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How turbulence sets boundaries for fusion plasma operation

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The operational space for safe and efficient operation of a tokamak is limited by several constraints. Well known examples are the Greenwald density limit and the accessibility of high confinement (L-H transition). Their extrapolation to reactor machine size is based on empirical scaling laws. Both phenomena are related to turbulent transport. Large turbulent transport can lead to a transition to low confinement or trigger events finally leading to a disruption (the L-mode density limit).

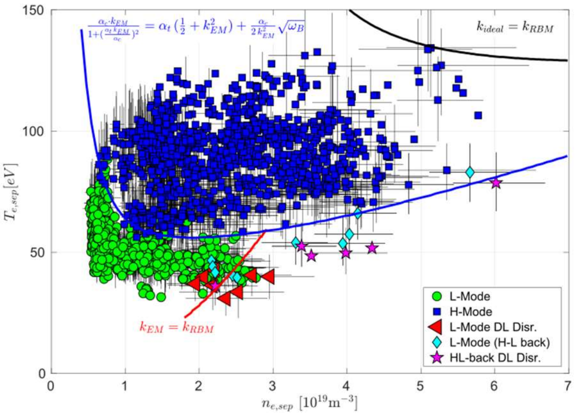

Figure 1 The separatrix operational space of ASDEX Upgrade in terms of density and temperature. Different confinement regimes are shown by different symbols. The derived operation boundaries are drawn by the lines. This figure is taken from Ref. [1].

The operational space is shown in Fig. 1 at a given plasma current (I_p=0.83 MA) and magnetic field strength (B=2.5 T) in terms of electron density and temperature at the separatrix measured with Thomson scattering. The database contains 1884 time averaged (300 ms) points of 123 discharges. Discharge phases in L-mode are shown by green circles, in H-mode by blue rectangles. The disruptive density limit is shown by red triangles and disruptions after a H-L back transition are shown by magenta stars.

The operation boundaries are analytically derived in terms of a combination of dimensionless parameters describing interchange-drift-Alfvén turbulence [2] (C,β_e,μ) without any free adjustable parameter. Here C is a normalized collisionality, β_e the dynamical plasma beta and μ the electron to ion mass ratio. It can be shown [1,2] that the parameter $\alpha_t = (1+\tau_i)C\omega_B$ describes rather gentle drift-wave dominated turbulence below one and rather violent resistive ballooning mode (RBM) dominated turbulence above one. ω_B weights the effect of the curvature [2]. Furthermore, we use three characteristic wavenumbers [1], the typical RBM wavenumber $k_{RBM} = k_{||}/\sqrt{(1+\tau_i)C\sqrt{\omega_B}}$. Wavenumbers below /above $k_{EM} = \sqrt{\beta_e/\mu}$ are electromagnetic/electrostatic dominated. Wavenumbers below/above $k_{ideal} = \sqrt{\beta_e\sqrt{\omega_B}/C}\,\frac{q_s R}{\lambda_\perp}$ are dominated by ideal/resistive effects, when in the electromagnetic regime. Here the safety factor q_s times the major radius R is the typical parallel length scale and $\lambda_\perp$ is the pressure gradient decay length [3].

The condition k_{RBM}=k_{ideal} let the RBM transit to an ideal ballooning mode. The well-known condition for the ideal ballooning mode α_{MHD}>α_{crit} can be shown to be equivalent to k_{RBM}=k_{ideal} using $k_{||}$=α_{crit} [1]. As shown in Fig.1 by the black line this condition provides an upper (non-disruptive) limit in density and temperature for operation in H-mode.

At the condition k_{RBM}=k_{ideal} the electrostatic RBM transits to an electromagnetic RBM. It is shown that when this condition (red line in Fig.1) is exceeded, disruptions occur. The operating range in L-mode is limited here to high densities. The condition also analytically agrees with the Greenwald limit in first approximation [1].

A condition separating L-mode and H-mode is derived in [1]. We consider here the power balance of the turbulence. We assume that at the L-H transition the energy transfer from the turbulence into the shear flow balances the energy transfer from the background gradients into the turbulence [4]. Thus, the turbulence is stabilized via the Reynolds stress as in Ref. [5]. We assume here that the ExB flow follows the ion pressure gradient [6]. However, further mechanisms are considered, too. Only the electrostatic part (k>k_{EM}) of the turbulence must be suppressed by the shear flow. The drive of the turbulence is composed of ITG and DW-RBM. At low collisionality, the DW stabilizes the RBM (diamagnetic stabilization [6]) and the energy transfer into the shear flow is more efficient [7]. The derived condition to separate L- and H-mode is shown by the blue line in agreement with the experimental data set. In summary, the here presented analytical description allows to narrow down the operational space very precisely.

References

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