UKAEA-CCFE-PR(19)39

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This is a preprint of a paper submitted for publication in Nature Reviews Physics

Filamentary plasma eruptions and their control on the route to fusion energy

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Abstract

Fusion is one of very few options for sustainable, low-emission, baseload power to the grid that is necessary to meet the energy needs of future generations. The tokamak is the most advanced approach to fusion and, with the construction of ITER, we are getting close to power plant conditions. While commercialisation of this key energy technology is a main driver for tokamak plasma physics research, it is nevertheless a field that is rich in fundamental science, including complex phenomena such as self-organisation and bifurcations, and fast magneto-hydro-dynamic (MHD) events.

For example, as the heating power is increased above a threshold, the tokamak plasma suddenly bifurcates to a state of high confinement, creating a region of high plasma pressure gradient at its edge. This is a fascinating piece of plasma physics, but the focus here is on the consequence of this bifurcation, rather than its cause – understanding the ensuing repetitive sequence of explosive filamentary plasma eruptions called Edge Localised Modes (ELMs).

ELMs on next step tokamaks, such as ITER, will likely cause excessive erosion to plasma facing components, and therefore must be controlled. There are several options, but one is the use of a system of current-carrying coils positioned around the plasma. Our understanding of filamentary plasma eruptions will be vital to make fusion energy a reality.

1. Tokamaks and plasma confinement

Fusion is a promising solution for sustainable, low-emission, baseload power to meet the energy needs of future generations. The fuel required, deriving ultimately from the deuterium contained in seawater and the lithium used to breed tritium, is plentiful and available. The radioactive waste generated would be relatively small using low activation materials that have already been identified. Further optimisation of the materials used in construction of the fusion power plant could reduce waste even more, completely eliminating long-lived isotopes. Fusion power plants would produce no greenhouse gases, and so have the potential to contribute a significant fraction of our future energy mix without a detrimental impact on climate change. The realisation of fusion energy is truly one of the grand challenges facing the humanity, with enormous societal benefits, and we are getting close to a solution.

The most advanced fusion reactor design is the tokamak. As well as a key facility on the pathway to fusion energy, it offers a rich variety of plasma physics, exhibiting a range of fundamental phenomena from magnetic reconnection, through turbulence to features of complex systems such as bifurcations and self-organisation. In this review we focus on one particularly interesting and important aspect of tokamak plasmas – repetitive, violent, filamentary eruptions called Edge Localised Modes (ELMs).

A tokamak confines the energy and charged particles of the plasma in a toroidal chamber with a magnetic field – a magnetic trap. This magnetic field has two orthogonal components - one that is created by a system of current-carrying, often D-shaped, coils around the plasma, and one that is created by a current that is induced in the plasma. The resulting magnetic field lines spiral around a set of nested toroidal flux surfaces, providing an effective plasma confinement system that can be heated to conditions approaching those required for fusion energy (see Figure-TOK). Experiments were carried out at the JET tokamak in 1997 using deuterium and tritium, producing 16 MW of fusion energy while requiring 25MW of plasma heating [JET-1999]

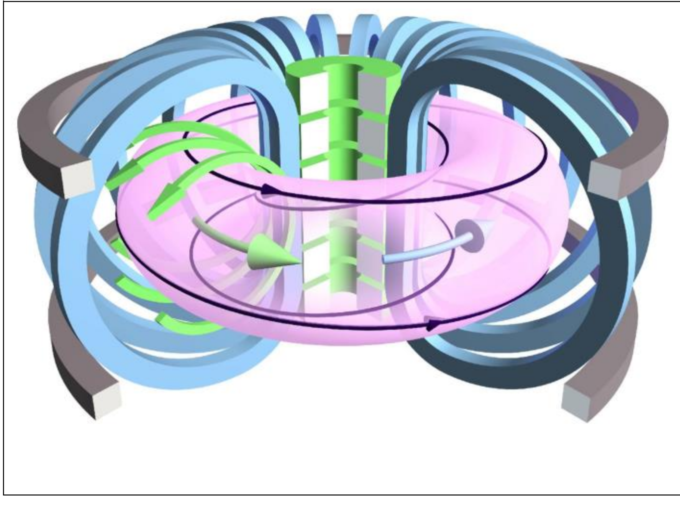


Figure-TOK:
A typical tokamak configuration uses (blue and grey) current carrying coils to generate part of the required magnetic field. A current (green arrow) is induced in the plasma to generate further magnetic fields which result in helical magnetic field lines (black line). The charged particles of the plasma follow these field lines to leading order, creating an effective plasma confinement system. Image credit UKAEA

At low heating powers the edge of the plasma is characterised by fine scale plasma turbulence; this leads to a loss of heat and particles and hence limits the core plasma pressure that is achievable with a given heating power [Dudson-2008]. This is the so-called "Low Confinement Mode", or L-Mode of operation.

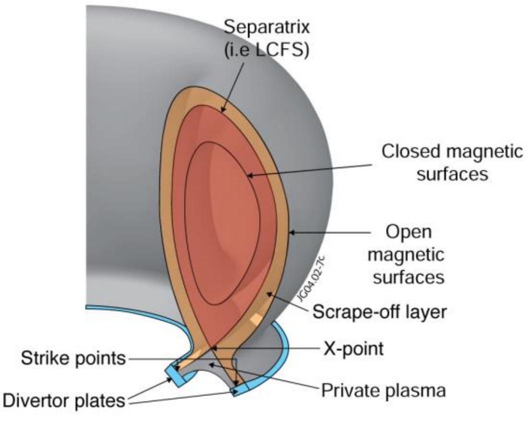
If the plasma heating power is increased above a threshold, the plasma spontaneously self-organises into an improved or "High confinement" (H-mode) regime (see [Wagner-2007] and references therein). This bifurcation, the L-H transition, typically occurs on a timescale of milliseconds. In the H-mode regime the edge plasma turbulence is dramatically suppressed. The mechanism is believed to be associated with a strong plasma flow shear at the plasma edge; this breaks up the turbulent eddies, reducing the particle and energy transport to generate what is called an edge transport barrier [Wagner-2007]. This barrier, typically a few centimetres wide in a plasma that is 1-2 m across, leads to a steep pressure gradient at the plasma edge. This acts as an insulating envelope around the plasma, raising the whole core pressure. The increase in core pressure leads to an increase in overall confinement of a factor of two or so; thus, even though the edge transport barrier is only the outer few percent of the plasma, it is incredibly important for fusion performance, and key for ITER to achieve its fusion performance targets.

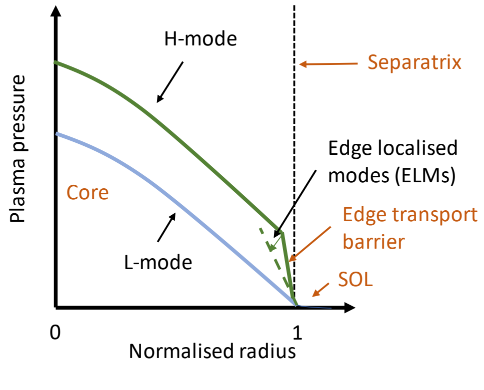
If it exceeds a certain limit, the high pressure gradient in the edge transport barrier is sufficient to drive explosive plasma instabilities, which are called Edge Localised Modes, or ELMs [Leonard-2014]. They exhibit themselves as a sequence of fast, repetitive filamentary plasma eruptions. ELMs are a concern for next step tokamaks, such as ITER, because they are predicted to cause excessive erosion of the surrounding material surfaces [Loarte-2003]; they are also interesting from a fundamental plasma physics point of view, as will be discussed in this review.

Equilibrium pressure and current profiles and tokamak regions

The plasma in a tokamak can be split up into a two regions defined by the topology of the magnetic field in those regions. The core or confined region has magnetic field lines that lie within a series of nested toroidal flux surfaces. These nested flux surfaces can sustain a pressure gradient. Outside this confined region there is a region of open field lines that connect to the exhaust or divertor plates. This is called the scrape off layer (SOL). This change in topology from closed to open field lines also introduces a magnetic X-point on a special flux surface called the separatrix which separates the confined region and the scrape off layer. This magnetic geometry is produced by placing a current carrying coil underneath the divertor plates.

We can describe a tokamak plasma equilibrium in terms of the shape of flux surfaces and the pressure and current density as a function of the flux. The pressure profile is determined by the transport processes in the plasma. The transport across the core region is thought to be 'stiff' meaning that it is difficult to change the pressure gradient in this region. In L-mode the pressure goes smoothly towards zero at the edge of the confined region. In H-mode there is a suppression of edge turbulence leading to an edge transport barrier and strong edge pressure gradient region. This raises the core pressure, thus improving the overall confinement.





The left figure shows the geometry of the different regions of the tokamak. (Image credit: UKAEA) The right figure compares L-mode and H-mode pressure profiles in a tokamak plasma as a function of minor radius across flux surfaces from the centre of the plasma to the edge.

2. Edge-Localised-Modes (ELMs)

2.1 Filament formation physics

With features reminiscent of solar eruptions, ELMs are explosive, filamentary events, aligned along the magnetic field. They eject large amounts of energy and particles from the confined region – typically 5-15 % of the total energy stored in the plasma – in a short amount of time (100-300μs), resulting in large heat fluxes to plasma facing components. The way these heat fluxes scale to future, larger tokamaks, including ITER, is a cause for concern [Loarte-2003]. Thus, as well as the strong motivation driven by inherent scientific curiosity, there is a high priority need to understand ELMs, to quantify their impact in ITER, and develop control techniques; indeed, there is concern that ELMs will need to be completely avoided in tokamaks beyond ITER (e.g. demonstration power plants).

Over the past decade much improved fast camera technology has allowed us to directly observe these filaments and their characteristics, building on the first observations on MAST [Kirk-2004]. Their properties have been probed using a variety of diagnostic instruments employed on a number of the world's tokamaks to provide a detailed picture of their physical properties [Kirk-2009]. Figure-FIL shows examples from the MAST tokamak at two different stages of the eruption. It clearly shows that during the ELM event narrow plasma filaments push out from the edge transport barrier region of the confined plasma into the Scrape Off Layer (SOL); this is a region of open magnetic field lines enclosing the hot core that guide the plasma to the armoured target plates of the divertor at the top/bottom of the tokamak, where it deposits its energy. The filaments are subsequently observed to separate from the edge of the plasma and travel out radially towards the vacuum vessel wall, carrying with them particles and energy. The filaments exist for the time over which particles are being released into the scrape off layer. In the early stages of their evolution they are observed to rotate toroidally with the edge plasma, before decelerating toroidally as they accelerate radially outwards towards the vacuum vessel wall. As the filaments move out, they twist to remain aligned with the local magnetic field lines.

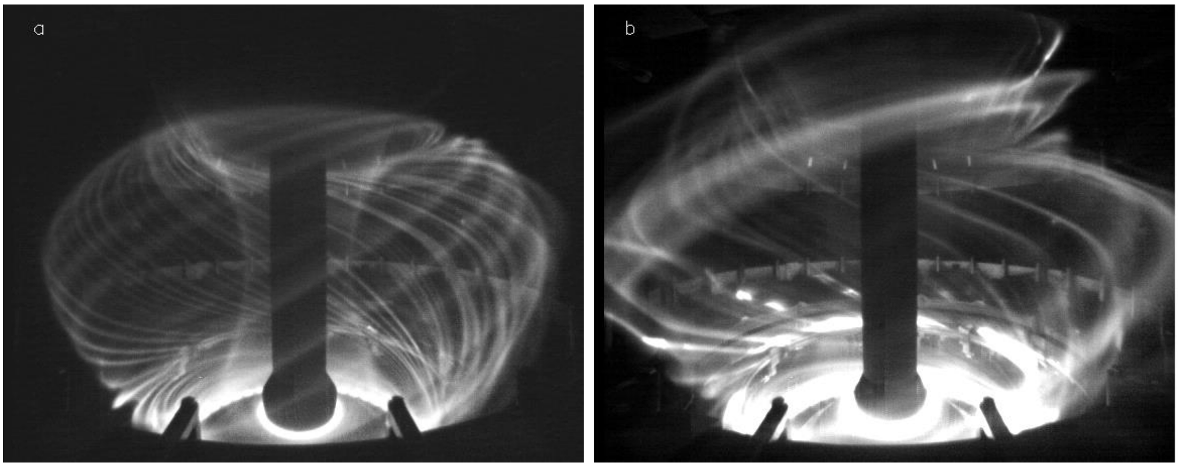


Figure-FIL:
Visible images captured on MAST using a 5μs exposure time a) at the start of an ELM and b) during the eruption of the filamentary structures.

The basic ELM mechanism can be understood from the ideal magnetohydrodynamic (MHD) model, which approximates the plasma as a fluid with high (effectively infinite) electrical conductivity. There are two basic ideal MHD instabilities associated with ELMs: the ballooning mode [Connor-1979] and the kink (or peeling) mode (see [Wilson-2006] and references therein). The ballooning mode is driven by the steep pressure gradient of the edge plasma. The kink/peeling mode results from the strong so-called bootstrap current density generated by the high pressure gradient at the plasma edge [Bickerton-1971]. As a result, both ballooning and peeling modes are destabilised which couple to drive peeling-ballooning modes. Large ELMs are believed to be triggered by these peeling-ballooning modes. [Hegna-1996, Connor-1998bis, Snyder-2002].

MHD, ballooning modes and kink modes.

The plasma can be treated as a single, highly conducting fluid model of the plasma to illustrate the most important physics of ELMs in this review. This model comprises conservation of mass, momentum and energy including terms for the electromagnetic effects and also Maxwell's equations to close the system. This is called magnetohydrodynamics, or MHD. A further approximation, that the fluid is a perfect conductor, can be made and this is called Ideal MHD. Ideal MHD is often a very effective model of the plasma especially on the fast timescales associated with ELMs. Ideal MHD predicts that the plasma is frozen to the magnetic field. If resistive terms are included the magnetic field lines can break and reconnect to form a new magnetic topology. Fluid models for tokamak plasmas are not suitable in all situations, and sometimes particle models are required to describe the physics more fully, for example finite Larmor radius effects, or wave-particle resonances.

Two MHD instabilities that are key to the ELM are the ballooning mode and the kink (or peeling) mode, both of which can be understood from the ideal MHD model. The ballooning mode is driven by the pressure gradient in the plasma, combined with the curved magnetic field in the torus (called curvature). On the inboard (high magnetic field) side of the tokamak the curvature of the magnetic field lines stabilises the pressure driven mode but not on the low field side. If the free energy in the pressure gradient exceeds the energy required to bend magnetic field lines, the mode grows in this unstable region of the tokamak and produces the structure characteristic of the ballooning mode, fig A. The kink mode is a current driven instability, fig B. It causes a straight cylindrical plasma column to become helical or kinked. The perturbation grows because in the concave regions magnetic pressure is increased and in convex regions the magnetic pressure is reduced, and this causes the deformation to grow further.

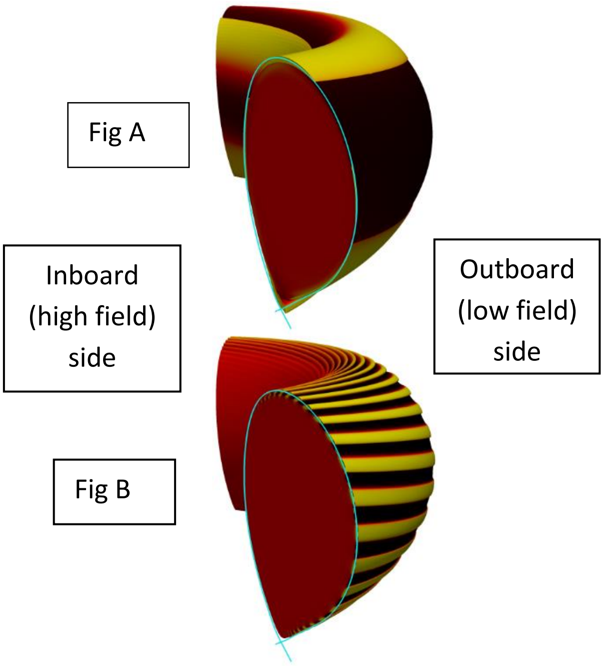


Figure-PB: The top plot shows a characteristic external kink mode; this is not only localised to the low field side, but also perturbs the inner, high field side of the flux surfaces. The bottom plot shows a characteristic ballooning mode displacement of a flux surface. The instability is aligned to the magnetic field and localised to the outboard or low magnetic field side of the tokamak.

The following simple picture presents itself for how an ELM cycle occurs. At the beginning of the ELM cycle (just after the previous ELM) both the pressure gradient and current density are low and the plasma is stable. The plasma is still being heated and so the pressure gradient and edge current amplitudes steadily increase as the edge transport barrier re-establishes itself, typically broadening at the same time. This proceeds until the peeling-ballooning mode stability limit is reached, at which point the ELM is triggered, causing a crash in the edge pressure and current for the cycle to start again.

While this simple "cartoon" picture of the ELM cycle is helpful, the plasma dynamics between ELMs is much more complicated. It is often found experimentally that following an ELM, the edge gradients first recover only in a narrow region in the immediate vicinity of the plasma edge, and this region steadily broadens as the full edge gradient region builds [Burckhart-2010, Dickinson-2012, Hatch-2015]. The pressure gradient is initially held below the peeling-ballooning instability threshold by transport that is driven by residual turbulence in the edge transport barrier region. However, as the transport barrier width broadens, the pressure gradient required for the peeling-ballooning instability reduces until an ELM is triggered [Snyder-2011, Saarelma-2018]. A further issue is the concept of second stability – for sufficient current density, the pressure gradient to drive a ballooning mode is substantially increased, allowing a steeper edge pressure gradient and influencing the evolution of the edge transport barrier width between ELMs (e.g. as observed on JET [Maggi-2015, Bowman-2018]).

The model that we describe here is for the most violent type of ELMs, so-called type-1 ELMs [Zohm-1996], but there exist other types, with smaller eruptions and higher frequencies. Their physics is different to type-1 ELMs, and they are much less well understood, but their smaller size would be desirable for ITER and future devices [Oyama-2005]. Since these smaller ELM-types do not erupt so explosively from the plasma, and there is no universally accepted model, we consider them to be beyond the scope of this review, and only address the most common type-1 ELMs.

Analytic theory of the early nonlinear evolution of the ballooning mode provides an explanation of why the ELM is such an explosive event [Wilson-2004]. For a ballooning mode to grow, it must bend the magnetic field lines that thread through the plasma; this takes a lot of energy. Instability arises when the free energy associated with the pressure gradient exceeds this field line bending energy. The nonlinear theory predicts that as the ballooning mode grows, it modifies the magnetic field structure in such a way that the stabilising effect of field line bending is reduced, thus enhancing the net drive and accelerating the ballooning mode ever harder even at fixed pressure gradient. This positive feedback mechanism drives explosive growth, consistent with the violent eruptions that are observed experimentally. The way that the field line bending is minimised is through the formation of filamentary structures, which are elongated in the direction along magnetic field lines, but increasingly narrow in the perpendicular direction (in the magnetic flux surface) as they erupt. Thus, the theoretical picture is one of narrow filaments of plasma erupting violently from the edge transport barrier on a typical time-scale of order 50-100 microseconds.

This theory for the early nonlinear phase of the ELM has been further developed to a fully nonlinear ideal MHD model. The perfect plasma conductivity of this model means that the magnetic field topology must be conserved – the field lines cannot break and reconnect. The displacement of the resulting filaments is then predicted to saturate on a relatively fast timescale. Non-ideal processes, possibly involving reconnection, will then become important in determining how and where the heat and particles in the filament get to the first wall and divertor of the tokamak vessel. [Ham-2016, Ham-2018].

A wide range of diagnostics are used to understand the state of the plasma [Hutchinson-2002], combining the results from different diagnostic instruments reveals further properties [Kirk-2007]. For example, the filaments are composed of hot dense plasma, with density and temperature comparable to those of the edge transport barrier plasma that the ELM eruption originated from. In addition, they carry a significant amount of current from the edge plasma, which is consistent with the strong magnetic signature of ELMs, measured by magnetic sensors around the device [Vianello-2011].

2.2 The ELM energy loss Mechanism

We have so far in this review provided a theoretical picture of ELMs in terms of an ideal MHD model. A consequence of this model is that there can be no net transport – the plasma and magnetic field remain tied together within the filament as it erupts. Of course, there is transport as a result of the ELM, and to quantify this we need to go beyond the ideal MHD description. Understanding particle and energy losses is important to predict the potentially damaging consequences for future fusion devices (including ITER) and develop control and avoidance strategies. Direct evidence that non-ideal effects become important includes the observation that plasma filaments eventually disconnect from the confined region and travel all the way out to the first wall; this cannot happen if the plasma in the filament remains frozen to the magnetic field. Thus, while it is clear that energy is transferred from the filament to the open field lines in the SOL, the precise physical mechanism remains unclear. Nevertheless, there are various ideas that have been proposed, some of which require magnetic reconnection [Wilson-2006]. One possibility is that the hot filaments could simply break off from the confined plasma (either through reconnection or by drifting across magnetic field lines) and decay in the SOL. Thermal energy stored in the filaments has been measured (e.g. using Thomson scattering on MAST) and this shows that at any one time they collectively only carry approximately one fifth of the total thermal energy lost in an individual ELM event [Kirk-2007, Beurskens-2009]. Recent studies also suggest that most of the energy is lost in the direction parallel to the magnetic field [Eich-2017]. These observations suggest that transport mechanisms are at play in addition to the observed breaking off of filaments. The filaments must either directly act as a conduit for the hot plasma to travel from the confined plasma to the SOL, or there is a degradation of the transport barrier leading to an enhanced flux during the ELM. We therefore require other mechanisms in addition to the direct transport from the filaments, as we now discuss.

In the "leaky hosepipe" model, the filament is assumed to remain connected to the confined plasma on the inboard (high field) side, but because of the ballooning nature of the instability, pushes out into the SOL on the outboard side. It therefore provides a conduit to rapidly transport heat from the confined plasma into the SOL, where it leaks into the exhaust region – note that the pressure difference of the plasma inside and outside the filaments increases as they erupt, enhancing this diffusion [Becoulet-2003, Kirk-2007]. A "squirting hosepipe" model is similar to the leaky hosepipe, but the magnetic field lines within the filament reconnect, to join with those of the SOL to create a continuous path for hot plasma to siphon from the confined plasma directly onto the divertor target plate. In a mechanism we will call the "ergodised edge model", as the current carrying filaments erupt from the edge transport barrier, they perturb the magnetic field structure; this generates chains of magnetic islands by forced magnetic reconnection which then overlap to produce an ergodised magnetic field in the edge region. This ergodised field has reduced confinement and so plasma is lost to the SOL [Alladio-2008, Evans-2009, Rack-2012,]

Amongst the experimental evidence for which mechanisms are dominant, there are indications that magnetic reconnection does occur during ELMs. Measurements of microwave bursts were obtained on MAST [Freethy-2015], suggesting that electrons are accelerated at the beginning of the ELM, presumably by electric fields which could be created by magnetic reconnection of the filaments. On the ASDEX Upgrade (AUG) tokamak, accelerated fast ions were also measured, together with Soft X-Ray and electron cyclotron emission bursts at the beginning of the ELMs [Galdon-2018, Galdon-2018bis], consistent with a reconnection event resulting in particle acceleration.

As the capability of high performance computers advances, high fidelity nonlinear MHD simulations are becoming feasible and have the potential to reveal much more of the physics of ELM filaments. These are extremely challenging, requiring multiple time and length scales to be resolved – for example from the micro-second eruption timescale to the 10s of milli-second or longer edge transport barrier evolution timescale. Even more challenging is the resolution of extremely narrow layers that form in the vicinity of rational surfaces in low resistivity plasmas, which makes MHD simulations at realistic plasma resistivity extremely challenging (and we know that this influences the physics).

In the last decade, much progress has been made, particularly in terms of pushing resistivity closer to the experimental conditions [Pamela-2011, Pamela-2017]. A number of codes have added weight to the international consensus that type-1 ELMs are indeed linked to peeling-ballooning modes, and that the filamentation of the edge plasma plays a major role in the nonlinear dynamics of the instability [Snyder-2009, Becoulet-2017]. Figure-CAM shows nonlinear MHD simulations of an ELM filament using the JOREK MHD code [Huysmans-2007] compared to camera images from an experiment.

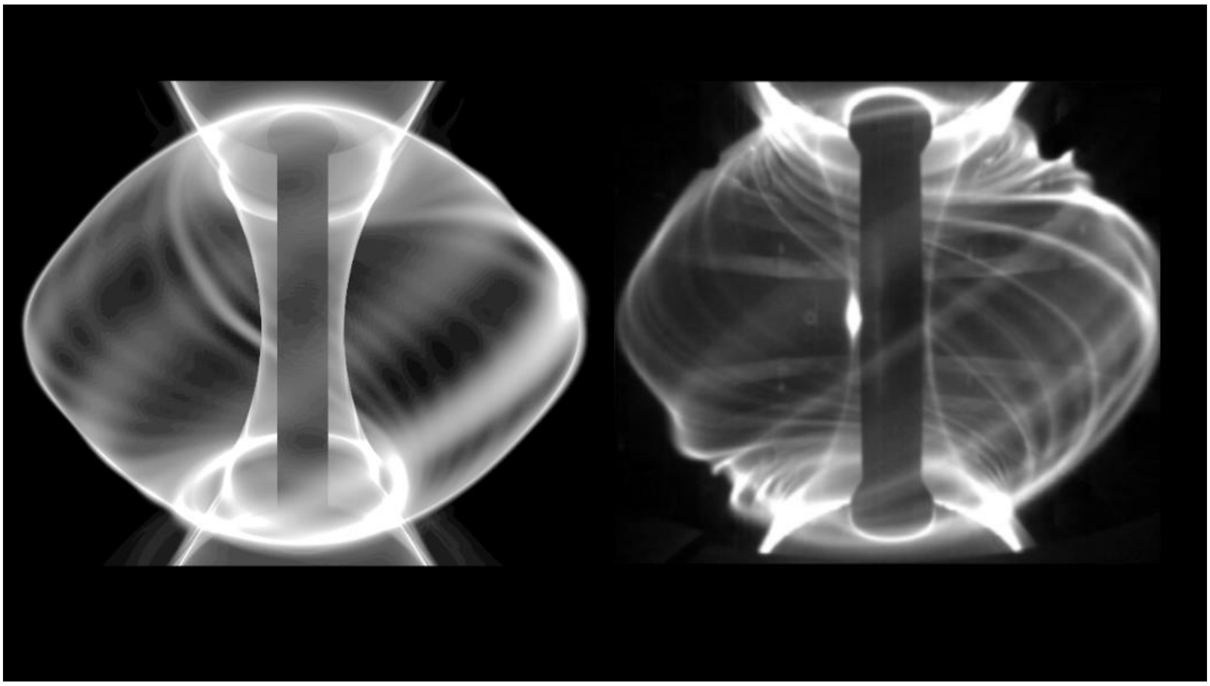


Figure-CAM:
Comparison of an ELM simulation (left) for a MAST experiment with the fast-visible camera image (right)

The wide array of experimental measurements mentioned above has been used to provide a qualitative validation of these nonlinear simulations, which typically push the boundary of what is possible with modern computers and computer science. This includes the poloidal rotation of the filaments during ELM precursors, typically 1-10km/s, which has demonstrated that filaments rotate toroidally due to the momentum injected into the plasma by energetic neutral beam injection (NBI) heating systems, and poloidally due to diamagnetic and neoclassical effects [Becoulet-2017]. The current carried by filaments, which is typically of the level of the bootstrap current at the plasma edge before the ELM onset, is also well reproduced in MHD modelling [Ebrahimi-2017]. The number of filaments that erupt in a given ELM (equivalent to the toroidal mode number, n), has also been shown to be well described by simulations.

There are some key measurements that can also provide more quantitative comparisons between the experiments and simulations and which, most importantly, address the fundamental characteristics of ELMs: their size (how much energy they expel from the plasma), and their impact on wall surfaces; these are both essential to understand for future reactors. On the JET tokamak, simulations could reproduce relatively well a range of experiments with ELM sizes varying between 20 to 250kJ, and peak wall heat-fluxes from 25 to 350 $MW.m^{-2}$ [Pamela-2016,Pamela-2017]. An important aspect of these JOREK simulations is that they add weight to the theoretical interpretation discussed above that most of the energy is lost along ergodic magnetic field lines that connect the plasma with the divertor plates. Figure-ERGO shows the evolution of field lines during an ELM starting from before the ELM, developing through the early phase and finally at the ELM peak.

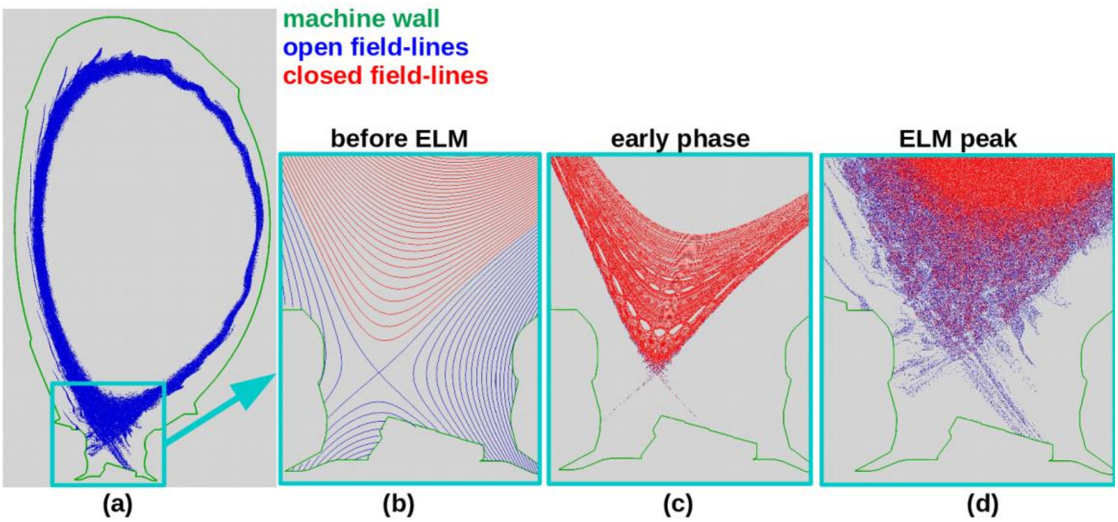


Figure-ERGO: Field lines are traced in a JOREK simulation of a JET-like plasma during an ELM, a) the plasma cross section and region of interest . b), c) and d) show the evolution of the field lines during the ELM. b) before the ELM the confined region has closed (i.e. infinitely long) field lines whereas the field lines in the SOL are open and relatively short; c) in the early phase of the ELM the field lines are perturbed and magnetic islands are produced and; d) at the ELM peak these magnetic islands have become large enough to mix open and closed

The encouraging agreement between theory, simulations and experiments [Kirk-2014] has shed significant light on the transport mechanisms of ELMs, but the picture is not yet complete and there remain significant challenges for simulations. For example, the ergodic magnetic field that is predicted to be formed at the plasma edge to provide enhanced transport during ELMs, can only occur via magnetic reconnection [Huysmans-2009]. In an MHD model, this is a slow process. Thus, even though simulations can reproduce the energy loss mechanism and the filamentation relatively well, they typically exhibit a slightly lower rate of energy loss, which results in a longer duration of the MHD activity [Pamela-2017]. It is not clear which physics effect(s) is (are) missing from current MHD simulation models that could accelerate the predicted ELM timescales, but we highlight two candidates here.

The first is the nonlinear stability of the ELMs. This effect has been predicted theoretically, and reproduced in various simulations [Pamela-2017, Pamela-2016, Henneberg-2014]. It is now clear that, as the plasma pressure progressively approaches the critical stability limit of the MHD peeling-ballooning modes, ELMs seem to emerge out of underlying fluctuations at the edge of the plasma. This coupling between filaments and fluctuations of different wavelengths could be a fundamental effect for the ELM onset and its violent nature.

The second is related to kinetic effects that cannot be captured by MHD models alone, such as a role for electron inertia. The fluid approach of MHD relies on the assumption that the plasma is sufficiently collisional to maintain a Maxwellian velocity distribution to leading order, but this is not true for very hot plasmas at the edge of large tokamaks, and this has several consequences. The transport of energy along magnetic field lines in fluid models is described by a local collisional diffusivity, but kinetic effects, such as non-local transport due to fast electrons at the tail of their distribution, clearly would lead to very different energy transport mechanisms to the divertor [Brodrick-2017]. This in turn has another consequence, namely that if hot electrons escape the plasma much faster than the ions, this will result in significant return currents required to maintain the quasineutrality of the plasma; these additional currents could, perhaps, contribute to the degradation of the edge confinement.

In summary, the progress in computational capabilities is enabling ever higher resolution MHD simulations, that are needed to capture nonlinear effects in highly conducting plasmas; as they advance, the agreement with experimental observations continues to improve. Nevertheless, fluid simulations have their limitations, and hybrid kinetic-MHD models are also emerging. These could finally deliver a truly predictive capability for filamentary eruptions – both for tokamaks and in astrophysics – and provide the basis from which to develop avoidance and control strategies.

3. ELM control strategies

The heat and particles deposited by type-1 ELMs on the divertor and first wall components of future devices, such as ITER, will cause unacceptable damage so strategies to avoid or control ELMs have become important. The most straightforward way to avoid ELMs is, of course, to run in L-mode. However, unless an alternative pathway to improve the confinement time in an L-mode plasma can be found, this would result in much lower core pressure than H-mode operation in a given sized device. How then, can we use our physics understanding of type-1 ELMs to mitigate or control them?

An appropriate place to start when considering answers to this question is the evolution of the operational point (edge current density and pressure gradient), towards the stability boundary for peeling–ballooning modes [Snyder-2004] where we expect an ELM to be triggered. If the boundary is reached sooner, either by increasing the speed at which the edge transport barrier evolves or by lowering the threshold for instability then the ELMs would be more frequent (assuming that the ELM crashes to the same pressure gradient and current density).

There is a robust experimental relationship between the ELM frequency (f_{ELM}) and the type-1 ELM size (ΔW_{ELM}): $f_{ELM}.\Delta W_{ELM}$=0.2-0.4P, where P is the input power to the plasma [Herrmann-2002]. Hence increasing the ELM frequency can lead to less energy being released by each ELM; this is called ELM mitigation. The question then moves to how one can increase the ELM frequency. Several techniques have been successful; for example pellet injection where pellets of deuterium ice are fired into the plasma one after another, in quick succession. Each one causes a rapid rise in the local pressure gradient [Lang-2004, Baylor-2013, Futatani-2014], driving the edge pressure locally across the instability threshold to trigger an ELM; the ELM frequency is then paced at the frequency of pellet injection. Alternatively, fast vertical motions of the plasma (kicks) can be applied using the coils that create the confining magnetic field. These result in an increase of the edge current density, which then triggers ELMs at the frequency of the plasma vertical motions [Degeling-2003, DeLaLuna-2015]. Both techniques have been used to successfully reduce the size of the ELMs as their frequency increases [Garzotti-2010]. It is important to note that while the type-1 ELM size reduces as the ELM frequency increases, the area on the divertor that the ELM interacts with is reduced [Jakubowski-2009, Eich-2017]. This indicates that damage from ELMs is only truly mitigated if we leave the type-1 ELM regime and either suppress ELMs or move to a small ELM regime [Viezzer-2018].

The application of non-axisymmetric edge magnetic field perturbations is a further ELM control technique. This technique can be used to produce smaller, more frequent ELMs or to supress them completely. ELM suppression has been achieved on several tokamaks [Evans-2004, Suttrop-2018, Jeon-2012, Sun-2016]. An example is illustrated in Figure-RMP where two discharges are illustrated, one without and the other with the application of resonant magnetic perturbations (RMPs). Type-1 ELM suppression at ITER-relevant “low collisionality” (which corresponds to a low ratio of density to square of temperature) using RMPs is believed to arise because the pressure gradient in the edge is held below the peeling-ballooning stability limit. Ideally, we would like to eliminate ELMs altogether, while holding the plasma in the highest performance H-mode; however, as can be seen from Figure-RMP the price paid for suppression of the ELMs is a drop in the overall stored energy of the plasma.

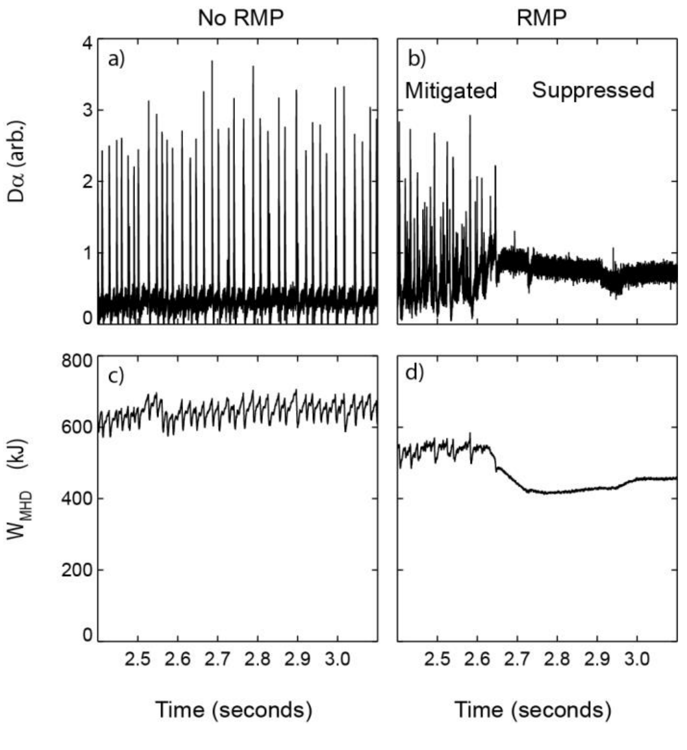


Figure-RMP:
a), b) time traces of D_α light emission from the divertor and c), d) the stored energy in the plasma (W_{MHD}). The left hand panels are for a shot with no magnetic perturbation (RMP) applied and the right hand side for a shot with an RMP applied. AUG data extracted from W. Suttrop et al Nucl. Fusion 58 (2018) 096031

We are still uncertain how this suppressed state is established and, in particular, where the transport comes from to stop the edge transport barrier evolving back to the parameter regime where the peeling-ballooning mode is unstable. Part of the mechanism is a reduction in the edge pressure gradient, which is due mainly to the edge region density drop – the so-called ‘pumpout effect’ – while the edge temperature does not drop and might even increase. Experimentally, the pump-out is observed once the magnetic perturbations are of sufficient magnitude and well enough aligned with the magnetic field line pitch [Liu-2011]. While this enhanced density transport may be due to ergodic fields in the plasma edge, it may also be due to the effect of the lack of axisymmetry induced by the magnetic fields on small scale instabilities that drive turbulence. Another part of the suppression mechanism that has been proposed is that a magnetic island forms close to the top of the edge transport barrier, which then prevents the edge transport barrier width broadening thus keeping the peeling-ballooning instability threshold high [Wade-2015]. However, the production of such a well localised island places stringent constraints on the flow profiles of the plasma that would produce very strict access conditions. Recent work has shown that such flow profiles are not a necessary constraint for ELM suppression [Suttrop-2018, PazSoldan-2019]. These studies suggest that 3D plasma distortions may lead to turbulent transport effects playing a role. For example, recent work has shown experimentally and theoretically that ballooning instabilities can be localised toroidally when magnetic perturbations are applied for ELM control and such localisation may lead to enhanced transport. [Willensdorfer-2017].

Our understanding of what is required for ELM suppression has advanced significantly in recent years, but a challenge is to reliably extrapolate these results to the conditions required for ELM suppression on ITER. Developing such a predictive capability for an RMP ELM control strategy is an active area of research.

4. Conclusions and open questions

The quality of plasma confinement is key on the pathway to fusion power by magnetic confinement fusion. The most robust high confinement regime to date is the H-mode of tokamak plasmas. An undesirable feature of H-mode operation is the repetitive, large filamentary plasma eruptions, called ELMs that, if uncontrolled, will do significant damage in future tokamaks, such as ITER. These eruptions are rather reminiscent of solar eruptions and an intriguing question, not addressed here, is whether there are common elements of physics [Cowley-2003]. Certainly, the question of how these filaments disconnect from the main plasma is of interest to both solar and tokamak physicists.

We have a good understanding of the trigger mechanism for the largest, so-called type-1 ELMs in terms of an ideal MHD instability called the coupled peeling-ballooning mode. Analytic theory provides explanations for why ELMs are such explosive events, and also why the eruptions form into the filamentary structures that are observed. Ideas for the energy and particle loss mechanisms are emerging, and the state of the art in high performance computer simulations is helping to quantify these losses. Nevertheless, a truly predictive capability remains elusive, largely due to the disparate temporal and spatial scales that must be resolved, especially in high temperature, high electrical conductivity plasmas that characterise the tokamaks of today, as well as future reactors. It seems likely that these simulations will need to capture the challenging physics associated with reconnection and a stochastic magnetic field, which probably require physics models that go beyond the relatively simple fluid models of today's simulations to provide quantitative predictions.

The combination of physics understanding and empirical scalings based on experimental evidence suggests that the ELMs on ITER will be large and cause excessive erosion to material surfaces unless they can be controlled or avoided. We have described some of the options available to control ELMs on ITER, either mitigating their impact by increasing their frequency and reducing their losses, or completely suppressing them using resonant magnetic perturbations to influence the edge transport barrier properties. Experiments on today's tokamaks have demonstrated that RMPs have potential to completely suppress ELMs, but the mechanism is complicated by the complex way that the plasma responds to them. Specifically, the plasma creates currents that tend to screen the resonant magnetic perturbations, except in special situations. Explaining how these RMPs increase the transport preventing the plasma from reaching the peeling-ballooning stability limit, and the requirements of the RMP coils remain open challenges that likely requires a kinetic, rather than fluid, plasma model to fully understand the physics.

While it has not been the subject of this review, which focuses primarily on ELM filament physics and control, it is worth pointing out that there are plasma operational regimes that provide the high level of confinement required for ITER to achieve its fusion power objectives, but do not suffer from ELMs. Amongst these are the so-called I-Mode and the QH Mode [Whyte-2010, Burrell-2016]. These are also the subject of much research to assess whether their beneficial properties extrapolate to ITER and demonstration fusion power plants.

To conclude, our understanding of ELMs and their mitigation/suppression in tokamak plasmas has advanced significantly over the past two decades, enabled largely through targeted, collaborative international research programmes. That understanding has revealed a rich and complex variety of plasma physics that challenges theory, experiment and advanced simulation to provide a quantitative predictive capability. This challenge pushes the boundaries of plasma physics, driven both by our inherent scientific curiosity, and a need for a viable solution for future fusion reactors.

Acknowledgements

The authors gratefully acknowledge the comments on this manuscript given by Samuli Saarelma, William Morris and Jack Connor.
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work has been part-funded by the RCUK Energy Programme [grant number EP/P012450/1]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk
Simulations published in this review have benefited from the support of EUROfusion on the MARCONI HPC cluster (CINECA-Italy), as well as the support of PRACE on the MareNostrum HPC cluster (BSC-Spain).

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