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Understanding and Control of Transport in Advanced Tokamak Regimes in DIII–D[1]

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The DIII–D program focuses on development of Advanced Tokamak regimes with sustained high fusion performance accomplished via pressure and current profile control. Ion thermal transport in these regimes can locally approach neoclassical values. Momentum, particle and, less often, electron thermal transport are also reduced. Optimization is approached through study of the transport processes governing formation, expansion, and sustainment of the low transport region. Internal transport barriers (ITB) often form in neutral beam (NBI) heated discharges with flat or hollow current profiles when the $\mathbf{E}\times\mathbf{B}$ shearing rate $\omega_{E\times B}$ becomes large enough to suppress turbulence and its associated transport. With co-NBI (rotation $\|$ plasma current), the pressure gradient and toroidal rotation terms in the radial force balance $E_\mathrm{r} = (Z_\mathrm{i} e n_\mathrm{i})^{-1}\nabla p_\mathrm{i} - v_{\theta \mathrm{i}} B_\phi + v_{\phi \mathrm{i}} B_\theta$ oppose, requiring one to dominate for large E_r. The central $\omega_{E\times B}$, dependent on the *gradient* of E_r, is calculated largest with co-NBI. This may explain the absence of a distinct power threshold in DIII–D co-NBI discharges, while those with counter-NBI exhibit unambiguous ITB formation only with $P_\mathrm{NBI} \geq 10$ MW (weak, transient barriers occur at lower power levels). Pellet injection can reduce or eliminate this threshold. ITB expansion can broaden the pressure profile, increase stability limits and improve bootstrap alignment. Results from other devices indicate the ITB radius, ρ_ITB, often follows the radius of the minimum safety factor, $\rho_{q\,\mathrm{min}}$, implying that control of $\rho_{q\,\mathrm{min}}$ might be a technique to expand the ITB. A rapid initial current ramp and early, high power co-NBI was used to obtain $\rho_{q\,\mathrm{min}} \approx 0.9$ in DIII–D. ITBs occurred at $\rho_\mathrm{ITB} \approx 0.4$–$0.5$, indicating little connection to $\rho_{q\,\mathrm{min}}$. ρ_ITB often coincides with cancellation of opposing terms in the force balance, so that both E_r and $\omega_{E\times B}$ are small. With counter-NBI, there is no such cancellation, and larger ITB radii have been observed. If an L–H transition is triggered during ITB formation, a reduced transport region can be formed encompassing the entire plasma, with no distinct barrier. Neoclassical ion transport throughout the plasma was previously obtained in such discharges with an ELM-free edge, terminated by edge MHD instabilities. A similar regime with an ELMing edge and ion diffusivities a few times neoclassical has been produced and sustained with $\beta_\mathrm{N} H_{89} \approx 9$ for up to 2 s. A key feature of these discharges is a significant bootstrap current ($f_\mathrm{BS} \geq 50\%$), with a flat bootstrap profile across most of the plasma. Additional current drive is required only near the half-radius for sustainment. Future plans include providing this current via ECCD.

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