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Midplane Separatrix Requirements for Achieving Divertor Detachment in DIII-D

EX-D

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Simultaneous 2D measurements of the divertor density and temperature in DIII-D show the transition from fully attached to completely detached sub-eV recombining conditions as a function of both core plasma density and power; the data show the midplane separatrix density threshold for divertor detachment is proportional to the square root of the input power. Simultaneous scrape-off-layer (SOL) measurements at the plasma midplane show little change in the heat flux width with density (inferred from λ_{Te}) up through the detachment onset, extending previous multi-machine SOL heat flux scaling results obtained at much lower Greenwald fractions [1]. The measured midplane separatrix pressure gradient, $\nabla p_{e,sep}$, increases with density as expected from the ideal ballooning mode stability limit.

Reliable sub-eV 2D electron temperatures were measured by Thomson scattering for the first time in a detached divertor (Fig. 1), and complemented with high-n D_{Balmer} and $D_{Paschen}$ spectral monitoring as indicators of the volume recombination rate. Divertor T_e measurements extending well below 1 eV are essential for comparing simulation codes to experiment because radiative recombination rates increase by nearly an order of magnitude as $T_{e,div}$ falls from 1 to 0.5 eV. At the highest densities, the decrease in electron pressure at the target is apparent even as the midplane $p_{e,sep}$ continues to increase. Mapping the data onto the divertor flux surfaces reveals the complete collapse of $T_{e,div}$, and formation of a MARFE which remains stable be-low the X-point. Matching the detachment density threshold and radiation loss are key challenges for simulating reliable divert-or operation in future burning plasma experiments.

The measured SOL pressure gradient is found to scale with the ideal ballooning mode pressure limit as calculated by BALOO (Fig. 2); how-ever, the gradient is below the critical value possibly due to non-ideal effects such as plasma resistivity. At the midplane separa-trix, the total pressure gradient, $\nabla p_{tot,sep}$, increase modestly and peaks at detachment onset then

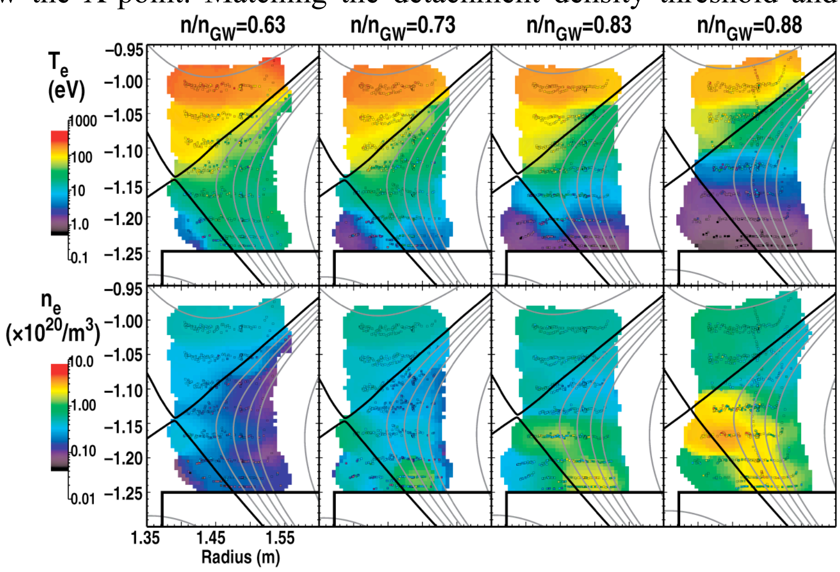

Fig. 1. Reconstructed 2D T_e and n_e in (left to right) attached, high recycling, partially detached, and fully detached conditions.

begins to decrease, suggestive of a role in setting the heat flux width. The radial T_e gradient, $\nabla T_{e,sep}$, is found to decrease ~ linearly from the attached to detached divertor. With increasing n/n_{GW} fraction, n_e and $\nabla n_{e,sep}$ increase while T_e, T_i, ∇T_e and ∇T_i all decrease, indicating the rise in ∇p is due to an increase of the density and its gradient.

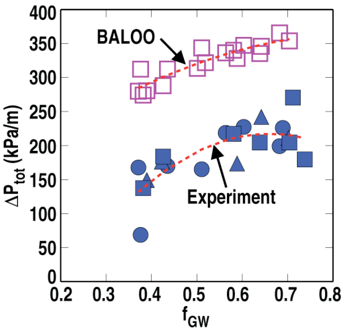

Fig. 2. ∇p_{tot} vs n/n_{GW} through the detachment transition with P_{inj}= 4.1 MW. Closed symbols are from experiment. Open boxes are from BALOO modeling.

Upgrades to the high-resolution core [2] and divertor Thomson scattering (DT) [3] diagnostics on DIII-D have allowed the most accurate characterization of detachment onset at any fusion device to date. Data quality near 5 eV where charge exchange between plasma ions and recycling neutrals reduces the peak ion flux to the target is improved, and measurements of T_e is extended to ~0.5 eV where volume recombination processes become dominant, reducing the ion flux and plasma pressure, and increasing line radiation which cools the divertor. Strike point sweeping was employed to allow 2D characterization of inter-ELM T_e and n_e using the DT system. Multistep sequences of discharges with increasing line-averaged density were run through the transition from attached, high recycling, partially detached, and finally, a fully detached divertor. The result shown here expands on a previous experiment [4] in which P_{inj} was scanned in a similar manner, but $n_{e,bar}$ was not scanned over a wide n/n_{GW} space.

The parallel electron pressure gradient in the divertor is found to increase through the high recycling stage and detachment onset, and then relaxes through to the fully detached state, consistent with the influence of momentum loss and recombination near the OSP. Correlations between plasma parameters at the midplane separatrix and conditions measured in the divertor are shown for H-mode discharges at each of three levels of heating power (2.7 MW, 4.1 MW, and 9.7 MW) (Fig. 3). $n_{e,sep}$ at the onset of detachment is found to be proportional to P_{inj} [Fig. 3(a)] while $P_{e,sep}$ is proportional to P_{inj} [Fig. 3(b)]. The radial gradient scale length $Ln_{e,sep}$ is found to grow as detachment is approached, and more quickly for higher P_{inj}. The temperature gradient scale length, related to λ_q, stays relatively constant during the density scan [Fig. 3(c)]. At low n/n_{GW}, $P_{e,OSP}$ scales well with $P_{e,sep}$ but as detachment is reached, the rollover in $P_{e,OSP}$ at lower P_{inj} is apparent even as $P_{e,sep}$ continues to increase [Fig. 3(d)].

These 2D measurements with divertor sweeps provide an invaluable constraint on boundary plasma modeling in progress for these discharges, including cross-code comparisons of results from OEDGE, UEDGE and SOLPS in order to test transport physics for matching key detachment parameters (target conditions, location of the ionization front) and comparisons of rates for atomic and molecular process-ses. Future experiments are planned at DIII-D to expand detachment operational space in B_T and I_p, revealing more about the roles of parallel transport and drifts in the divertor in the transition to detachment.

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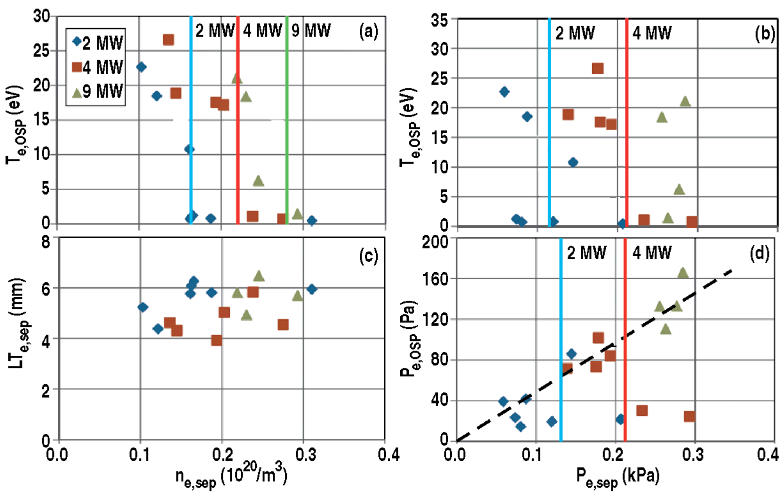

Fig. 3. Divertor plasma parameters vs various parameters for H-mode discharges in the transition from attached to detached operation.