the plasma energy, major radius R, inverse aspect ratio $\varepsilon = a/R$ where a is the minor radius, elongation κ and M the effective isotope mass in atomic units in typical L-mode plasmas are well described by the ITER89-P [1] power law expression given in eq. (1).

$$\tau_{ITER89-P} = 0.048\, I^{0.85} (n/10)^{0.1}\, B^{0.2}\, P_L^{-0.5}\, R^{1.5}\, \varepsilon^{0.3}\, \kappa^{0.5} M^{0.5} \tag{1}$$

with units of s, MA, 10^{19} m^{-3}, T, MW, and M. Other L-mode scaling expressions have been proposed in the past but ITER89-P is currently the most commonly used scaling and it will here be used as baseline for the typical L-mode confinement regime i.e. improved L-mode confinement is characterised by an enhancement factor $H \equiv \tau_E/\text{ITER89-P} > 1$. Notice that ITER89-P is a Bohm-like or long wavelength scaling [2].

It must be emphasised that regimes with $H < 1$ exist. Macroscopic phenomena [3] e.g. sawteeth may easily result in $H \sim 0.8$ if the sawtooth inversion radius becomes large and thereby a large portion of the plasma cross-section becomes affected by the sawtooth temperature flattening. For example in the high current limiter results obtained with IC and NB heating on JET [4] the 7 MA plasmas have a large sawtooth inversion radius and the results are clearly below the scaling prediction.

It is also possible to get the power deposition of the auxiliary heating wrong. Off-axis heating generally results in poorer confinement although there are important exceptions.

The main reason for mentioning these two effects is that sawtooth stabilisation and power deposition profile optimisation are prerequisites for many of the enhanced confinement regimes discussed in this paper.

2.1 Improved L-mode regimes

Enhancement factors H in the range 1.4 - 2 have been achieved in the following regimes/modes labelled: Improved Divertor Confinement (IDC); Improved L-mode (IL); Strange (S); Counter NB injection (Ctr. NB); Pellet Enhanced Performance (PEP) and LH Enhanced Performance (LHEP). All these regimes exhibit improvements to the confinement in the plasma core and except for the LHEP-mode increased density profile peaking on-axis. This is also true for the temperature profiles except for the Ctr. NB . Sawtooth suppression seems also to be an import aspect of the improved confinement phase. In the PEP- and LHEP-mode current profile modifications leading to regions of negative magnetic shear may also be contributing to the observed confinement improvements.

The **IDC-mode** on JT-60 [5] is obtained with high power $P_{NB} > 12$ MW in $H^\circ \rightarrow H^+$ plasmas. The transition from L → IDC is slow. The radiation in the core plasma drops whereas the radiation from the divertor region increases to $P_{rad}^{div} / P_{NB} \leq 50\%$. The neutral pressure around the main plasma decreases which suggests that the main plasma recycling is reduced. The IDC-mode reaches a quasi steady state with an improvement in confinement which is correlated with the decrease in bulk radiation. The discharge is sawtoothing throughout. Electron density n_e and temperature T_e are increased with no substantial changes to the profiles shapes. There is a density threshold for this mode which depends on P_{NB}, B, safety factor q, distance to the wall and direction of the ion-∇B drift. Finally gas puffing destroys this mode.

The **IL-mode** on JFT-2M [6] can appear after a H $\rightarrow$ L transition in plasmas with NB heating (Co-injection of H_e into D^+). The L $\rightarrow$ IL transition does not take place if the density decay after the H-L transition is not limited by gas puffing and the sawteeth are suppressed. During the IL-mode the line average density increases slowly and the profile becomes highly peaked. The edge electron temperature stays at the L-mode level but the central value is maintained at the H-mode level resulting in a peaked T_e profile as well. The confinement is comparable to that of the H-mode i.e. $H \leq 2$ but is associated with improved core confinement. The pressure gradient inside $r/a < 0.8$ is larger than that observed in the H-mode. The IL-mode is easiest to obtain at high I and B. The wall conditioning also seems to be critical.

The **S-mode** on JIPP T-IIU [7] is observed with high power IC heating (P_{IC} > H-mode threshold). The L $\rightarrow$ S transition is seen as a sudden increase in H_α-light emission which then returns to its previous level. After the transition the density increases and the profile peaks but also the edge value increases. A reduced edge electron temperature results in a peaked T_e profile as well. The ion temperature stays constant but the neutron yield increases. The improvement in τ_E can be as much as 40% corresponding to a 40% increase in density. It is unclear if this means $H \sim 1.4$.

With **Ctr. NB** heating on ASDEX [8] peaked density profiles have been achieved despite the power and particle deposition profiles being broader than for Co. injection. If the heating pulse is long enough and wall-carbonisation is used to prevent a rapid impurity accumulation in the centre a factor of 1.4 improvement in confinement compared to that of Co. injection has been obtained. A highly peaked density profile results when the sawteeth are suppressed. In this case, however, the T_e profile is initially peaked and then becomes hollow. Notice there is also an improvement in angular momentum confinement [9]. The transition into this regime is a gradual one.

In the previous regimes the peaked density profile arose from the auxiliary heating. It is also possible to create an ohmic target plasma with a highly peaked density profile using pellet fuelling. The electron temperature profile is usually hollow. Sawtooth activity can be suppressed by pellets. If sawteeth are not suppressed less peaking is achieved. Therefore it is an advantage to inject pellets into a plasma with no sawtooth activity e.g. by injecting in the current ramp phase before the $q = 1$ surface has entered the plasma. The **PEP-mode** is obtained by strong central heating of such an ohmic target plasma. On JET [10] the central density decays slowly but the profile remains peaked in the centre while the enhanced phase lasts. Both the electron and ion temperatures become peaked in the centre and reach central values > 10 keV. The safety factor on axis q(o) also increases and the central region may have reversed magnetic shear due to the bootstrap current $I_B \sim 0.2$ I associated with the steep pressure gradient in the central region. Inside the radius $r/a \leq 0.3$ the plasma is close to the first stability limit for ballooning modes. In the PEP phase a factor of 2 improvement in both the ion and electron transport has been achieved in the central region. The overall improvement in confinement is typically H ~ 1.6.

In the **LHEP-mode** on Tore Supra [11] improved core conditions have been obtained with LH heating and current drive. The time evolution of a LHEP discharge is as follows. The improved phase is reached in two steps. After the turn on of LH power the central electron temperature rapidly increases to ~ 5 keV then a second later it increases to its final value ~ 8 keV on a slower time scale. The enhanced pulse lasts ~ 7 sec. A 40% improvement in confinement is observed. In the LHEP phase sawteeth are suppressed and the current density profile flattens in the centre. The flattening is due to a non inductive current driven slightly off-axis by LH, $I_{LH} \sim 0.9$I. The central safety factor increases from ~ 1 to 1.7. The pressure peaks in the central region. The bootstrap current is $I_B \sim 0.1$ I. It is believed that a region of negative magnetic shear develops in the centre and in that respect the LHEP-mode resembles the PEP-mode. The core is found to be ballooning stable.

3. SUPER SHOT REGIME

It is possible with NB heating to decouple the ions and electrons and create plasma conditions with $T_i >> T_e$ at low densities. This mode of operations has naturally been labelled the **hot ion mode**. In order to obtain this mode a centrally peaked low target density is required for the NB to achieve central power and particle deposition. If this is achieved the density peaking will increase and improve the central deposition of NB even further. If sawteeth are suppressed the end result is strongly peaked density and temperature profiles with improved confinement in core plasma. Usually in these plasmas the fast ion energy content is large and the total energy confinement time can be as large as 3 x ITER89P. On TEXTOR this kind of mode is called the **I-mode** [12] whereas TFTR use the label **Super Shots** [13].

Density control is a prerequisite for entering and sustaining this regime i.e. high wall pumping leading to low recycling is required. On TFTR the Super Shots are distinguished from L-mode plasmas by the value of the recycling coefficient R. In Super Shots R ~ 0.6 whereas in L-mode R ~ 1. Different wall materials and conditioning techniques have been employed to achieve this. The latest technique used in TEXTOR [14] is siliconisation or boronisation. The use of silicon also results in a radiation profile which is peaked near the edge thereby reducing the heat load on the limiter and the risk of impurity blooms. TFTR [15] now use He discharge cleaning and Li pellets to condition the carbon composite fibre tiles on the limiters.

It may be important to notice that the confinement in TFTR Super Shots show no power degradation in contrast to the I-mode and Hot ion mode on other machines. Finally it has been observed on JT-60[16] that the ion temperature profile steepens at the q = 3 surface.

4. H-MODE REGIMES

The H-mode confinement regime has now been achieved with almost all possible auxiliary heating methods including ohmic heating alone and the regime is no longer restricted to diverted plasmas. The L → H transition is normally seen as a drop in H_α or D_α light intensity and at the same time steep edge gradients in density and temperature appear. How fast the transition is and how large a region is affected differ apparently from machine to machine. In general the confinement in the H-mode phase is twice as good as in the L-mode phase and this is mainly associated with the appearance of an edge confinement barrier due to the steeper edge temperature and density gradients. The latest power law expression for the thermal energy confinement in ELM-free H-mode [17] is.

$$\tau_{\mathrm{ITERH93-P}} = 0.036\, I^{1.06}\, n^{0.17}\, B^{0.32}\, P_L^{-0.67}\, R^{1.79}\, \varepsilon^{-0.11}\, \kappa^{0.66}\, M^{0.41}$$

with units of s, MA, 10^{19} m^{-3}, T, MW, and M. Notice that ITERH93-P is a Gyro-Bohm like or short wave length scaling [2]. Hence it is recommended that results obtained in the H-mode regime are compared to ITERH93-P instead of ITER89-P.

The input power must exceed a threshold in order to achieve the transition to the H-mode. Typically the threshold increases with increasing B and n above a minimum value for n but also other factors are important such as the direction of the ion ∇B-drift (in SN-X), plasma to wall distance and condition of the wall which can change the threshold by a factor of 2. By combining threshold data from different size tokamaks the threshold with machine size has been found [18] to increase with the plasma surface area S or as $R^{2.5}$.

Instabilities named Edge Localised Modes (ELMs) because they affect the outer region of the plasma are encountered in the H-mode regime. Three different forms of ELMs have been identified and classified as Type I, II and III [19]. The instabilities are believed to be associated with the steep pressure gradient in the edge getting near to ballooning limits. It is usually the type I ELMs which limit the confinement in the H-mode regime at high power and with these ELMs present the confinement is typically 10-15% lower than that predicted by ITERH93-P. Notice that a steady state ELM-free H-mode has so far not been achieved whereas for the ELMy H-mode this is not a problem.

Enhanced H-mode regimes are characterised by a normalised confinement time $\tau_N \equiv \tau_E$/ITERH93-P significantly greater than one. A group of five operating scenarios have been reported which exhibit very high confinement i.e. $\tau_N \leq 2$ and where the main improvement in confinement is due to an enhancement of the H-mode confinement barrier in the outer region of the plasma. The characteristic features of these scenarios will be presented in section 4.1. Another group of 3 operating scenarios have been reported which exhibit enhancements $\tau_N \sim 1.5$ and where the improvement in confinement has been achieved by adding enhanced core confinement to normal H-mode confinement. The characteristic features of these will be presented in section 4.2. The common features of the enhanced H-mode regimes will be summarised in Section 5.

4.1 Enhanced H-mode confinement in the outer region of the plasma

The **VH-mode** (DIII-D), **hot ion VH-mode** (JET), **high bootstrap VH-mode** (JET), **high $\varepsilon\beta p$ H-mode** (JT-60U) and **high $\varepsilon\beta p$ regime** (TFTR) all have enhanced confinement in the outer region of the plasma. The main characteristics of these regimes are presented below.

On DIII-D [20] first boronisation then an all graphite wall conditioned by baking and He glow discharge cleaning made it possible to achieve plasmas with significantly reduced levels of high and low Z impurities. Oxygen, Carbon and N_i levels were reduced by factors of 6, 2 and 10-15, respectively. At the same time the neutral deuterium content in the wall was significantly reduced leading to low recycling of deuterium. Under these conditions the radiated power remains low ($P_{rad}/P_{inj} \leq 30\%$) in the ELM-free H-mode phase and a second transition occurs to an improved confinement phase, **the VH-mode** in which values of $\tau_N \sim 2$ are reached. The transition is characterised by the disappearance of density fluctuations associated with momentum transfer events (MTEs) and an increase in the toroidal rotation velocity shear in the region $0.6 < \rho < 0.9$. The increase in the region of increased rotational flow shear $V'_{EXB} \equiv \frac{B}{B_\phi}\frac{d}{dr}\left(\frac{E_r}{B}\right)$ where the electric field E_r is determined from $E_r = \frac{1}{eZ_i n_i}\nabla P_i - V_{\theta i}B_\phi + V_{\phi i}B_\theta$ and B is the total magnetic field correlates well with the improvement in confinement. The transport barrier observed near the edge in 'normal' ELM-free H-mode has become wider and extends further into the plasma. Magnetic braking experiments [21] using small non axisymmetric external error fields to reduce the toroidal rotation shear and leads to a reduction in the confinement time. This suggests that the enhancement of confinement is due to turbulence suppression by sheared rotation flow and that a positive feed back loop may be operative via the force balance determining E_r. The that rotation may not be the only candidate for closing this feedback loop and it has not been established what kind of turbulence is being stabilised. The rise in τ_E after the transition increases with increasing P_{NB} but high density or higher recycling at high power prevents access to this phase and long ELM-free phases. The achieved enhancement does not depend on elongation ($1.7 < \kappa < 2$) but increases with increasing triangularity in DN-X discharges. An optimum for safety factors $4 < q_{95} < 6$ is observed. Increases in internal inductance l_i are too small to explain the enhancement. The VH-mode phase is often terminated by rapid ELMs. This may be initiated by ideal edge localised kink modes due to a large bootstrap current density near the edge associated with the large pressure gradient near the edge. The edge region in these plasmas is in the 2nd stable region for ballooning modes. A steady state situation is never reached. Attempts have been made to reduce the edge current density by a ramp down of the current but this does clearly not lead to a steady state either.

It has been possible in the H-mode to establish a hot ion plasma as outlined in Chapter 3. In general the improvements in the central region lead to confinement enhancements of 20-40% compared to ITERH93-P. Improved wall conditions can lead to VH-mode in a hot ion plasma. On JET [22] the use of better shaped Carbon Composite fibre tiles as target together with beryllium evaporation have resulted in **Hot ion VH-modes** with $\tau_N \leq 2$. These have been labelled VH-modes due to similarities with the results from DIII-D. There may however also be some significant differences between the results from JET and DIII-D. On JET [23] the L $\rightarrow$ H transition in these type of discharges may have a very fast transition and then the transport changes very rapidly over a very large radial region $0.5 < \rho < 1$ resulting in the formation of a very large transport barrier on a fast timescale. Therefore most of the enhancement in confinement is achieved at the transition. Often a period with ELMs follows where τ_E is reduced but when the ELMs disappear τ_E jumps or increases rapidly to its previous level. A 2nd transition from ELM-free H-mode to VH-mode has so far not been observed.

The **high bootstrap VH-mode** on JET [24] is achieved with IC heating of a low density target plasma in a DN X-point configuration. Strong gas puffing is used to assist the IC-coupling to the plasma. The VH-mode plasma appears after the disappearance of ELMs and sawteeth. In these plasmas $T_e \sim T_i$. In contrast to the hot ion VH-mode the toroidal rotation in the centre is very low and even decreases during the VH-mode phase [25]. The edge has access to 2nd stability and the bootstrap current reaches values $I_B/I \sim 0.7$.

JT-60U use boronisation and He GDC to condition the walls. The **high $\varepsilon\beta p$ H-mode** [26] appears with NB heating of a low target density plasma in the following way. In the initial phase of the NB the density and ion temperature profiles become very peaked. Then there is a drop in D_α and the central values of n and T_i increases and $\tau_N \sim 1$. This is called the high $\varepsilon\beta p$ phase. In this phase the T_i and toroidal rotation profile have steep gradients at the $q = 3$ surface. A MHD event precedes the high $\varepsilon\beta p$ H-mode phase in which the edge n and T_i increases strongly and the strong gradients at $q = 3$ have disappeared. The normalised confinement reach $\tau_N \sim 1.8$ in this phase and rotational flow shear is increased in the outer region.

Li conditioning has made it possible for TFTR [27] to obtain a **high $\varepsilon\beta p$ regime** with $\tau_N \leq 1.9$. Values of $\varepsilon\beta p \geq 0.7$ is achieved by rapidly decreasing the plasma current just prior to high power NB. These plasmas are characterised by a peaked current profile ($l_i > 2$ and current reversal in the outer region) and a broad pressure profile. The large enhancement in confinement is seen when the discharge makes a transition into an ELM-free H-mode. The largest enhancement has been obtained when $I_1/I_2 > 1.5$ where I_1 and I_2 are the currents before and after the ramp, respectively; $I_2 \leq 1.4$ MA and $\varepsilon\beta p \sim 1$. When $\varepsilon\beta p \sim 1$ the plasma shape is oblate ($\kappa \sim 0.8$). The non-inductive NB and bootstrap currents amount to 90% of the total current in this regime.

4.2 H-mode with enhanced core confinement

The **PEP H-mode** (JET), **CH-mode** (PBX-M) and the DIII-D **high $\varepsilon\beta p$ H-mode** all have enhanced core confinement added to normal H-mode confinement. The main characteristics of these regimes are given below.

The peaked density profiles of the PEP L-mode have been combined with the edge related confinement of the H-mode on JET [22, 28] leading to enhancement factors $\tau_N \sim 2$ transiently. As the density peaking relaxes the enhancement reduces to $\tau_N \sim 1.5$. It is essential the pellet injection takes place prior to the onset of sawteeth before the $q = 1$ surface has entered the plasma. Immediately after the pellet injection, strong NB, IC or combined heating is applied. The best enhancement is achieved utilising the central power deposition of IC. The **PEP H-mode** phase typically last 0.5 - 1.0 seconds. The steep pressure gradient near the centre drives enough off-axis bootstrap current to make the current profile hollow and produce a central region of negative shear. The region of improved core confinement is however somewhat larger than the region of negative shear. The q-profile features an off-axis minimum. The evolving bootstrap current drives q(o) up and q_{min} down. The core of the plasma is in the region of 2nd stability against ideal ballooning mode. the access to 2nd stability is opened up by two factors:

i) In most cases $q_{min} \geq 1.2$ which joins the lst and 2nd stable regions for a plasma with low positive shear.

ii) The negative shear region exists without a lst stable boundary.

As the current profile evolves q_{min} drops below ~ 1.1 and the plasma becomes ballooning unstable which suggests that this could be the case of termination of the PEP H-mode phase. The particle confinement is also significantly improved and impurity accumulation in the centre is a serious problem.

IB heating may stabilise sawteeth and generate peaked density profiles as well as peaking of electron and ion temperature. In PBX-M [29] using IB during a NB heated H-mode the above effect has resulted in enhanced NB core deposition of power and particles causing an increase of the neutron source strength. The IB power deposition is localised just inside the $q = 3/2$

surface where a steepening of the density and temperature profiles is observed. The bootstrap current associated with this pressure gradient is off-axis as in the PEP H-mode. The density outside the enhanced region decreases resulting in a further enhancement of the peakedness. So far the duration of the core enhanced phase has only been limited by the duration of the IB heating pulse but impurity accumulation may be a problem. The phase has been named core H-mode (**CH-mode**) since kinetic analysis indicates that in excess of 60% of the stored energy is confined within r/a = 1/2.

The **high $\varepsilon\beta p$ H-mode** on DIII-D [30] is obtained in the following way. A transient very high β_p configuration with a large fast ion population and strong MHD activity is established in the early phase of NB heating. On a resistive time scale, the current profile broadens from the ohmic shape towards a profile characteristic of a combination of NB current drive and bootstrap current. during this phase q(o) increases and the enhanced phase appears when $q(o) > 2$ as an increase mainly of central density but also the central electron and ion temperature rise. This leads to a peaked pressure profile and a region with reversed magnetic shear. The region of improved confinement extends to $\rho \leq 0.4$.

5. SUMMARY

The confinement in L-mode is well described by Bohm-like or long wave length scalings (e.g. ITER89-P). An increased peakedness of the density and temperature profiles together with suppression of sawteeth are almost common features of all the improved L-mode regimes and the Super Shot regime i.e. improvements of core confinement. The exceptions are the LHEP-mode with no increased density peaking, the Ctr. NB-mode with hollow temperature profiles and the IDC-mode with sawtooth activity. However other distinct features such as changes to the current profile (LHEP and PEP); low recycling (Super Shots, I- and IDC-mode); control of impurities (Super Shots, I-, IDC- and Ctr. NB-mode); large fast ion energy content (Super Shots, I- and Hot Ion mode) and radiative cooling (IDC- and I-mode) may be just as important in obtaining the improved confinement.

The confinement in H-mode (ELM-free) is well described by gyro Bohm-like or short wavelength scalings (e.g. ITERH93-P). So far steady state has only been achieved in H-modes with ELMs in which the confinement is typically 15% lower than that of ELM-free H-modes. In order to achieve the H-mode regime two conditions must be satisfied. The target density must be above a minimum value and the power must exceed a threshold which varies with density, magnetic field and size etc. Because the H-mode confinement scales like gyro Bohm it is better to use the normalised confinement time τ_N instead of the enhancement factor H in order to identify enhanced H-mode confinement regimes. Eight regimes have been identified which have τ_N significantly above one. They can be divided into 2 groups according to where in the plasma the main enhancement in confinement occur and how large the enhancement is. Adding enhanced core confinement to H-mode confinement has resulted in typical values of $\tau_N \sim 1.5$. The PEP H-mode (JET), CH-mode (PBX-M) and DIII-D high $\varepsilon\beta p$ results belong to this group. Enhancement of the H-mode confinement barrier in the outer region of the plasma has lead to values $\tau_N \sim 2$. This has been observed in the VH-mode (DIII-D), hot ion VH-mode (JET), high bootstrap VH-mode (JET), high $\varepsilon\beta p$ H-mode (JT-60U) and the TFTR high $\varepsilon\beta p$ regimes. The common features of the enhanced H-mode regimes are as follows. $^{1)}$ They have all been achieved with improved wall conditions and lower recycling i.e. increased control of impurities, radiation and density; $^{2)}$ The ohmic target density has been low except for the PEP H-mode and CH-mode; $^{3)}$ They have been obtained with centrally peaked NB and/or IC power deposition profiles; $^{4)}$ Sawteeth and ELMs have been suppressed; $^{5)}$ The bootstrap current is substantial in all these plasmas; $^{6)}$ They all have a region which has access to the 2nd stable ballooning regime and $^{7)}$ so far all the regimes have only been obtained transiently.

The exact reasons for the improvements in confinement in the different regimes are not yet known. In each regime the enhancement appears to be associated with local changes in either density gradients, rotational flow shear, current profile (magnetic shear) and/or temperature profile (e.g. finite Larmor radius stabilisation). At present it is very difficult to determine which of the changes are causing the enhancement or which are a consequence of it. To make progress in resolving the above better time and spatial resolution of both the profile and fluctuation measurements close to the transitions are required.

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