Density Limit in Peeling-Limited Pedestals At and Above the Greenwald Value in DIII-D High Poloidal Beta Plasmas EX

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Recent analysis on DIII-D has found that in high poloidal beta plasmas, high pressure, peeling limited pedestals with pedestal normalized beta $\beta_{N,ped}$>1.5 and pedestal top density n_{ped} at or above the Greenwald density n_G ($n_G=I_P/\pi a^2$) have been achieved with high global parameters of normalized beta β_N>3 and energy confinement H_{98}~1.2-1.7. Higher heating power allows higher pedestal density above the Greenwald value and higher pedestal pressure, with an instability ultimately limiting the pedestal density and pressure. MHD modeling indicates that the experimental profiles with high normalized pedestal pressure gradient and high edge current density lie near the peeling-mode unstable boundary and a peeling-mode is likely destabilized. The high poloidal beta with strong Shafranov shift opens Super-H-like channels that allows the pedestal density to go beyond the Greenwald limit: the pedestal pressure and pedestal beta increase with pedestal density even when the pedestal density is above the Greenwald value, until the pedestal reaches the instability boundary, where giant ELMs occur.

To maximize fusion gain, most tokamak reactor designs require simultaneously peeling-limited pedestal and high-density operation with density close to or above the Greenwald limit [1]. Recently, several physics models and theories are proposed to explain the Greenwald density limit, but so far most of these studies focus on a high collisionality edge. However, the density limit in a peeling-type pedestal could be very different from the ballooning type pedestal. It is unknown whether a density limit exists for a peeling-type pedestal and what governs the underlying the physics. As illustrated in Fig. 1, DIII-D experiments show that operation at high poloidal beta is a path to achieving pedestals that are simultaneously high density and peeling limited, which could provide a good test platform to study the density limit physics of peeling limited pedestals. This scenario could provide references for reactor designs, and for reactor-relevant pedestal studies

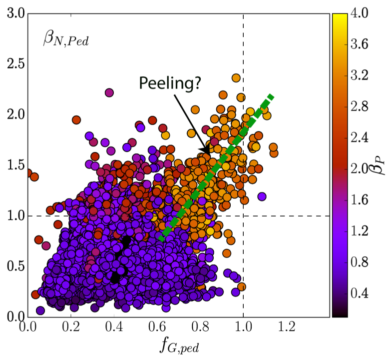

Figure 1. $\beta_{N,ped}$ vs n_{ped}/n_G and colorbar represents the beta_P

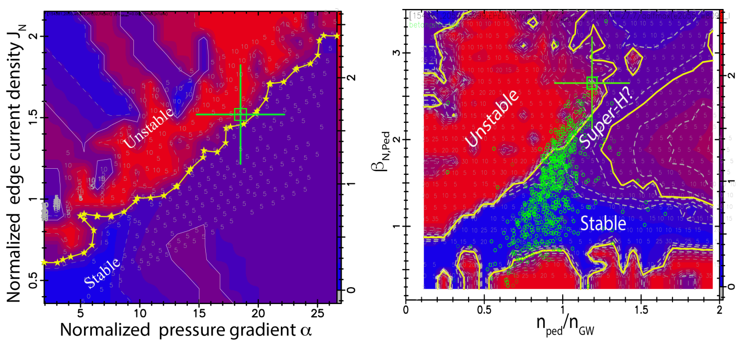

Figure 2. Left: ELITE calculations show the experimental profiles lie at the peeling boundary with high normalized pressure gradient and high edge current density, Right: ELITE calculations for $\beta_{N,ped}$ vs n_{ped}/n_G, showing the super H channel opens in the high beta poloidal plasma. The yellow lines indicate the Peeling-ballooning boundary. Raw experimental data are overlaid as the green circle, and kinetic equilibrium used for this calculation are marked as the green square with 20% errorbar.

In DIII-D high poloidal beta plasmas, as shown in Fig. 1, high normalized pressure with pedestal normalized beta $\beta_{N,ped}$>1.5 and high pedestal top density n_{ped} around or above the Greenwald density n_G have been achieved, while maintaining high energy confinement H_{98}~1.2-1.7. Higher heating power and higher beta allow higher pedestal density above the Greenwald value and higher pedestal pressure, with an instability ultimately limiting the pedestal density and pressure. In contrast, in DIII-D low poloidal beta plasmas, the normalized pedestal pressure is much lower, e.g. $\beta_{N,ped}$ <0.9 at n_{ped}>0.8n_G, and the energy confinement factor H_{98} is lower than unity.

As can be seen in Figure 2, ELITE modeling with kinetic equilibrium reconstructions confirms that the experimental profiles with high normalized pedestal pressure gradient and high edge current density lie near the peeling-mode unstable boundary. It is noted that the ballooning boundary is strongly suppressed due to the high pedestal α_{MHD} due to high poloidal beta and strong Shafranov shift. Further edge MHD modeling using MARS and GATO finds the low-n (toroidal mode number) mode unstable in the pedestal region and the mode could be destabilized by rotation suggesting the nature of peeling mode.

The pressure at the top of the peeling type pedestal is about twice higher than that in the ballooning type pedestal. As can be seen in Fig.1, in the high poloidal beta plasmas, the pedestal pressure increases with the pedestal density, suggesting the nature of peeling-mode limited pedestal. As shown in Fig. 2, the high poloidal beta with strong Shafranov shift opens Super-H-like channels that allow the pedestal density to go beyond the Greenwald limit, consistent with results in Fig.1. In contrast to the ballooning pedestal, the high pedestal density increases the pedestal pressure and pedestal beta to $\beta_{N,ped}$>2.0, until the pedestal reaches the instability boundary predicted by ELITE scans, where giant ELMs occur. Profile measurements show that the giant ELMs cause a large reduction of the edge pressure and a much smaller reduction of the core pressure. Magnetic measurements indicate the giant ELMs are dominated by strong n=1 component, consistent with peeling-mode induced instability and GATO calculations. Nonlinear BOUT++ simulations reproduce the strong pedestal pressure reduction by the giant ELMs which is driven by the low n instabilities.

In addition, the experiments also found that ITB (internal transport barrier), n_{ped}~0.9 n_G, peeling limited pedestal could be simultaneously achieved with high heating power in high β_N plasmas, see Fig. 3. The plasma self-consistently transitions from the strong pedestal state + weak ITB with n_{ped}~n_G to a strong ITB +slightly lower pedestal pressure with n_{ped}~0.9n_G. In both states the pedestals lie near the peeling-limited boundary, as indicated by the ELITE calculations. This relationship between the ITB and the pedestal confirms previous studies of the interactions between core and pedestal transport [2], but requires further investigations. This is an ideal reference for many reactor designs that utilize both peeling-limited pedestal and ITB to maximize the fusion gain.

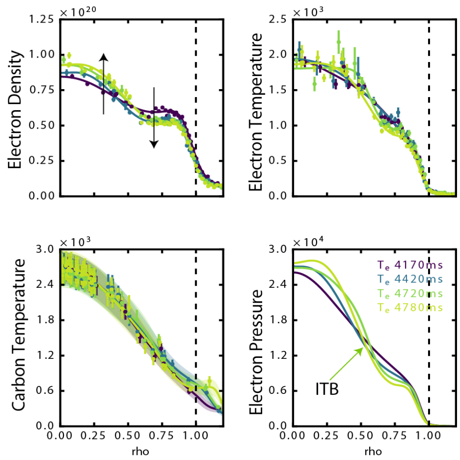

Figure 3. ITB + n_{ped}~0.9 nG+ peeling limited pedestal vs weak ITB + n_{ped}~1.0 nG pedestal

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[1] S. Ding *et al*, *Nature* **629** (2024) 555
[2] L. Wang *et al, Nature Commun.* **12** (2021) 1365