Effect of diamagnetic flow stabilization on pedestal stability in JET and its importance for isotope mass effects

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Experimental results have shown that changing the isotope mass from deuterium to tritium in JET-ILW can lead to an increase in the electron pedestal pressure p_e^{ped} due to an increase in the electron pedestal density n_e^{ped} [1, 2, 3]. This is due to an increase in the pedestal gradients and not in the pedestal width [1]. The increase of the pressure gradient with increasing effective mass A_{eff} has been explained via resistive MHD and by a change in the diamagnetic stabilization [1]. The results discussed in [1] were however obtained with a simple model for the diamagnetic stabilization and were also shown to be sensitive to the exact implementation. The present work aims to more properly model these effects using the visco-resistive code JOREK [4], which self-consistently treats the diamagnetic flows.

The present work is based on the JET deuterium shot 96208 and tritium shot 100247, both at 2MA/2.3T and performed with the same gas rate. The two pulses have also similar β_N. The corresponding profiles of T_e, n_e and p_e are shown in figure 1. The increase of A_{eff} leads to a small decrease in T_e^{ped}, a large increase in n_e^{ped} and a resulting small increase in p_e^{ped}.

The JOREK simulations in this work uses the same experimental equilibrium used in [1] for 96208 but then extends the profiles outside the separatrix. In JOREK the equilibrium profiles are then run for several ms (in simulation time) to allow boundary conditions to propagate and self-consistently set up the equilibrium flows that are not included in the initial equilibrium. After the stationary state is reached, a resistivity scan was performed to determine the most unstable toroidal mode. The results are shown in figure 2(a) for the modes n = 5,10,15,20,25,30. The experimental profiles are stable at $\eta = \eta_{neo}$ but at slightly higher resistivity, pedestal modes start to be destabilized. An increase in the resistivity by 25% to $\eta = 1.25\eta_{neo}$ leads to

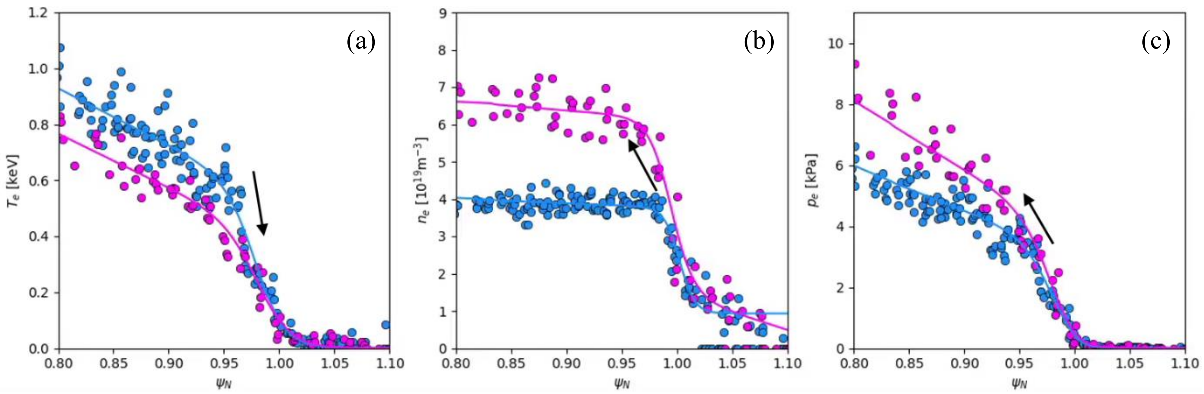

Figure 1. Profiles of electron temperature (a), density (b) and pressure (c) as a function of ψ_N for deuterium shot 96208 (blue) and tritium shot 100247 (magenta)

an unstable $n = 15$ mode. Since $n = 15$ remains the most unstable mode for all the values of resistivity tested, for efficiency hereafter only $n = 15$ has been considered. For key results also the other modes have been considered to confirm that $n = 15$ remains dominant. The temperature perturbation of the $n = 15$ mode can be seen in figure 2(b) where the mode is localized in the span $\psi_N = 0.98 - 1.0$ at the foot of the pedestal with a clear ballooning behavior, being localized mainly at the low field side.

At $\eta = \eta_{neo}$, the experimental pedestal profiles of the D pulse are stable (see figure 2(a)). To ascertain the critical pedestal height, heat and particle sources have been added at the pedestal top to build the pedestal, until an unstable mode starts growing. When T_e^{ped} is increased at fixed n_e^{ped}, no unstable modes are found as shown in figure 3(a) with the red data. However, when n_e^{ped} is increased at fixed T_e^{ped} an n=15 mode is driven unstable by a moderate increase in the density. The critical profiles have been determined by linearly interpolating $\gamma = 0$ from the first two unstable points. The critical p_e^{ped} with increasing n_e^{ped} is higher than the experimental one by 25% as seen in figure 3(b) but lower than the one predicted by linear ideal MHD shown in [1] where the critical p_e^{ped} is 80% higher than the experimental one. The reason for the different behavior with increasing

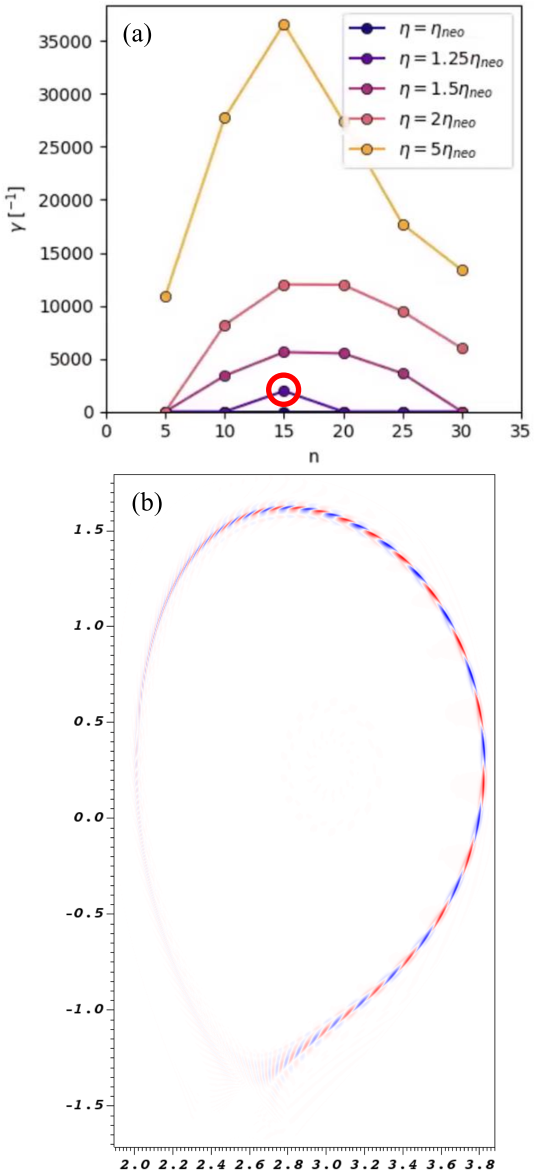

Figure 2. (a) Growth rate as a function of toroidal mode number n for various levels of η for the experimental profiles of shot 96208 and (b) temperature perturbation of the point circled in red in (a).

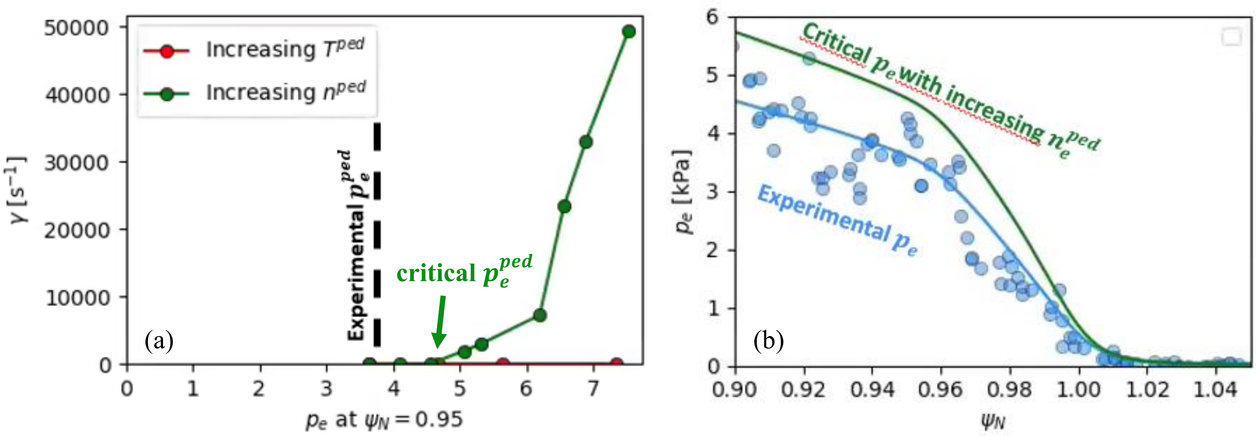

Figure 3. (a) Growth rate of the $n = 15$ mode as a function of electron pressure at $\psi_N = 0.95$ for increasing T_e^{ped} at fixed n_e^{ped} (red) and for increasing n_e^{ped} at fixed T_e^{ped} (green) and (b) the critical p_e profile from increasing n_e^{ped} (green) along with the experimental p_e (blue) for 96208

n_e^{ped} and increasing T_e^{ped} can have two main sources. The first is their different effect on collisionality and, consequently, on the bootstrap current. The second is through the impact on the diamagnetic flow effects as the diamagnetic frequency ω^* scales as $\nabla p/n$. Increasing T_e^{ped} leads to an increase in ω^*. Therefore, the increased ∇p_e due to the increased T_e^{ped}(which can destabilize the modes) is compensated by the increase in the diamagnetic stabilization. Instead, increasing n_e^{ped} does not affect ω^* and the corresponding increased ∇p_e is not compensated by any increased diamagnetic stabilization. Hereafter, we will consider only results obtained using n_e^{ped} scans. Note that in the modeling $T_i = T_e$ has been assumed. This has been verified experimentally with charge exchange measurements till the pedestal top. At the separatrix $T_i > T_e$ is possible. This would have direct impacts on the diamagnetic flows and therefore on the critical n_e^{ped}. This could explain the discrepancy between the critical and experimental n_e^{ped} for the deuterium pulse 96208.

To assess the effect of the isotope mass on the critical n_e^{ped}, the n_e^{ped} scan shown in figure 3(a) has been repeated but changing the isotope mass A_{eff} from 2 (deuterium) to 3 (tritium). The increase in A_{eff} led to a higher critical n_e^{ped} by 20% as seen in figure 4(a). This effect can be ascribed mainly to a change in the diamagnetic stabilization. This is proved in figure 4(a) by rescaling only the diamagnetic flow term τ_{IC} (purple line). Changing only τ_{IC} leads to a result similar to changing the isotope mass in the whole simulation. Quantitatively, the predicted increase in n_e^{ped} is smaller than the experimental one, but qualitatively a good agreement is obtained. The comparison between the predicted n_e profiles using deuterium and tritium for 96208 along with the experimental data of 96208 (deuterium) and 100247 (tritium) can be seen in figure 4(b). The effect when going from deuterium to tritium is also smaller than what was seen in the resistive modeling in [1], where a simplified estimate for the diamagnetic

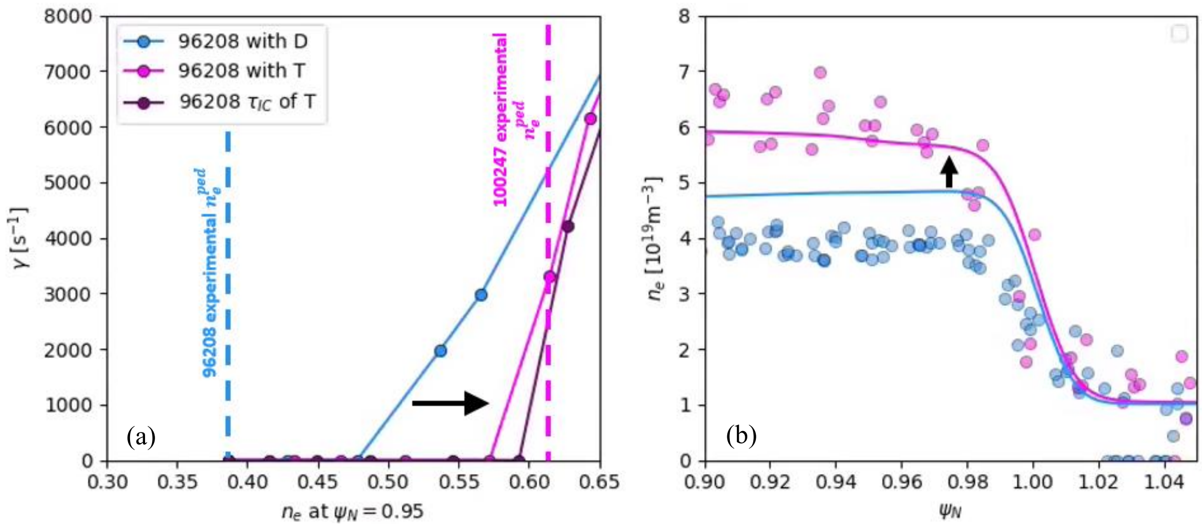

Figure 4. (a) Growth rate of the $n = 15$ mode as a function of electron density at $\psi_N = 0.95$ for 96208 using deuterium (blue), tritium (magenta) and only rescaling the diamagnetic flow term τ_{IC} consistently with a change from D to T (purple) and in (b) the critical n_e profile of 96208 with D (blue) and T (magenta) along with the experimental HRTS data

stabilization was used. It should however be noted that not only the isotope mass is different between the two shots. 100247 also has lower pedestal temperature. A lower temperature in the tritium pulse could allow for a bigger increase in the density when switching from deuterium to tritium.

The critical profiles are highly dependent on the value of the resistivity used in the simulations. The resistivity depends on the value of Z_{eff} which is quite uncertain in this work [1]. Therefore, a sensitivity test on resistivity has been done by increasing η from $\eta = \eta_{neo}$ to $\eta = 1.25\eta_{neo}$. As shown in figure 5, the increase of the resistivity moves the predicted n_e^{ped} to lower values for both deuterium and tritium. The effect of changing the isotope mass remains similar however with a 25% increase in n_e^{ped}.

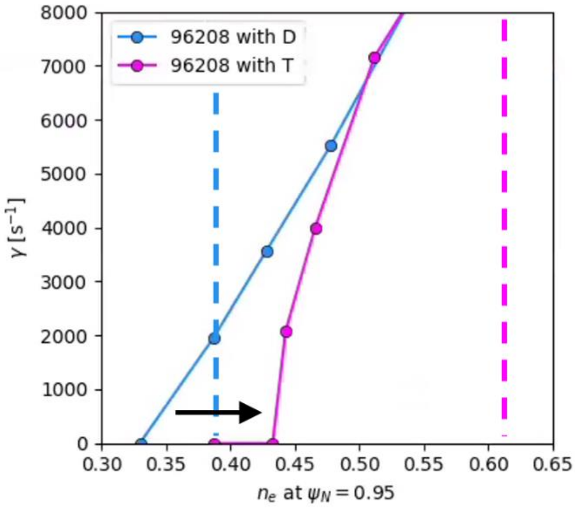

Figure 5. Growth rate of the $n = 15$ mode as a function of electron density at $\psi_N = 0.95$ for 96208 using deuterium (blue) and tritium (magenta) with $\eta = 1.25\eta_{neo}$. The dashed lines mark the experimental values for 96208 (blue) and 100247 (magenta)

In conclusions, using the JOREK code the present work has shown that for these pulses, increasing T_e^{ped} by a factor two is not sufficient to drive the pedestal unstable, instead it is necessary to increase n_e^{ped} to obtain an unstable mode. This is likely an effect of the diamagnetic stabilization. Changing the isotope mass from D to T leads to an increase in the critical n_e^{ped} (and consequently also p_e^{ped}) of approximately 20%. This is qualitatively consistent with experimental results. The effect has been identified to be due to the increased stabilization of the diamagnetic flows which scales with $\sqrt{A_{eff}}$. The results in this work highlights that it is the balance between the instability drive and the stabilizing effects of the diamagnetic flow that is key to understanding the ELM triggering mechanism and not just the instability drive on its own, as also noted in [5].

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