Second Technical Meeting on Long-Pulse Operation of Fusion Devices

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High density as an avenue towards high confinement quality and core-edge integration in advanced tokamaks

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Recent high poloidal beta (β_P) scenario experiments on EAST and DIII-D have made coordinated breakthroughs for high confinement quality at high density near the Greenwald limit. Experiments on DIII-D have achieved f_{Gr} (=line-averaged density/Greenwald density) above 1 simultaneously with H_{98y2} around 1.5, as required in compact steady-state fusion pilot plant designs but never before verified in experiments. Compatibilities of high confinement core with small ELMs and fully detached divertor have been demonstrated separately in DIII-D high β_P experiments with $f_{Gr} \sim 1.0$. Experiments on EAST have nearly doubled the ion temperature at $f_{Gr} \sim 0.9$, confirming the predict-first results of simulations. Density gradient amplification of turbulence suppression at high β_P is the underlying physics that can explain, in both devices, the achievements of improved confinement at high density.

EAST long pulse H-mode experiments have reached a world record duration of 400 seconds, but with $T_i \ll T_e$. Transport modeling indicated that the ions are limited by ITG modes. Modeling also suggested potential solutions, including reduced magnetic shear, and enhanced density gradients. Following this guidance, various approaches were pursued on EAST. The experiments directly show that a strong enhancement of Ti happens with a single short pulse (100 ms) of impurity injection at $f_{Gr} \sim 0.9$. But it can only happen in the appropriate conditions, i.e. a combination of low magnetic shear and high density gradient, as predicted by the earlier modeling.

On DIII-D, a synergy between increased H_{98y2} and increased f_{Gr} is observed in low-l_i plasmas with strong gas puffing, due to the build-up of an internal transport barrier (ITB) at large radius in the temperature and density channels. Sustained $1.0 < f_{Gr} \leq 1.25$ and $H_{98y2} \sim 1.5$, as required in many fusion pilot plant (FPP) designs, are achieved for the first time [Ding, *Nature* (2024), https://doi.org/10.1038/s41586-024-07313-3]. The experimental approach for high f_{Gr} is to elevate the core density by developing a strong ITB, while keeping the pedestal density below the Greenwald limit. Transport simulations show lower turbulent energy transport at higher density gradient due to stronger α-stabilization effect. Simulations also reveal that the favorable trend of low transport at high density is only expected when increasing the density gradient at high local safety factor (q) and high β, thus at high β_P to ensure strong turbulence stabilization. Sustained small ELMs and reduced divertor heat load are observed simultaneously in the $f_{Gr} > 1.0$ and $H_{98y2} \sim 1.5$ phase. Increased separatrix density is believed to be a part of the physics that leads to realization of the small-ELM regime. Excellent compatibility of actively controlled full divertor detachment with high density and confinement ($f_{Gr} \sim 0.9$, $H_{98y2} \sim 1.5$) has been demonstrated in separate DIII-D high ⊠P experiments [L. Wang, *Nat. Commun.* **12** (2021) 1365]. Despite decreased pedestal pressure when entering detachment, a stronger ITB, facilitated through self-organization, leads to improved confinement, in contrast to the confinement degradation with divertor detachment commonly observed in standard H-modes. These results demonstrate the possibility of integrating excellent plasma confinement at high density with an efficient divertor solution, an essential step towards steady-state FPPs. Supported by the US DOE under DE-FC02-04ER54698 and DE-SC0010685.

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