INVESTIGATION OF DENSITY LIMIT PROCESSES IN DIII-D*

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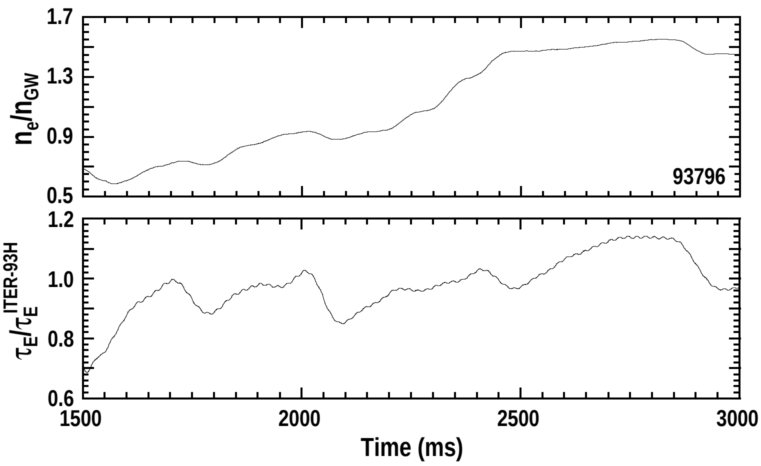
We have succeeded in significantly exceeding the Greenwald density limit [1] $\left(\bar{n}_e \geq 1.5 \times n_{GW},\, n_{GW} = I_p / \pi a^2\right)$ with good energy confinement $\left(\tau_E \geq 1.1 \times \tau_E^{ITER-93H}\right)$ using pellet injection and divertor pumping. One of these discharges is shown below.



Greenwald scaling has presented a challenge to the plasma physics community because theories predict additional dependencies, e.g. heating power (P_{heat}) and impurity concentration (n_Z/n_e). The scaling has consequences for fusion reactors: many D-T reactor designs must operate above this limit to be economically competitive with other energy production technologies. Theories indicate that several distinct processes exist which can limit density in either the core, edge, or divertor plasma. Motivated by ITER's need to operate at $n_e > n_{GW}$ with H–mode energy confinement, a multi-year experimental campaign has been carried out in DIII–D to investigate these density-limiting processes. These processes include divertor detachment (which can lead to

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divertor collapse), particle confinement and fueling limits, MARFE formation, and MHD activity and are discussed in this paper.

When the divertor temperature reaches a few eV, partial divertor detachment is observed and the plasma pressure and ion current near the divertor strike point drop. If the density is increased further, the divertor temperature drops and the divertor radiation increases resulting in thermal collapse. This is followed by effective impurity penetration into the core plasma, a sudden reduction of edge temperature, and shrinkage of the current channel and/ or the formation of an X–point MARFE. Experimentally, H–mode confinement is lost if the density is increased after the onset of partial detachment. We have studied the scrape-off layer (SOL) and divertor conditions at detachment; we find semi-quantitative agreement of the critical upstream n_e with models, but the observed heating power dependence of the critical n_e is weaker than predicted. We bypassed divertor collapse as a density limiting process by particle source profile control. The SOL n_e was maintained below the divertor collapse limit with divertor pumping, and the ratio of $\bar{n}_e$ to SOL n_e was increased with pellet fueling.

A reduction in particle confinement time as $\bar{n}_e$ approaches n_{GW} was proposed [1] as the mechanism behind the Greenwald limit. However, we observed [2] no correlation between the particle confinement time and n_e/n_{GW} for pellet-fueled discharges. We observed a stronger than linear plasma current dependence of the density decay time following pellet injection. In addition, pellet fueling efficiency was found to decrease with heating power. At high B_t with heating power near the L-H confinement transition limit, pellets produced H-L transitions which rapidly ejected the pellet density in <10 ms. Access to high density was achieved by operating at low B_t, giving more margin over the L-H threshold.

We compared edge plasma parameters at MARFE formation to those predicted by models and found semi-quantitative agreement. We have also derived [3] an edge density limit which scales as $\left(I_p^{0.96} / a^{1.9}\right) * \left(P_{heat} R\right)^{0.17} \left(n_Z / n_e\right)^{-0.1}$, i.e. comparable to Greenwald scaling. This limit was obtained by examining MARFE onset requirements in the presence of the ITER-89P energy confinement scaling. In practice, MARFEs were avoided by low edge safety factor operation and divertor pumping.

We find that MHD modes can be de-stabilized at densities as low as $\bar{n}_e/n_{GW} \sim 0.8$ during pellet fueling; the cause is unclear. MHD activity was observed over a wide heating power range but was avoidable at $P_{heat} < 3$ MW. By operating at reduced heating power ($\beta_N < 1.7$), we have suppressed these modes.

By studying each process and selecting conditions to avoid it, we have achieved H–mode discharges at $\bar{n}_e/n_{GW} \sim 1.5$ for up to 600 ms. These discharges were ELM-free, and owing to core impurity accumulation, ended in a central radiative collapse. Our effectiveness in heating the center was limited by the neutral beam technique; the heating deposition became hollow during the high density phase. This will not be a problem in burning plasmas in which the alpha heating profile will always be centrally peaked.

[1] GREENWALD, M., TERRY, J.L., WOLFE, S.M., EJIMA, S., BELL, M.G., KAYE, S.M., NEILSON, G.H., Nucl. Fusion **28**, 2199 (1988).

[2] MAINGI, R., MAHDAVI, M.A., JERNIGAN, T.C., LA HAYE, R.J., BAYLOR, L.R., et al., "Investigation of Physical Processes Limiting Plasma Density in DIII–D," Phys. Plasmas **4**, 1752 (1997).

[3] MAHDAVI, M.A., MAINGI, R., LA HAYE, R.J., JERNIGAN, T.C., PETRIE, T.C., et al., "Recent H–Mode Density Limit Experiments on DIII–D," to be submitted to Phys. Rev. Lett.