Peeling limited pedestals in JET, MAST-U and TCV: effect of density and isotope mass in deuterium and tritium-rich plasma on pedestal structure and stability and validation of pedestal predictions for ITER.

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ITER needs to operate in mixed deuterium/tritium plasmas with a pedestal temperature $T^{ped} \approx 4-5keV$ to reach Q=10 [1]. At this temperature, despite the strong sensitivity to the separatrix current density [2], the ITER pedestal will be likely be limited by peeling modes [3,4]. Moreover, ITER is supposed to operate at high separatrix density (n_e^{sep}) with a ratio $n_e^{sep}/n_e^{ped} > 0.5$ [5,6]. Most of present day results show a strong degradation of the pedestal performance with increasing n_e^{sep}/n_e^{ped} [7]. However, so far, experimental results in peeling limited pedestal are mainly from DIII-D [8] and only in deuterium low n_e^{sep}/n_e^{ped} plasmas with non-metal walls. All European machines have operated so far in ballooning limited pedestals.

In the past 3 years, the EUROfusion program has invested a significant effort to reach peeling limited pedestals, with the goal of assessing the physics and validate the pedestal predictions in ITER-relevant pedestal scenarios. This work presents the results achieved. The highlights are:

- peeling limited pedestal have been achieved in JET-ILW, MAST-U and TCV, with type I ELMs
- peeling limited pedestal can be achieved also in metal wall machines, with T_i^{ped} up to 2.2keV, $\nu_{ee}^{*ped} \approx 0.1$ and $\rho_i^{*ped} \approx 0.002$ in JET-ILW, approaching ITER values.
- the multi-machine comparison shows consistently that in peeling limited pedestals high n_e^{sep}/n_e^{ped} operation does not degrade the pedestal pressure
- the unique results achieved in the DTE3 campaign in JET-ILW shows that in peeling-limited plasmas the increase of the isotope mass from deuterium to mixed deuterium/tritium plasma leads to a 20% increase in the pedestal pressure.
- the Europed code [9] reasonably predicts the pedestal behavior for ITER-relevant pedestals.

Reaching peeling limited pedestals in the European machines has required reaching previously unexplored operational spaces. In JET-ILW, peeling limited pedestals have been obtained by operating at high q_{95} ($1.4MA/3.8T, 25MW$). In MAST-U, by high power operation and using an optimized plasma shape ($0.75MA/0.5T, 3.2MW$). In TCV by operating at low density and high power combining NBI with ECRH heatings ($0.15MA/1.4T, 2.1MW$). These strategies have turned out to be successful in all the three machines, as proved in figure 1, where the pedestal stability of three experimental plasmas is shown. In all the three machines, the experimental pedestal (the star) is limited by low-*n* peeling modes.

Gas rate scans in the peeling limited scenarios have allowed to investigate the role of the density on pedestal structure and pedestal stability. The experimental results show a very different behavior of the pedestal vs density between peeling limited and ballooning limited pedestals. While all previous results in ballooning limited scenarios show a decrease of the pedestal pressure with increasing n_e^{ped}, in the peeling limited scenarios the pedestal pressure increases with increasing n_e^{ped} (see for example figure 3). This different behavior is due to the stabilizing effect of the density on the peeling modes. Moreover, by varying the gas rate, it has been possible to reach $n_e^{sep}/n_e^{ped} \approx 0.8$ while keeping low pedestal collisionality ($\nu_{ee}^{*ped} < 0.25$). As shown in figure 2, the multi-machine experimental results show consistently that, in peeling limited pedestals, the increase of n_e^{sep}/n_e^{ped} has no major effect on the pedestal performance.

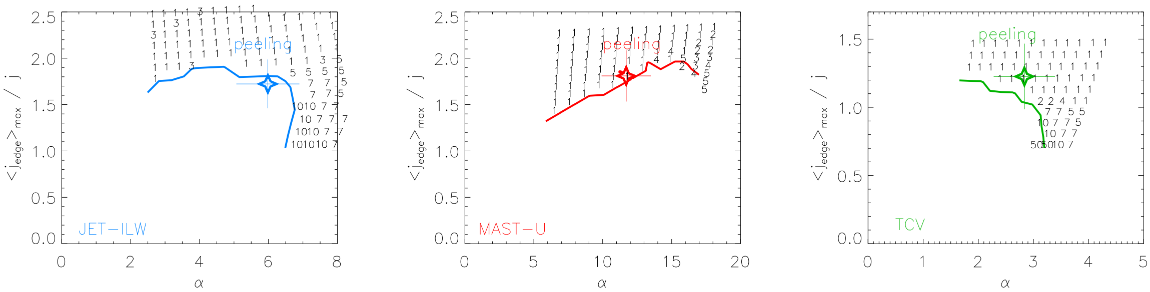

Figure 1. Pedestal stability of experimental profiles in the peeling scenarios of JET-ILW, MAST-U and TCV. In all three machines, the experimental pedestal (the empty star) is limited by low-n peeling modes. The numbers show the toroidal mode number of the most unstable mode and the continuous line shows the stability boundary

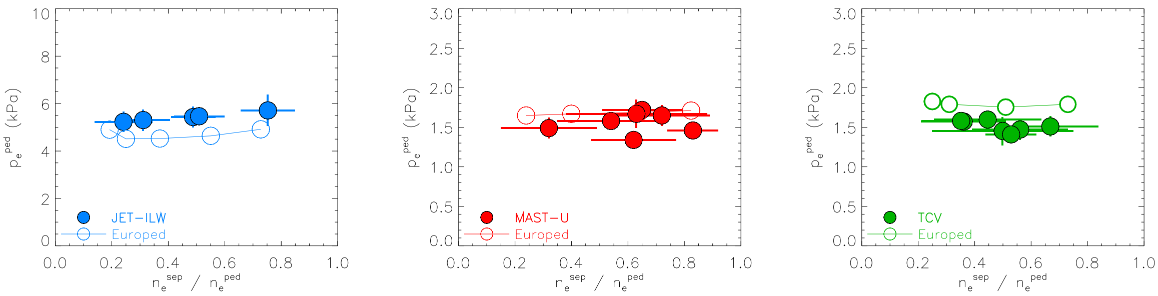

Figure 2. Pedestal pressure versus n_e^{sep}/n_e^{ped} in the peeling limited plasmas of JET-ILW, MAST-U and TCV (full circles) and corresponding Europed pedestal predictions (empty circles)

Then, a unique isotope mass scan, from pure deuterium plasma to tritium-rich plasmas, has been performed in the JET-ILW peeling limited scenario. The increased isotope mass leads to an increase in the pedestal density and in the pedestal pressure by approximately 20%, as shown in figure 3. This increase is ascribed to an improved particle transport with increasing isotope mass combined with the improved pedestal stability driven by the above mentioned n_e^{ped} stabilization on peeling modes.

This new large set of experimental data collected in the peeling limited scenarios has allowed a thorough validation of the pedestal predictive code Europed [9]. The Europed predictions show a reasonable agreement with the experimental results in all the three machines (see for example figure 2), proving the validity of pedestal predictions in peeling limited scenarios. Therefore, Europed has been applied to ITER to test some of the key expectations for type I ELMy H-modes. Preliminary results are very promising, suggesting, for example, no degradation of ITER pedestal at high n_e^{sep}/n_e^{ped}.

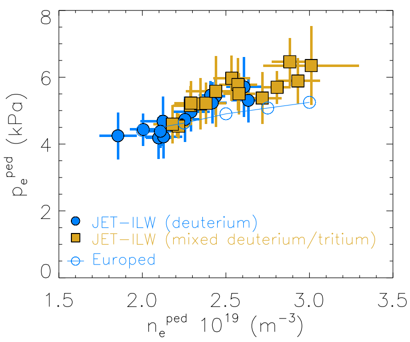

Figure 3. Pedestal pressure vs n_e^{ped} in JET-ILW peeling limited plasmas for pure deuterium and for mixed deuterium/tritium plasmas. Europed pedestal predictions are shown with empty circles.

In conclusion, by reaching the new peeling scenario in JET-ILW, MAST-U and TCV, the work has led to three positive results for ITER. (1) The pedestal pressure increases with increasing n_e^{ped}, showing that the ITER performance might be improved with pellet fueling. (2) The high n_e^{sep}/n_e^{ped} operation expected in ITER will not have a negative impact on ITER performance. (3) Operating in mixed deuterium/tritium plasmas will improve the ITER performance.

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