PHYSICS OF ADVANCED TOKAMAKS*

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Significant size and cost reductions in a fusion power plant core can be realized if simultaneous improvements in the energy replacement time, τ, and the plasma pressure or beta, $\beta_T = 2\ \mu_0 \langle P \rangle / B^2$ can be achieved in steady-state conditions with high self-driven (bootstrap current) fraction. Significant recent progress has been made in experimentally achieving these high performance regimes and in developing a theoretical understanding of the underlying physics. Theoretical predictions of reduced transport and improved stability for both increased magnetic shear and reduced magnetic shear have led to the identification of two possible high performance steady state scenarios: one with low or negative central magnetic shear, NCS, (or reversed shear, RS) and one with high edge magnetic shear, high ℓ_i. Through optimization of the internal magnetic shear, enhanced confinement and stability have been achieved in several tokamaks, accompanied by improvements in fusion performance. JT-60U NCS deuterium discharges have reached equivalent break-even conditions, Q_{DT} (equiv) = 1.

The improved confinement is a synergistic effect of magnetic shear stabilization of MHD and stabilization of microturbulence by sheared E×B flow. A reduction in the ion thermal transport to near neoclassical values and a reduction of particle transport are observed in NCS discharges in a number of tokamaks Reduced electron thermal transport is also observed, but less universally. There is a reduction in the measured density fluctuations, correlated both temporally and spatially with the reduction in transport. Reduced fluctuation levels and the reduced transport are consistent with E×B flow shear stabilization of microturbulence: when the E×B shearing rate exceeds the linear growth rate of the most unstable mode, fluctuations and transport are reduced. Negative or near zero magnetic shear and elevated q(0) provide stability to both large scale MHD and high n ballooning modes in the core as well as reduction in the linear growth rate of the microturbulence. Numerical simulations indicate that other factors such as high T_i/T_e contribute to reduced growth of the turbulence. In the high ℓ_i discharges, the improved edge confinement is correlated with both the increased E×B shear and the increased magnetic shear.

Strong plasma shaping and broad pressure profiles, provided by the H–mode edge, allow high beta operation with good confinement. Ideal and resistive stability analysis indicates the performance of discharges with strongly peaked pressure profiles is limited to low $\beta_T/(I/aB) \equiv \beta_N \leq 2.3$, consistent with the experimentally observed beta limit. The stability limit in shaped equilibria can be significantly increased by broadening the pressure profile for both NCS and high ℓ_i scenarios: $\beta_N \sim 5$ has been obtained in high triangularity double-null divertor discharges with good confinement, $H = \tau/\tau_{ITER-89P} \sim 4$. Although such discharges to date have been obtained transiently and without good bootstrap alignment, self-consistent numerical simulations indicate that high performance NCS and high ℓ_i regimes are compatible with steady state high bootstrap current operation with modest current drive requirements.

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