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Progress and issues in understanding the physics of ELM dynamics, ELM mitigation, and ELM control

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Abstract. Recent experimental progress in understanding the dynamics of type I ELM, small/no ELM regimes to achieve ELM mitigation and active ELM controls is reviewed. As for the type I ELM dynamics, the smaller growth rate of the ELM precursor relative to the Alfvén frequency, the importance of ELM filaments to evaluate the ELM heat load, the evolution of pedestal pressure in the recovery phase, and the effects of edge toroidal rotation and toroidal field ripple on ELM energy loss have been observed in many devices. In low collisionality ($\nu_e$) small/no ELM regimes, the type V ELM has been obtained with one or two filaments in $\nu_e<$1 condition. Small normalized ELM energy loss less than 1% has been achieved in the grassy ELM regime in non-rotating plasmas. The highest pedestal pressure has been achieved with smaller edge toroidal rotation counter to the plasma current in the QH-mode. ELM control/suppression by pellet pacing and external magnetic field perturbation has been demonstrated, and so that a design activity of ELM control coils for ITER has started. Various effects of the edge toroidal rotation upon ELM characteristics have been found such as ELM energy loss (ELM frequency) in the type I ELM regime and the grassy ELM regime, changes in edge harmonic oscillation and achievable pedestal pressure in the QH-mode regime, and a screening effect in evaluation of island formation by ELM control coils.

1. Introduction
High-confinement mode (H-mode) plasma with edge localized mode (ELM), the so-called ELMy H-mode, has been considered as part of the standard operating scenario with $Q = 10$ in ITER. Although ELMs play an important role in the particle control needed to achieve stationary H-mode plasmas, instantaneous heat load transferred to divertor target plates due to ELM has been considered as an important and urgent issue in ITER [1, 2]. Therefore, extensive studies of ELM dynamics [3, 4] and models/theories of ELMs [5] have been made for a better prediction of ELM size in ITER. In addition to this research into the type I ELM regime, small/no ELM regimes as an alternative regime [6, 4] and various active ELM control methods are also investigated to establish small ELM heat load operation in ITER. Nevertheless, further investigations to gain understanding of the physics of ELMs are required to address the remaining issues of ELM heat load in ITER.

The acceptable level of the ELM heat load is determined by the heat load limit of 0.5 MJ/m² for both of the tile materials, carbon and tungsten, which are candidates for the plasma facing components (PFCs) of the ITER divertor [7]. The value has been reduced to half of the previous assessment reported in [1, 2]. In addition to this, the observation of an asymmetry of the divertor heat load between inner and outer divertor target plates ($P_{OUT}/P_{IN}=1/2$) [8] and the reassessment of ELM wetted area (1.3 m² for inner divertor), based on the expected SOL width in the outer midplane, of ~5 mm [9]
have caused a considerable reduction in the acceptable ELM energy loss ($\Delta W_{\text{ELM}}$) for ITER from 5 MJ to 1 MJ, which corresponds to about 1% of the pedestal stored energy ($W_{\text{ped}}$) [10]. In addition to this severe requirement upon ELM size, higher pedestal pressure ($p_{\text{ped}}$) is required to achieve $Q = 10$ plasma in ITER, because all transport models predict higher $Q$ values at higher pedestal temperatures with fixed plasma density [11]. Therefore, simultaneous achievement of high $p_{\text{ped}}$ and small $\Delta W_{\text{ELM}}$ in the ITER relevant low collisionality condition should be achieved to establish the ITER standard operating scenario.

Studies of ELM physics have been recognized as an important research area contributing not only to ITER, but also to common MHD phenomena in a torus system. The ELM-like burst at the plasma edge has been observed in helical devices such as W7-AS [12] TJ-II [13] and LHD [14, 15]. The characteristics of ELM-like oscillation and its relation to edge MHD modes were investigated in LHD [16]. Looking at ELMs from a broader viewpoint, an explosive event similar to ELMs with filamentary structures can be found in space plasmas such as a solar flare [17]. Both ELMs and solar flares exhibit interesting non-linear dynamics in magnetized plasmas.

In this paper, recent progress and remaining issues in understanding the physics of ELMs are reviewed in terms of the dynamics of type I ELM, ELM mitigation by small ELM regimes or steady ELM free regimes, and active ELM control methods. Section 2 summarizes experimental observations of type I ELM dynamics such as ELM precursors, edge stabilities determining ELM threshold, filament structures in the collapse phase, recoveries of $p_{\text{ped}}$, effects of the toroidal rotation ($V_T$) and the toroidal field (TF) ripple on the $\Delta W_{\text{ELM}}$. Section 3 describes progress in small/no ELM regimes such as the expansion of the operational regime of type V ELM, the investigation of ELM frequency dependence on $V_T$ in the grassy ELM regime, and the mechanism of ELM suppression and the role of $V_T$ in the QH-mode regime. Active ELM controls using pellet injection and external magnetic field perturbations are described in section 4. Finally, section 5 discusses the importance of $V_T$ in determining ELM characteristics.

2. Dynamics of type I ELM

The series of collapses and recoveries of the edge pressure and the current caused by ELMs plays a fundamental role in the control of heat and particles to achieve a quasi-steady H-mode in ELMy H-mode plasmas. The dynamics of type I ELM consists of several different phases, such as a precursor phase as a linear growth phase of MHD instability, a collapse phase as a non-linear evolution of MHD instability, and a recovery phase where the lost edge pressure and current are recovered for the next ELM. Since the $\Delta W_{\text{ELM}}$, the rate of increase in the plasma stored energy ($dW/dt$) determined by inter-ELM transport, and the evolution of the edge bootstrap current in the recovery phase determine the ELM frequency, the whole process of ELM dynamics must be understood to achieve the better prediction of ELM characteristics in ITER. In this section, the recent progress in edge stability analyses determining the $\Delta W_{\text{ELM}}$ and experimental observations of fast type I ELM dynamics measured with fast, local and multi-dimensional edge plasma diagnostics are described.

2.1. Edge stability and precursor phase

The edge stability is strongly affected by the plasma shape. The plasma elongation ($\kappa$) and the plasma triangularity ($\delta$) are well known as important parameters. In addition to these parameters, squareness ($\zeta$) [18] and sharpness ($\sigma$) [19, 20] have recently been found to change the edge stability. The pedestal performance and ELM characteristics during $\zeta$ scan around a shape similar to ITER ($\zeta = 0.35$) while keeping the $\delta$ fixed has been investigated in DIII-D [21]. As $\zeta$ increased from 0.32 to 0.405, the $p_{\text{ped}}$ decreased from 14 kPa to 9 kPa, which is consistent with the stability analysis of the measured profiles. Since the $\Delta W_{\text{ELM}}$ also decreased by the same ratio as the $p_{\text{ped}}$, the normalized ELM energy loss ($\Delta W_{\text{ELM}}/W_{\text{ped}}$) was almost constant over the $\zeta$ scan.

The radial profile of the linear eigenfunction of edge MHD modes such as the peeling-ballooning mode reveals the region expected to be affected by ELM [22-24]. It is important to understand what parameters can change the radial profile of the linear eigenfunction to predict the ELM size in a future
device. Although the edge stability is mainly determined by the edge pressure gradient and the edge current density, the effect of the pressure profile and the current density profile inside the pedestal has been found by the MHD stability analysis using the MARG2D code [25]. With a shape similar to ITER, the radial profile of the edge MHD mode is expanded by the spreading of the envelope of the edge ballooning mode structure due to the increase in the pressure gradient inside the pedestal and by the decrease in the toroidal mode number of the most unstable mode due to the increase in the current density inside the pedestal.

When the edge plasma condition reaches a stability limit, the ELM precursor is often observed in density, temperature and magnetic fluctuations indicating a linear growth phase of edge MHD modes. The study of ELM precursor is important to reveal the MHD modes which trigger ELMs. In JT-60U, clear density and temperature precursors are observed 100-350 μs before the onset of ELMs [26]. One of the important parameters to characterize the ELM precursor is the growth rate, as shown in figure 1. A systematic study in JT-60U showed that the growth rate normalized to the Alfvén frequency \( \gamma / \omega_A \) is about 0.1%. A similar density precursor was also observed in MAST. The edge interferometer exhibited a growth of density fluctuation with \( \gamma / \omega_A \approx 0.5% \) as shown in figure 5(d) in [27]. A precursor in magnetic fluctuation with the frequency of 50-100 kHz was observed in low collisionality edge plasmas (0.2 < \( \nu_e^* \) < 1) with large ELMs in Alcator C-Mod. The mode amplitude grows at the rate \( \gamma / \omega_A \sim 1% \) as shown in figure 3(a) in [28]. All three observations indicate a small growth rate of the ELM precursor, \( \gamma / \omega_A = 0.1-1% \).

The origin of the ELM precursor has not been identified experimentally. One candidate is the rotating seed filaments formed at the plasma edge. In MAST, the density precursor could be measured with an edge interferometer before the filaments are visible in the fast camera [29]. However, such density perturbation seems to continue to exist after the filaments are visible in the camera. Therefore, the density precursor may be a growing structure which develops into the filaments. Further investigation using more sensitive edge plasma diagnostics should reveal the direct relation among the ELM precursor, seed filaments and edge MHD modes.

2.2. Collapse phase and ELM filaments

During the collapse phase after the precursor phase, pedestal particles and energy are quickly released to the scrape-off-layer (SOL) plasma due to ELM. The duration of the collapse phase has been reported to be ~200 μs in a number of devices, and various diagnostics indicate that the collapse of the pedestal structure is localized to the outer midplane [3]. Recent experiments making fast and local measurements in the SOL/divertor plasma region reveal that filamentary structures during the collapse phase as shown in figure 2 can be considered

![Figure 1](image1.png)  
**Figure 1.** Time evolution of the density precursor measured with the O-mode reflectometer (upper) together with the magnetic fluctuation (lower) in JT-60U. Normalized growth rate of the amplitude of the density fluctuation to the Alfvén frequency was \( \gamma / \omega_A \sim 0.1% \). No detectable magnetic precursor was observed in this case.

![Figure 2](image2.png)  
**Figure 2.** Fast visible image obtained during type I ELM in MAST (\( \Delta W_{\text{ELM}} \sim 1.4 \text{ kJ} \) and \( W_{\text{ped}} \sim 11.8 \text{ kJ} \)).
as a common feature of type I ELM in most tokamaks (Recent publications: Alcator C-Mod [28], ASDEX Upgrade [30, 31], DIII-D [24], JET [32, 33], JT-60U [34, 35], MAST [27, 29] NSTX [36, 37]). A comparison of the spatial and temporal structure of ELM filaments in various devices is given in [38]. Therefore, the importance of ELM filaments in evaluating the ELM heat load is highlighted in this section.

The propagation of ELM filaments in the SOL region has been measured with various diagnostics such as fast camera (infrared and visible imaging), Thomson scattering, probes, and beam emission spectroscopy (BES). Among these, one of the important experimental results is the evaluation of the filament energy content from Thomson scattering, which shows that each filament contains up to 2.5 % of $\Delta W_{\text{ELM}}$ in MAST [39] and JET [40]. Therefore, apparently some amount of ELM energy loss (e.g. 25% of $\Delta W_{\text{ELM}}$ in the case of 10 filaments) is carried by filaments both to divertor plates and to the first wall depending on the radial and toroidal velocity of the filaments.

The inter-machine comparisons between MAST and ASDEX Upgrade in terms of the radial transport of ELM filaments and e-folding lengths of the ion saturation current have also been performed [41]. The filaments rotating toroidally and poloidally with velocities close to that of the pedestal are detached from the edge plasma. Then, the velocity decreases as the filaments propagate radially. In both devices, the e-folding lengths of the ion saturation current of filaments exhibit a weak dependence on $\Delta W_{\text{ELM}}/W_{\text{ped}}$.

In contrast to the above observation, the fraction of ELM energy loss arriving at the divertor plates exhibits a strong dependence on the ELM size, as observed in JET [32, 33]. As the $\Delta W_{\text{ELM}}/W_{\text{ped}}$ increases, the ELM heat load transferred to the divertor plates decreases as shown in figure 3, which implies that the ELM heat load carried to the first wall by filaments becomes larger. In the case of large ELMs with $\Delta W_{\text{ELM}}/W_{\text{ped}} \sim 0.28$, more than 50% of $\Delta W_{\text{ELM}}$ should accordingly be deposited on the first wall. Therefore, to obtain a reliable prediction of the respective ELM heat loads on the divertor plates and its parameter dependence including precise evaluation of the energy content in each filament are important.

### 2.3. Recovery phase

During the collapse of the pedestal structure, the edge $E_r$ shear structure, which plays an important role in suppressing edge turbulences, is also destroyed. Several ms after the collapse, the edge $E_r$ shear structure forms again. Then, the $p_{\text{ped}}$ starts to recover together with the further increase in the edge $E_r$ shear structure toward next ELM [22]. The temporal and spatial evolutions of pedestal parameters in the recovery phase have been investigated in DIII-D [42]. Although the ion and electron pedestal temperatures tend to saturate during long ELM cycles, saturation of the electron density is typically not observed. Looking at the behavior of the electron pedestal pressure ($p_{e,\text{ped}}$) and its gradient ($\nabla p_e$), most of the lost $p_{e,\text{ped}}$ and $\nabla p_e$ are recovered within the first 10-20 ms (~20% of an ELM cycle). Then, both $p_{e,\text{ped}}$ and $\nabla p_e$ gradually evolve toward the next ELM. The behavior of the total stored energy exhibits the same trend as the time evolution of $p_{e,\text{ped}}$.

The thermal transport properties in DIII-D plasmas have also been estimated from the experimental temperature and density profiles, and calculated conductive flux profiles in the edge plasma [43]. The inferred thermal diffusivities, both $\chi_i$ and $\chi_e$, increase with time between ELMs. Observed change in
the thermal diffusivities seems to be consistent with the observed change in the time scale of the recovery phase in $T_i$ and $T_e$.

In contrast to the case of DIII-D, both pedestal parameters and the total stored energy typically linearly recover toward the next ELM in JT-60U typically [44], even if the edge electron heat diffusivity during the inter-ELM phase is close to the level of the neoclassical ion heat diffusivity [45]. The different time scale in the recovery phase can be understood by a peeling-ballooning model as shown in figure 4. In DIII-D, there first is fast recovery of the pressure gradient ($\nabla p$) corresponding to the movement to the right inside the stable region, and after this, edge current density gradually recovers together with small recovery of $\nabla p$ toward the peeling-ballooning stability limit. On the other hand, in JT-60U, chiefly $\nabla p$ is lost and then this recovers to near the ballooning stability limit. In order to confirm this kind of model, the direct measurement of the change in the edge current density as well as the edge pressure gradient over the ELM cycle will be required.

2.4. Effects of toroidal field ripple and toroidal rotation on ELM energy loss

The effects of the $V_T$ on type I ELM characteristics have been investigated in JT-60U [46]. As counter $V_T$ and/or fast ion losses due to TF ripple increased, $\Delta W_{\text{ELM}}/W_{\text{ped}}$ decreased while the edge $\nu_e^*$ remained fixed. An increase in $\Delta W_{\text{ELM}}/W_{\text{ped}}$ was also observed in the JT-60U/JET dimensionless identity experiments together with the reduction of fast ion losses and consequent smaller counter $V_T$ when perpendicular NBIs were replaced with tangential NBIs with negative-ion sources [47]. In order to distinguish between effects of the $V_T$ and the TF ripple on the ELM characteristics and the pedestal performance, dedicated ripple experiments have been performed in JT-60U [48, 49].

In order to reduce the ripple amplitude ($\delta_{\text{ripple}}$), ferritic steel tiles are installed inside the vacuum vessel in JT-60U. In this way, the $\delta_{\text{ripple}}$ at the outer midplane can be reduced from ~1.7% without FSTs to ~1% with FSTs, in large plasma configurations with plasma volume ($V_p$) of ~75 m$^3$. Figure 5. (a) Normalized ELM energy loss as a function of toroidal rotation speed at the top of pedestal in JT-60U. Two different ripple amplitude (with and without FSTs) are compared in large plasma configuration ($V_p$ ~ 75 m$^3$). Data are from [48, 49]. (b) Collisionality dependence of normalized ELM energy loss in JET ripple experiment [50].
5(a) compares the dependence of the $\Delta W_{\text{ELM}}/W_{\text{ped}}$ on the $V_T$ with and without FSTs [48, 49]. As counter $V_T$ increased, the $\Delta W_{\text{ELM}}/W_{\text{ped}}$ decreased with the same trend appearing both with and without FSTs. Although the $P_{\text{ped}}$ changes slightly in the course of the $V_T$ scan, the change in the $\Delta W_{\text{ELM}}$ is much larger than that in the $W_{\text{ped}}$. This result indicates that it is $V_T$ not $\delta_{\text{ripple}}$ that plays an important role in determining $\Delta W_{\text{ELM}}/W_{\text{ped}}$. In addition to this, it also indicates that not the torque input but rather the resultant $V_T$ is important, because the same $\Delta W_{\text{ELM}}/W_{\text{ped}}$ is obtained in plasmas without FSTs heated by co-NBIs and in plasmas with FSTs heated by balanced-NBIs.

In the usual operation of JET, the 32 TF coils produce very low $\delta_{\text{ripple}}$ of 0.08%. The TF system can also be configured in such a way as to feed different currents to the odd and even set of coils. In this operation mode, the $\delta_{\text{ripple}}$ can actively be changed by selecting the appropriate current differential between each set of coils. As the $\delta_{\text{ripple}}$ increases, the amplitude of type I ELMs appears to be smaller in terms of the $D_a$ emission from the divertor. To quantify this observation, figure 5(b) shows the collisionality dependence of the $\Delta W_{\text{ELM}}/W_{\text{ped}}$ during the $\delta_{\text{ripple}}$ scan [50]. Even with similar $\nu_e^*$, the $\Delta W_{\text{ELM}}/W_{\text{ped}}$ can be reduced as the $\delta_{\text{ripple}}$ increases. It also can be seen that it is difficult to separate the effect of $\delta_{\text{ripple}}$ and $V_T$ in JET plasmas, because $V_T$ which is in the same direction as the plasma current (co-$V_T$) is also reduced as the $\delta_{\text{ripple}}$ increases.

Since analysis shows that the MHD stability of the two devices is similar and probably cannot explain the observed difference in ELMy H-mode performance [51], the $V_T$ and the $\delta_{\text{ripple}}$ have been focused upon as the major difference between JET and JT-60U. Therefore, new inter-machine experiments on the $V_T$ and the $\delta_{\text{ripple}}$ have been performed in both devices using plasma with matched shapes [52]. Similar to the dedicated ripple experiment in JT-60U shown in figure 5(a), larger co-$V_T$ seems to increase the ELM energy loss and also reduce the ELM frequency. Especially, the ELM frequency normalized to the loss power through the separatrix ($P_{\text{sep}}$) seems to be correlated with $V_T$ in both devices. As co-$V_T$ increases, smaller ELM frequency is observed, indicating larger $\Delta W_{\text{ELM}}$.

The $\Delta W_{\text{ELM}}/W_{\text{ped}}$ can be reduced by changing $V_T$. However, the minimum level of $\Delta W_{\text{ELM}}/W_{\text{ped}}$ is still larger than 2% even in plasmas chiefly rotating in the counter direction as shown in figure 5(a). Further reduction of $\Delta W_{\text{ELM}}/W_{\text{ped}}$ is required to achieve the acceptable level for ITER.

3. Small/no ELM regimes
Several small ELM or no ELM (steady ELM free) regimes with good confinement properties, such as EDA, grassy ELM, HRS, QH-mode, type II and type V ELM, have been obtained in various devices, as summarized and categorized in [6]. All these regimes show considerable reduction of the ELM heat load onto divertor target plates in contrast to conventional type I ELM. The $\Delta W_{\text{ELM}}/W_{\text{ped}}$ in these regimes has been evaluated as less than ~5% as shown in figure 6. Since the values in some regimes are determined by the resolution limit of the diagnostics for the $\Delta W_{\text{ELM}}$ measurement, the level of $\Delta W_{\text{ELM}}/W_{\text{ped}}$ in all these regimes seems to be acceptable in ITER.

Another important parameter to discuss the applicability of these alternative regimes to ITER is the edge $\nu_e^*$. Although the operational space shown in figure 6 indicates that some regimes seem to be separated by $\nu_e^* \sim 1$, in NSTX the operational space of type V ELM regime can be expanded toward low $\nu_e^*$ regime ($\nu_e^* < 1$) by increasing the plasma triangularity up to $\delta \sim 0.75$ [53]. Therefore, the type V ELM regime is now
considered as a different regime from the HRS regime in JFT-2M and the EDA regime in Alcator C-Mod, even though the type V regime also exhibits the characteristics of the enhanced recycling. The existence of edge fluctuations is considered as the reason for the enhanced recycling in HRS [54] or EDA [55] regimes. The fact that no edge fluctuations are observed in the type V ELM regime is another big difference between the type V ELM regime and the HRS/EDA regimes.

In this section, the recent progress on some small ELM or no ELM regimes, such as type V ELM, grassy ELM and QH-mode regimes, obtained with low $\nu_e^*$ plasmas are summarized.

3.1. Type V ELM regime
A single null configuration has been found to be a required condition to obtain the type V ELM regime in NSTX [56]. Since ITER cannot operate using the double null configuration and $\Delta_{\text{sep}}$ (the distance between the separatrix and the flux surface through the upper X-point at the outer midplane) should be kept at 4 cm, the fact that type V ELM can be obtained with a larger gap makes this favorable for ITER. In low $\delta$ plasmas, the type V ELM regime can be obtained when $\Delta_{\text{sep}} \geq 1.5$ cm. In high $\delta$ plasmas, a slight movement in the plasma configuration, where the upper X-point is pulled upward by $\sim 4$ cm from a balanced double null configuration, changes the ELM characteristic from the type I ELM to the type V ELM. This small change corresponds to $\Delta_{\text{sep}} \sim 0.5$ cm [53].

The spatial structure of the type V ELM has been investigated using various diagnostics such as fast visible camera, ultra-soft X-ray array, interferometers, magnetic probes and gas-puff imaging [53, 37, 56]. Dedicated measurements using these diagnostics reveal the following characteristics of the type V ELM. The Type V ELM appears as single or sometimes double filaments aligned with the magnetic field. The filament first appears on the closed field lines near the top of the H-mode pedestal. There is a clear electromagnetic $n = 1$ precursor rotating counter to the plasma current before the type V ELM crash. Then, the filament propagates toroidally in the direction counter to the plasma current. The filament drifts radially outward as it moves toroidally, eventually appearing on visible camera images of the entire plasma and the divertor region. Figure 7 compares the fast visible camera images of the type V ELM and the type I ELM. Similar behavior of some filaments was observed in the type I ELM shown in figure 2 and figure 7(b), while a single filament along the open field line corresponding

\[\text{Figure 7. Visible camera image of (a) single filament taken in type V ELM and (b) many independent filaments taken in type I ELM. Type V ELM is obtained in lower single null configuration, which has a second X-point inside a vacuum vessel. Background frame is subtracted in both figures [53].}\]
to the normalized poloidal flux of 1.49 (far outside the second X-point) was clearly observed in type V ELM. These differences between the type I ELM and the type V ELM indicate that the number of filaments is also important in determining the ELM amplitude and to distinguish ELM types. However, the identification of the underlying instability responsible for the onset of the type V ELM requires further investigation.

3.2. Grassy ELM regime

The grassy ELM regime discovered in JT-60U is a small ELM regime which combines tolerable ELM energy losses with low pedestal collisionality and no degradation of pedestal pressure. To enter the grassy ELM regime in JT-60U, several important parameters have been found such as high safety factor ($q_{95}$), high $\delta$, and high poloidal beta ($\beta_p$) [57]. The importance of these parameters in reproducing grassy ELM has been confirmed in JET [58] and ASDEX Upgrade [59]. In addition to these parameters, $V_T$ has been found to influence the appearance of the grassy ELM in JT-60U, ELM frequency gradually increasing together with a reduction in the ELM amplitude as counter $V_T$ increases [23]. Since the $V_T$ in ITER plasma is expected to be small (e.g. ASTRA code predicts 0.26 kHz at the pedestal [60]), systematic study of the effect of $V_T$ on the appearance of the grassy ELM and its parameter dependence has been performed in JT-60U [61].

The ELM frequency observed for different $V_T$ and $\beta_p$ are summarized in figure 8(a). In order to change the toroidal rotation frequency while keeping a given $\beta_p$ fixed, combinations of tangential co-, ctr- and balanced-NBIs and perpendicular-NBIs were varied. The ELM frequency clearly increases with increase in counter $V_T$ independently of $\beta_p$. It is also found that there is a threshold value of $\beta_p$ in configuration with lower $\delta$ ($\delta < 0.5$). When the toroidal plasma rotation frequency becomes higher than ~1 kHz in the co-direction, on the other hand, type I ELM with a frequency of ~20 Hz is observed.

Figures 8(b)-(d) compare the time evolution of the stored energy in the plasmas marked in figure 8(a). In order to change the toroidal rotation frequency while keeping a given $\beta_p$ fixed, combinations of tangential co-, ctr- and balanced-NBIs and perpendicular-NBIs were varied. The ELM frequency clearly increases with increase in counter $V_T$ independently of $\beta_p$. It is also found that there is a threshold value of $\beta_p$ in configuration with lower $\delta$ ($\delta < 0.5$). When the toroidal plasma rotation frequency becomes higher than ~1 kHz in the co-direction, on the other hand, type I ELM with a frequency of ~20 Hz is observed.

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### Figure 8

- **(a)** ELM frequency dependence as a function of toroidal rotation frequency measured at the top of $T_i$ pedestal for different $\beta_p$ ranges. Corresponding toroidal rotation speed for typical plasma condition is also shown at the upper horizontal axis. (b)-(d) Time traces of the plasma stored energy correspond to the data marked with (b)-(d) in (a). Time traces of divertor $D_\alpha$ signal in grassy ELM are also plotted in (b) and (c). Data are from [61].
The $\beta_p$ achievable in co-rotating plasmas over the range of rotation frequency is limited, because the higher heating power resulting from the perpendicular NBIs provides larger counter $V_T$ due to ripple induced fast ion losses. It is expected that the grassy ELM will be obtained in plasmas with higher $\beta_p$ even at larger co-$V_T$ than 1 kHz, because grassy ELM is obtained in JET and ASDEX Upgrade with higher co-$V_T$ than that in JT-60U. Further survey of sufficient conditions to achieve grassy ELM and the understanding of the mechanism of change in the ELM type (or ELM affected area) with change in $V_T$ are important to establish an operation scenario for the grassy ELM in ITER.

3.3. QH-mode regime

The QH-mode regime, where confinement levels similar to those of standard ELMy H-mode plasmas can be sustained without any ELMs, were originally observed in DIII-D [62] and then produced in AUG [63], JT-60U [64] and JET [65]. In these QH-mode plasmas, counter-NBI heating and a large clearance between the plasma separatrix and the first wall (i.e. gap) are typically required to obtain QH-mode plasmas. The edge harmonic oscillation (EHO), which is considered to enhance the particle fluxes, is usually observed near the separatrix at the onset of the QH-mode plasma in all devices. The effect of the $V_T$ and the direction of the torque input have been investigated in JT-60U [23]. Since partial QH-mode phases are observed during co- and balanced-NBI heated plasmas with slightly counter or almost zero $V_T$, a dedicated experiment to confirm the threshold of the $V_T$ for entrance into the QH-mode regime as well as the physical mechanism of suppression of ELMs has been conducted.

After the reorientation of two neutral beam sources to allow co-, counter, and balanced NBI, that provides fine control of the plasma rotation in DIII-D, the investigation of effects of $V_T$ on QH-mode plasmas was performed [66, 67]. As is shown in figure 9, the pedestal density in the QH-mode can be increased by reducing the counter $V_T$ after changing the fraction of the co-NBI power while keeping the total NBI power fixed. With the lower torque (125730 and 125731) when the counter $V_T$ is reduced to less than ~20 km s$^{-1}$, ELMs return as the pedestal density increases. In QH-mode plasmas, enhanced edge particle transport caused by the presence of the EHO has been observed. During experiments varying the rotation speed, the EHO becomes less robust at the lower input torque. These experimental results indicate that changes in the EHO caused by the reduction of the counter $V_T$ are connected to the decrease in the edge particle transport.

A previous stability analysis using the ELITE code indicates that the typical QH-mode lies near a current limited stability boundary at high edge current density and high $\nabla p$ [68]. A peeling-ballooning stability analysis spanning the transition from QH-mode to ELMy H-mode has been performed [67, 69]. The operational points in ELMy H-mode are closer to or slightly beyond the calculated stability boundary, while those in QH-mode are just below the peeling boundary. Therefore, the ELMs reappear together with the change in EHO characteristics when the pedestal operating point crosses the stability boundary. However, the cause for the gradual change in the edge $\nabla p$ and the current density as counter $V_T$ is reduced is not yet understood.

These experimental results suggest that the operational space of QH-mode can be expanded into a better plasma configuration having a higher stability limit. This kind of plasma optimization has also

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**Figure 9.** Comparison of waveforms in rotation scan experiments in DIII-D. Discharges with less than 1/4 co NBI power fraction remain QH-mode (125734 and 125729), while those with larger co NBI power fractions and with smaller counter $V_T$ ~ 20 km s$^{-1}$ redevelop ELMs [66].
been performed in DIII-D [67]. The ELITE code has been used as a guide to optimize the plasma shape to achieve the widest possible stable operating region, and the new shape with different flux surfaces near the centerpost improves the overall edge stability. Using the new shape, the \( P_{\text{ped}} \) in QH-mode plasmas can be increased by a factor of two by reducing the input torque (by reducing counter \( V_T \)). Thus, the total plasma performance is also improved even though the input power is constant. These results demonstrate that the edge \( P_{\text{ped}} \) can be controlled by changing the input torque at constant input power while keeping the QH-mode phase. Making use of this optimization, record pedestal densities in the QH-mode reaching 50% of the Greenwald density limit (\( n_{\text{GW}} \)) can be achieved. As the counter \( V_T \) decreases, the EHO characteristics are changed so that the MHD oscillations detected by the Mirnov loops develop a broadband character with many of the dominant toroidal mode numbers, rotating in the direction of the plasma current. Further investigation to understand how these changes influence change in the transport will be required.

### 4. Active ELM control

In order to suppress or control the type I ELM, a variety of techniques have been studied in various devices as follows. Pellet pacing, this is, forced ELM triggering by continuous pellet injection, has been demonstrated in ASDEX Upgrade [70] and is planned for JET [71] and DIII-D [72]. In contrast to a pellet injection, no prompt ELM triggering has been achieved using a pulsed gas jet [73]. Edge current modification by vertical plasma displacement has been demonstrated in COMPASS-D [74], and reproduced in TCV [75] and ASDEX Upgrade [76] with a vertical position control system. Edge modulated ECH which produced a local pressure gradient was found in ASDEX Upgrade [77]. Recently, a quasi-stationary ELM-free H-mode regime was obtained during third-harmonic X-mode ECH in TCV [78]. Although the physical mechanism of the suppression of ELMs is not discussed in [78], the ELM-free period seems to be related not to the duration of the third-harmonic X-mode ECH but to the duration of the modulated ECH phase [79]. The achievement of steady H-mode with small ELMs has been achieved in JFT-2M with high \( m \) resonant modes (\( m > 10 \)) [80] and control of type III ELM frequency has been demonstrated in COMPASS-D [74]. The complete suppression of type I ELM by the \( n = 3 \) RMP producing edge stochastic magnetic field boundary, where the particle loss is enhanced, has been demonstrated in DIII-D with high \( \nu_e \) plasmas [81] and then expanded to ITER relevant low \( \nu_e \) [82]. In JET, \( n = 1 \) error field correction coils (EFC) can reduce the ELM amplitude together with higher ELM frequency [83]. Because of these successful ELM control using external coils, an installation of such control coils has been planned in MAST and ASDEX Upgrade. Technique to optimize \( \Delta W_{\text{ELM}} \) and \( P_{\text{ped}} \) with gas puffing (\( D_2, N_2, Ne \)) for advanced tokamak operation is also being studied in JET [84].

In this section, the recent results of pellet pacing (planned for ITER) and external magnetic field perturbation for ELM suppression (reviewed for ITER) are summarized.

#### 4.1. Pellet pacing

Since only a pellet injector for large size fueling pellets has been installed in JET, a demonstration of pellet pacing cannot be performed. However, the initial ELM trigger process initiated by the pellet has been investigated to confirm the concept of the pellet pacing in a large scale device [85]. The time evolution of \( D_\alpha \) signal in the pellet ablation monitor and magnetic fluctuation indicate the timing of ELM triggering, when only a small fraction (less than 1%) of the fueling size pellet is ablated and deposited. More information on the threshold condition for pellet produced perturbations, which trigger ELMs, will be investigated in JET with a new pellet injection system optimized for the pellet pacing.

In order to design a pellet injector optimized for ELM control and to predict the operation space of pellet pacing in ITER, the minimum penetration depth required for the forced ELM triggering is one of the most important parameters. Systematic analysis of the delay of ELM onset from the time the pellet crosses the separatrix has been performed in ASDEX Upgrade, and the result is summarized in figure 10 [86]. The seed location where the ablating pellet triggers an ELM lies with 99% probability
in a narrow range extending ±1.2 cm from the most probable position (peak of the probability function of the seed location) in the middle of the pedestal. The location is independent of the pellet mass and velocity. However, we have to confirm whether smaller pellets, which can only penetrate the middle of the pedestal, can trigger an ELM or not. In addition to this, the minimum penetration depth obtained in ASDEX Upgrade should be compared with other devices to find a reliable operational space for pellet pacing in ITER.

The operation space for the pellet pacing in ITER is determined by several parameters such as the pellet frequency required to reduce the $\Delta W_{\text{ELM}}$ to the acceptable level, the pellet size, the pumping speed, the particle confinement time, the fueling efficiency, and the minimum penetration depth for ELM triggering. The new criterion of the acceptable ELM energy loss described in the introduction requires a pellet frequency higher than 16 Hz, which is 10 times higher than the natural ELM frequency. An estimation of the operational space of pellet pacing in ITER has been performed assuming appropriate values of above mentioned parameters [87]. A combination of a pellet injector at the high field side (HFS) and one at the low field side (LFS) can create a reasonable operational space for pellet pacing at 16-22 Hz as shown in figure 11. The operational space is limited by the total pumped flux $S_{\text{tot max}}$ of 120 Pa m$^3$ s$^{-1}$ in the analysis. The uncertainties of the particle confinement time in each operational scenario define the possible operational range as shown by horizontal dashed lines.

In the analysis shown in figure 11, a pellet penetration to the top of pedestal is adopted as a conservative required condition for the forced ELM triggering. This requires a pellet size of $d > 4$ mm. However, if seed perturbation at the middle of pedestal is enough for the ELM triggering, a smaller pellet ($d = 3$ mm in [88]) can be used for pellet pacing at LFS. In order to accurately determine the operational space in ITER, further studies are required to reduce these uncertainties.

### 4.2. External magnetic field perturbation

In plasmas in DIII-D with ITER relevant $\nu_e^*$, type I ELMs are completely eliminated with radial magnetic field perturbations ($\delta b_r$) at the $q = m/n = 11/3$ surface exceeding $\delta b_r/B_T = 2.6 \times 10^{-4}$, where $B_T$ is the toroidal magnetic field on the plasma axis and the value is evaluated in a vacuum. The typical edge plasma response to RMP in ITER relevant $\nu_e^*$ plasmas is a significant change in the global particle balance. The pedestal density gradient is reduced, while the pedestal temperature gradient

![Figure 10](image1.png)

**Figure 10.** Probability density function of the seed location (dashed line) and electron plasma pressure profile as a function of the distance along the pellet path measured from the position of the separatrix. The pedestal top is located at about 6 cm [86].

![Figure 11](image2.png)

**Figure 11.** Operational space of pellet pacing in ITER. Horizontal and vertical axis are fueled particle flux from HFS and LFS pellet injectors, respectively. Horizontal dashed lines correspond to the estimate of the uncertainties of the knowledge of core particle transport for inductive, hybrid and steady state (SS) ITER scenarios [87].
increases modestly. Consequently, the electron pressure gradient across the pedestal region is reduced \[89\]. A strong relation between the size of the resulting pressure gradient and the suppression of the type I ELM has been found experimentally. The level of the change in pedestal profile varies with several parameters such as the RMP coil current, the RMP coil configuration, the edge safety factor, the NBI heating power, and the gas fueling rate.

These experimental observations of ELM suppression with RMP can be explained by the peeling-ballooning model \[66\]. Similar to ELM suppression in the QH-mode regime, the pedestal parameters can be kept either close to or well below the peeling-ballooning stability boundary as shown in figure 12. These results indicate that the edge ergodic layer produced by the RMP plays a role similar to the EHO in the QH-mode, driving substantial transport (especially particle transport) and providing steady H-mode plasmas without ELMs.

Figure 12. Peeling–ballooning stability diagram for a series of RMP ELM suppressed discharges (circles) compared with phases of similar discharges with ELMs (diamonds) \[66\].

After the modification of divertor configuration in DIII-D, complete ELM suppression with an ITER similar shape (ISS) was also demonstrated \[90\]. In the ISS configuration, a larger RMP coil current producing \( \delta B_r/B_T = 3.4 \times 10^{-4} \) is required for complete ELM suppression than the low \( \delta \) configuration. In addition to this, the resonant window in \( q_{95} \) is narrower in the ISS configuration which has higher magnetic shear. Nevertheless, the operational boundary between the ELMy phase and ELM suppression phase can be explained by the peeling-ballooning model \[69\], the same as in the case of low \( \delta \) shown in figure 12. From the comparison between the region of island overlap and the change in the \( Vp \) required for complete ELM suppression, a physics based required condition of the mode spectrum should be obtained in future research. For more accurate assessment, the effects of edge bootstrap currents on the \( q \) profile and the screening effect of the \( V_T \) on the resonant magnetic field should be considered.

In JET, active ELM control using a static external perturbation field with \( n = 1 \), generated by four EFCCs located far from the plasma, also has been demonstrated \[83\]. During the application of the \( n = 1 \) perturbation field, the ELM frequency increased by a factor of 4 and the amplitude of the \( D_\alpha \) signal decreased as shown in figure 13. The \( \Delta W_{ELM} \) normalized to the total stored energy, \( \Delta W_{ELM}/W_{total} \), dropped to values below 2%. Transport analyses shows no or only moderate

Figure 13. Waveforms of typical ELM control using EFCC in JET. (a) total input power and the stored energy, (b) EFCC current, (c) the line-integrated electron densities in the central chord (upper trace) and the pedestal chord (lower trace), (d) the electron temperature at the plasma center (upper trace) and at the pedestal top (lower trace), (e) the \( D_\alpha \) signal measured at the outer divertor, (f) the fast ion loss current and (g) magnetic fluctuation \[83\].
degradation of the energy confinement time during the ELM mitigation phase. The core and edge density are lowered by the density pump out, as shown in figure 13(c). It is noted that there is an operational window of the EFCC current amount which avoids a locked mode and achieves ELM mitigation [91]. The fact that the window seems to be wider in the case of $n = 2$ perturbation field indicates that a higher toroidal mode number is advantageous for ELM control without destabilizing the locked mode.

The effect of density pump out is a common characteristic in plasmas under the ELM control using external magnetic field perturbation. So far, the recovery of plasma density has not been achieved. However, a plasma operating contour (POPCON) plots for ITER in volume averaged density and temperature indicates that an averaged density of $0.6 n_{GW}$ is required to achieve $Q = 10$ (figure 93 in [92]). Therefore, it is important to investigate how to achieve controllability of the plasma density with external magnetic field perturbation.

Based on these successful ELM controls using external magnetic field perturbation demonstrated in DIII-D and JET, a number of possible designs of external and in-vessel coils generating the RMP for the ELM control in ITER have been analyzed for the reference scenarios (H-mode, Hybrid and Steady-State) taking into account physical, technical and spatial constraints [93]. The evaluation of RMP coils designs has been made to achieve an RMP spectrum that produces enough edge ergodisation and minimum central perturbation at minimum current. One possible candidate for the coil design for ITER comprises port-plug coils in the midplane port with 150 kAt, which could be reasonably adapted to various scenarios.

5. Importance of $V_T$ for ELM studies

As described in the previous section, the edge $V_T$ clearly affects ELM characteristics. In the type I ELM regime, the $\Delta W_{ELM}/W_{ped}$ can be reduced with smaller co-$V_T$ or larger counter $V_T$, the ELM frequency varying with the $V_T$ accordingly. In the grassy ELM regime, grassy ELM frequency rapidly increases while maintaining similar pedestal performance as counter $V_T$ increases. In the QH-mode regime, EHO characteristics and $\rho_{ped}$ seem to be changed by $V_T$.

Not only in the experiments, but also in the design of the ELM control coils, the importance of $V_T$ can be found. As described in the previous section, the level of central perturbation due to the external magnetic field perturbation is one of the important aspects of the optimization of the design. In such assessment, the screening effect of the $V_T$ should be taken into account. The possible screening of RMP is estimated using both analytical and numerical results from the JOREK code [94]. In the estimations of the degree of screening of the RMP by the $V_T$, there was a strong reduction of the magnetic field perturbation amplitude towards the plasma center, but relatively little change in the pedestal region where the resistive time and the toroidal rotation frequency have usually much smaller values than the plasma center. In other words, if the toroidal rotation frequency at the pedestal is larger than the current estimation of $0.3$ kHz in ITER, a higher coil current will be needed to generate an edge ergodic region with the same size.

All these results indicate the importance of a reliable prediction of the toroidal rotation velocity and/or frequency in ITER with TF ripple which produces an effective torque at the edge region. This effect on plasmas in JET and JT-60U with TF ripple has been modeled using the ASCOT code [95]. The analysis shows that the observed negative plasma rotation near the plasma edge requires extra negative torque, which might come from ripple losses of thermal ions, to satisfy the toroidal force balance. It is important to understand the physical mechanism determining the torque source profile with TF ripple and momentum transport properties for better prediction/modeling.

The physical mechanism of change in the ELM characteristics and the pedestal performance with change in $V_T$ is another issue. Two possible mechanisms can be considered here. One is that the $V_T$ affects the plasma transport and/or the edge fluctuation, which in turn causes the change in the edge $\nabla p$. In this mechanism, the edge radial electric field and its shear may play an important role. The other is that the $V_T$ profile directly affects the edge MHD stability, although experimentally relevant $V_T$ shear only has a stabilizing effect in the case of larger toroidal mode number ($n > 20$) [5]. Recently, a
new concept, edge localized resistive wall mode, has been proposed in the QH-mode [66]. To address this issue, dedicated and simultaneous measurements of plasma density, temperature, rotation and current profiles using high resolution edge diagnostics are required.

6. Conclusions

The recent improvement of edge plasma diagnostics provides a better understanding of the physics in the ELM dynamics. In precursor phase as a linear growth phase in MHD instability, a small growth rate of the type I ELM precursor, $\gamma/\omega_A = 0.1-1\%$, is observed. A phenomenon commonly observed during the collapse phase is the propagation of ELM filaments in the SOL region, which is important to evaluate the ELM heat load. However, the mechanism of the loss of particles and heat during the short-lived (~200 $\mu$s) collapse phase remains to be understood. After the ELM filament is ejected from the last closed flux surface, further investigation is required to answer the question whether there is a direct path from the pedestal to the divertor or not. The different evolutions of pedestal parameters observed in DIII-D and JT-60U in the recovery phase can be understood qualitatively introducing different operational point in a stability boundary determined by peeling-ballooning model. Direct measurement of the change in the edge current density during the ELM cycle will be required to validate this model quantitatively. Although the $V_T$ and the TF ripple clearly affect the $\Delta W_{ELM}/W_{ped}$, the mechanism by which the $\Delta W_{ELM}/W_{ped}$ can be reduced by making co-$V_T$ smaller or counter-$V_T$ larger is not yet understood. Moreover, the unacceptable level of the $\Delta W_{ELM}/W_{ped}$ for the type I ELM regime in cases including counter-rotating plasmas is still an important remaining issue for ITER.

The establishment of plasma operations in small ELM or no ELM regimes is especially important in ITER because ITER cannot accept the $\Delta W_{ELM}$ of type I ELMs. Therefore, further expansion of the operational space of various small ELM or no ELM regimes through multi-machine experiments and improved edge diagnostics is strongly encouraged. The progress achieved in low $\nu_e$ small ELM or no ELM regimes is as follows. A type V ELM regime in NSTX characterized by small ELM amplitude with one or two filaments can be obtained in lower collisionality ($\nu_e^* < 1$). The ELM frequency in the grassy ELM regime increases as the $V_T$ changes in the counter direction. A small $\Delta W_{ELM}/W_{ped} < 1\%$ is achieved with the grassy ELM in plasmas with small or no $V_T$. In QH-mode plasmas in DIII-D, higher $p_{ped}$ together with changes in EHO characteristics are achieved at smaller counter-$V_T$. The edge operational conditions can be kept just below the peeling boundary because of the existence of EHO/broadband fluctuations, which is considered as a physical mechanism of ELM suppression in the QH-mode regime.

Systematic studies of pellet pacing and the external magnetic field perturbation have progressed in developing ELM control methods applicable to ITER. The middle of the pedestal has been confirmed as a minimum penetration depth for forced ELM triggering. In JET, it has been found that only a small fraction of the fueling size pellet is enough for ELM triggering. Complete ELM suppression in DIII-D low $\nu_e^*$ plasmas with ITER similar shape was demonstrated. Because particle loss is increased by RMP, the pedestal parameters can be kept either close to or well below the peeling-ballooning stability boundary. This is why the ELMs are suppressed in RMP plasmas. ELM control with EFCC creating $n=1$ perturbation also was demonstrated in JET. Based on the results, both pellet pacing and external magnetic field perturbation seem to be effective in ITER. However, the narrow operational margin imposed by the uncertainties due to the lack of the knowledge concerning the forced ELM triggering case by pellet pacing and the density pump-out effect with external magnetic field perturbation are remaining issues to achieve $Q=10$ plasmas in ITER. New experiments using newly installed ELM control methods in various devices will contribute to establish active ELM control in the next-step device.

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