Non-linear MHD simulations of pellet triggered “ELMs”

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The injection of pellets into the H-mode edge pedestal is one option to control the frequency and thereby the amplitude of ELMs [1]. It has been observed that pellets can trigger an ELM in (almost) any phase of the natural ELM cycle. However the cause for the trigger is still largely unknown. The non-linear MHD code JOREK [2] is applied to study the possible causes for the pellet trigger of an ELM or ELM-like event. The JOREK code solves the reduced MHD equations in toroidal geometry on a domain including both open and closed field lines. In the present non-linear MHD simulations the pellet is represented by a large source term in the density equation. The source is localized both in the poloidal plane (in the edge pedestal) and in the toroidal direction.

The pellet source leads to a large density perturbation expanding in the parallel direction with approximately the local sound speed. In this simple pellet model the maximum density build up depends on the ratio between the source rate and the local sound velocity. The pressure inside this plasmoid, one of the possible driving mechanism for an MHD instability, depends on the parallel heat conduction relative to the cooling due to the particle source. In a 1-D (parallel) isothermal fluid model (i.e. with infinite parallel heat conductivity) it can easily be shown that the maximum pressure inside at the centre of the density source scales as $p = T\left(\left(S\delta/c_s\right)^2 / \left(\rho_0 + S\delta/c_s\right)^2 + 1\right)\left(\rho_0 + S\delta/c_s\right)$, where S is the particle source rate, δ the length of the source, ρ_0 the background density and $c_s = \sqrt{\gamma T}$ the sound speed. For large source rates, $S\delta/c_s \gg \rho_0$, this simplifies to $p_0 \approx 2T\, S\delta/c_s$, for small source rates to $p_0 \approx T\left(\rho_0 + S\delta/c_s\right)$. With a finite parallel conductivity, even though the density rises to much higher values, the maximum pressure is limited due to the cooling by to the particle source. Figure 1 shows the density and pressure in the pellet plasmoid as a function of the source rate for several values of the heat conduction from a numerical solution of the 1D fluid model including a parallel heat conduction $\kappa = K\left(T/T_\infty\right)^{5/2}$. As the density perturbation spreads in the parallel direction, the front steepens into a shock front moving with the sound speed (or higher, depending on the density source rate).

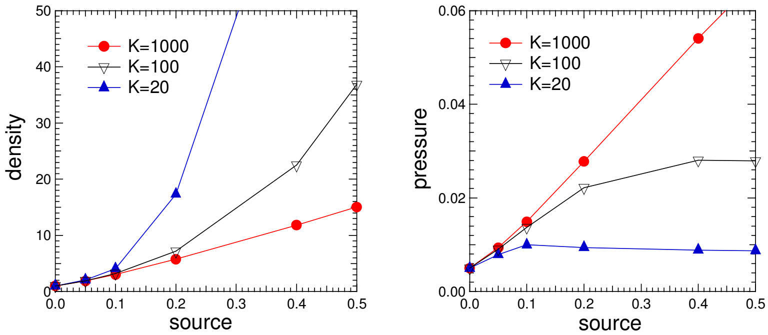

Figure 1 *Maximum density and pressure as a function of the pellet particle source rate from a numerical solution of a 1D Navier-Stokes fluid model.*

Circular plasmas

The influence of the amplitude of the pellet source and its position (low-field or high field side) on the possible trigger of a ballooning-like instability has been studied, first in circular plasmas. The initial equilibria (*a=0.92m, R=3m, B=3T, I=1.6MA,* β_p*=0.6*) are characterized by a large pressure gradient at the edge, representing the H-mode edge pedestal. The equilibrium is marginally stable to ballooning modes with toroidal mode numbers used in the simulation (*n=0-15*). The pellet is represented by a particle source at mid-pedestal (at *q=2.2*) with a horizontal, vertical and toroidal width of 3 cm by 23 cm by 70 degrees resp. The source amplitude has been varied from $S = 2.1\times10^{23} s^{-1}$ to $S = 2.1\times10^{24} s^{-1}$ (assuming a central density of $5\times10^{19} m^{-3}$). The central resistivity used in the simulations is $\eta = 5\times10^{-8}$, the ratio of the parallel to perpendicular heat conduction is $\kappa_{\parallel}/\kappa_{\perp} = 2.5\times10^{7}$. The grid size is defined by 51 radial cubic C^1 finite elements, strongly packed around the pellet position, and 128 poloidal elements.

At $S = 2.1\times10^{24} s^{-1}$ the pressure and density at the source build up in typically 10 τ_N ($\tau_N = \sqrt{\mu_0 m_D n_D}$ at $n_D = 5\times10^{19} m^{-3}$, $\tau_N = 4.6\times10^{-7} s$), after which they remain relatively constant. The maximum density increases locally by a factor ~7 and pressure by a factor ~5. On the same time scale, there is fast increase of the low-n toroidal harmonics.

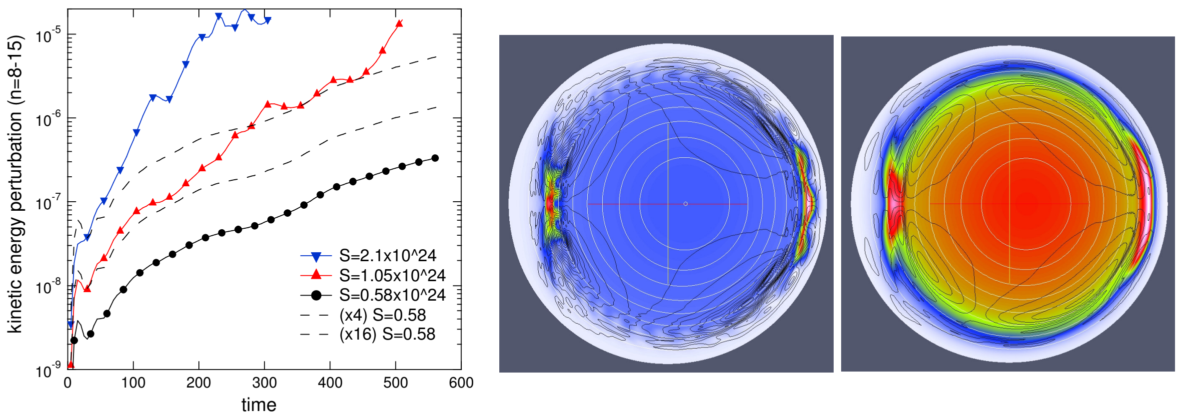

Figure 2 *Kinetic energy for the harmonics* $n = 8-15$ *as a function of time (*τ_N*) for 3 values of the pellet amplitude (*$S = 2.1\times10^{24} s^{-1}, 1.05\times10^{24} s^{-1}$ *and* $0.58\times10^{24} s^{-1}$*). Density (colour scale) and potential contours in the poloidal plane for* $S = 2.1\times10^{24} s^{-1}$ *(middle) and S=*$0.57\times10^{24} s^{-1}$ *(right).*

One can observe two phases in the response to the pellet source. The initial response scales linearly with the pellet amplitude (see Fig. 2). This response is most likely related to the pressure perturbation causing a loss of the axi-symmetric equilibrium. This includes the outward $E\times B$ drift of the density. For a large enough pellet source a ballooning-type instability develops in addition to the linear response. For pellets on the low field side, the ballooning instability leads to a deformation of the pellet cloud into a filamentary structure moving density outwards. The ballooning instability spreads poloidally over the whole flux surface. Also the pellet cloud at the high field side, arriving from the low field side after $2\pi R/c_s \sim 100\tau_N$, can become unstable. Here the instability is localized on the inside where the positive pressure gradient (opposite to the equilibrium pressure gradient) is destabilizing in the 'good' curvature region. This leads to density moving (predominantly) into the plasma (see Fig. 2, middle). There is a critical amplitude for the pellet source above which the ballooning instability develops. In this particular case the critical amplitude for the onset of the ballooning instability is $S < 1\times10^{24}s^{-1}$. A likely cause for destabilization is the high pressure inside the high density plasmoid and the associated local increase of the pressure gradient. The local cooling of the plasma due to the density source leading to an increase in the resistivity will also contribute to the destabilization.

For a pellet source on the high field side at mid-pedestal the behavior is globally very similar to the low field side pellets. Also in this case a ballooning mode can develop for large enough pellets (see Fig. 3). The instability develops first at the high field side plasmoid before the density perturbation has reached the low field side. This leads to density filaments being injected further into the plasma (see close up in Fig. 3, right). Only when the density perturbation reaches the low field are density filaments moving out of the plasma. The critical amplitude for the onset of the ballooning instability is very similar for high field side and low field side pellets.

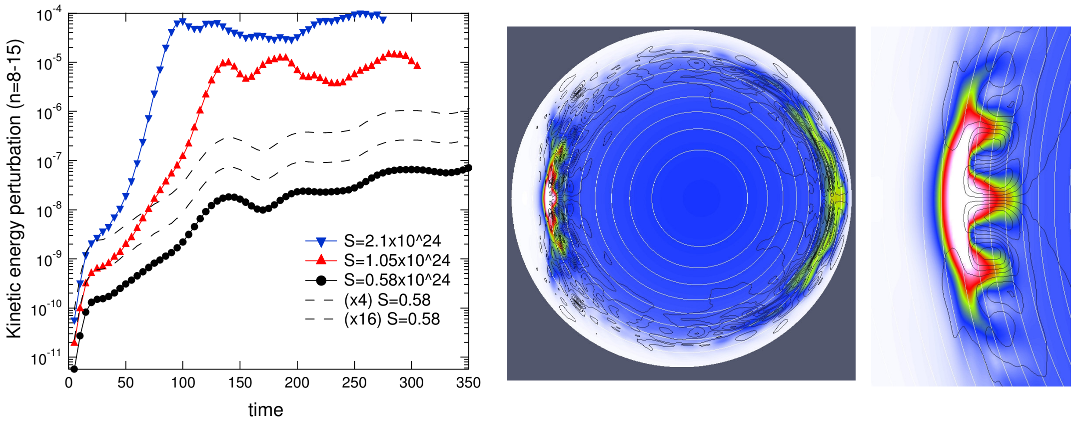

Figure 3 *(left) Kinetic energy of the harmonics $n = 8-15$ for high-field side 'pellets' as a function of the density source rate. (middle) The density and potential contours (black) at t=250 τ_N for the source rate $S = 2.1\times10^{24}s^{-1}$. (right) A close up of the unstable plasmoid on the high field side.*

To investigate the influence of the distance to the MHD stability limits on the critical amplitude, the pellet amplitude scan has been repeated with the total equilibrium pressure reduced from $\beta_p = 0.6$ to $\beta_p = 0.4$. The reduction in the pressure (and the pressure gradient in the pedestal) leads to an increase in the critical amplitude for the onset of a ballooning-type mode by about factor of 2, indicating a strong dependence of the critical amplitude on the distance to the MHD stability limit without the pellet perturbation.

X-point plasmas

The evolution of the plasma response to a 'pellet' (a large localized density source) in a JET-like H-mode plasma at mid-pedestal ($R_0 = 3.1m$, $a = 0.89m$, $B = 2.9T$, $I = 3.2MA$, $\beta_N = 1.0$) is qualitatively the same as in described above for circular plasmas. The pedestal pressure is chosen such that it is stable to ballooning modes (for the mode numbers and the resistivity, $\eta = 5\times10^{-8}$, used in the simulation). Fig. 4 shows the density contour of the pellet cloud at $t = 160\tau_N$ after the start of the pellet source at a source rate of $S = 2.1\times10^{24}s^{-1}$ in the outer mid-plane. At this time the number of ions has increased by 5%. As in previous non-linear

MHD simulations where the pellet was modeled as an initial density perturbation [3], a helical temperature perturbation develops on the (unperturbed) separatrix flux surface, aligned with the pellet cloud.

The heat flux convected to the target during the pellet evolution shows the formation of toroidally localized heat flux (after about $130\tau_N$ after the start of the pellet) at the position where the density (and temperature) perturbation reaches the x-point. At the x-point, the density flows across the separatrix onto the outer target. These 'prompt' density losses lead to a spiral structure in the heat flux with one 'stripe' in addition to the normal strike-point. This structure appears to be very similar to the structures observed during the JET pellet triggered ELMs [4]. In the MHD simulations this additional peak in the heat flux extends in the toroidal direction on a time scale of $100\tau_N$ to cover almost ¾ of the toroidal circumference. At this time most of the additional heat flux occurs at the original strike-point.

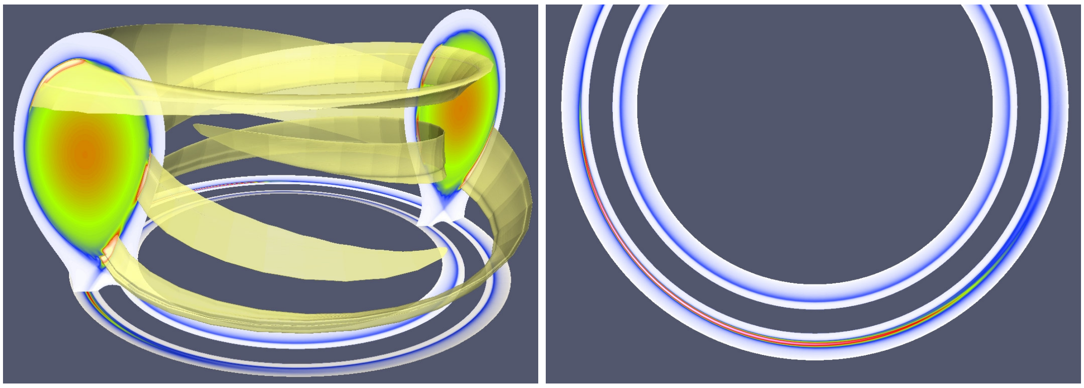

Figure 4 *(left) 'Pellet' evolution in a JET-like H-mode plasma. The density is shown on the slices and as a contour at the value of the central density. The lower rings show the heat flux convected to the target. (right) A close-up of the heat flux convected onto the target.*

Conclusion

3D non-linear MHD simulations of pellets in an H-mode pedestal show a plasma response linear in the pellet amplitude with in addition a destabilization of a ballooning–type mode for large enough pellets. The linear response could be interpreted as the pellet response observed in Ohmic and L-mode plasmas, the destabilisation of an MHD instability as the trigger of an ELM-like event. The pellet size at which the instability is triggered in the non-linear MHD simulations is significantly larger compared to experiment. This may be due to the relatively large size of the simulated pellet. The heat flux at the target due to the prompt pellet density losses at the x-point shows a single additional stripe similar to what is observed in JET [4]. A detailed comparison is needed to confirm a possible agreement.

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