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Theory of Nonlinear Ballooning Modes

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It is important to develop and control plasma scenarios which maximize the confined pressure in tokamak plasmas as these reduce the size and cost of a potential power plant. Instabilities limit the pressure in tokamak plasmas. This limit can be a hard, disruptive, limit or a soft limit which may result in a critical pressure profile. It is well known that transport barriers allow tokamaks to achieve much higher fusion performance but they have the disadvantage of hard, nonlinear ballooning, instabilities: such as the ELM for the edge transport barrier [1], and high plasma beta related disruptions for internal transport barriers, as seen experimentally in TFTR [2] or numerically in nonlinear MHD calculations [3]. An improved understanding of nonlinear ballooning stability will help us design configurations that have a soft limit, for example by staying below the critical pressure gradient for nonlinear stability. It may also explain experimental observations of ELMs and high plasma beta related disruptions on TFTR [2].

We review nonlinear ballooning theory and the MHD modelling of nonlinear ballooning modes, e.g. [3]. We then describe recent analytic work [4] on the nonlinear stability of a large aspect ratio tokamak plasma to finite ballooning displacements of thin elliptical magnetic flux tubes in the presence of a large pressure gradient region i.e. a transport barrier. We use a generalized form of Archimedes' principle to derive a differential equation which models the dynamics of such an ideal MHD flux tube. We solve this equation to find the equilibrium states of these flux tubes and calculate the energy of these equilibria. Above a critical pressure the energy stored in a tokamak plasma may be lowered by finite displacements of such tubes but not by infinitesimal displacements – i.e. they are metastable. Above a higher critical pressure such tubes become unstable to linear and nonlinear displacements. The distance the flux tubes are displaced in these states can be as large as the pressure gradient scale length. Triggering eruptions into these lower energy states leads to explosive dynamics, as seen in ELMs. We discuss how plasma transport is enhanced by displaced flux tubes and how this results in rapid loss of confinement. We describe a scan of pressure gradient and magnetic shear profiles looking at nonlinear stability. Finally, we describe how this work is extended to experimental tokamak geometries.

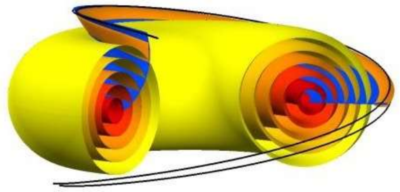

Figure 1: *Elliptical (orange) flux tube with* $r \sim \delta_2 \gg S \sim \delta_1$ *sliding along (blue) surface* $S = 0$ *parting surrounding (black) field lines. Note the tube's displacement is larger on the large R part of the flux surfaces – the tube balloons. The magnetic shear (*$s = rq'/q$*) causes the twist and narrowing of the tube on the inside.*

References

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