On the Transport Physics of the Density Limit

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Density limits define important operational constraints on magnetic confinement devices. Proximity to the density limit is characterized by strong reduction in particle confinement, a rise in edge fluctuations, edge cooling, and frequently, but not always, MARFE's and disruptions. Perturbative experiments suggest that density limits are fundamentally SOFT limits. Here we discuss the physics of the edge transport and turbulence as the density rises to Ng, the Greenwald limit. Several experimental studies of edge transport and fluctuations (1,2,3)-including work on the HL-2A tokamak (3)-noted a drop in long range correlation, flow shear and Reynolds work and a rise in fluctuations and particle transport prior to the onset of collapse of the edge shear layer as N->Ng.

Theoretical work (4) shows that the key parameter here is not density or collisionality , but rather electron adiabaticity. We show that zonal flow PRODUCTION drops precipitously in the hydrodynamic electron regime, as the non-diffusive vorticity flux (ie residual stress) declines in proportion to adiabaticity. A simple physical argument establishes that the familiar explanation of ZF production by eddy tilting fails in the hydrodynamic electron regime, as there, causality and Reynolds stress tend to decouple.This is in contrast to the familiar adiabatic regime, where the two are tightly linked. These arguments, and the results of the detailed calculation are reconciled with concepts of PV mixing. As zonal flow production decays in the hydrodynamic regime, particle transport increases dramatically. Thus, we conclude that reduced zonal flow production is the mechanism for particle confinement degradation which enforces the density limit in L-mode. A feedback loop which explains the resulting cooling front, MHDits effect on profiles and the possible triggering of MHD activity is proposed and discussed. Experimental results (3) agree with the prediction that the passage of adiabaticity from large (>1) to small (<1) correlates with the onset of degraded confinement at the density limit.

This analysis has several interesting implications and also suggests many further studies. We propose that the density limit is related to a kind of back-transition- from a drift-zonal flow state to one of strong, convective cell turbulence. Cooling waves ,MARFEs and disruptions are secondary. Inward turbulence spreading , an integral part of the turbulence dynamics, can broaden the region of strong transport and turbulence,and so induce temperature and current profile contraction leading to MHD instability. Edge adiabaticity ,which scales as T^2/n for drift wave turbulence, is identified as the critical local parameter.This suggests that T vs n trade-offs can be used to test the critical parameter and extend the regime of operating density. Several future studies are suggested. These include searching for hysteresis in N/Ng, perturbative experiments near Ng using SMBI, and studies of fluctuation-flow bispectra (2) vs N/Ng. Of course, a connection of local edge adiabaticity to the global Greenwald scaling has yet to be established and should be.

The density limit in H-mode appears tightly coupled to the H->L back transition.This is because the edge shear layer (ie transport barrier) in H-mode is held by the mean Er,set by the pressure gradient at the separatrix ,and not by turbulence driven flows. Indeed, a soft density limit in H-mode should be preceded by a back-transition since the threshold power rises with density (Hysteresis at high density is a critical open question here.). Thus, we focus first on the H-L back transition. Ongoing work (5) has constructed a reduced , ”box” model for coupled edge and SOL evolution.A key point here is that turbulence is suppressed in the edge but not in the SOL.Thus back-transitions can occur by turbulence spreading. A criterion for back-transition is derived. Ongoing work suggests that increasing SOL density will inhibit parallel transport in the SOL, thus forcing increased turbulence and cross-field transport in the SOL.This will in turn drive turbulence spreading from the SOL into the edge by penetration of the edge barrier,thus leading to a back-transition.

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