MF-I33

1st Asia-Pacific Conference on Plasma Physics, 18-22, 09.2017, Chengdu, China

Physics and Control of Macroscopic Instabilities in Magnetically Confined Fusion Plasmas

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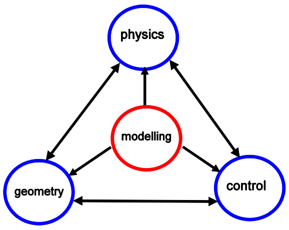
Successful realization of magnetic confinement of fusion plasmas towards reactors not only requires good understanding of plasma physics, but also relies on various degrees of control of the plasma behavior. The plasma physics generally involve multi-scale phenomena in both spatial and temporal dimensions, and thus generally requires different levels of descriptions - often crudely categorized into microscopic and macroscopic levels. Microscopic phenomena occur at small scales and typically have profound influence on the plasma transport and confinement. These microscopic perturbations are often inherently non-linear, involve self-organization, and are difficult to be actively intervened from the outside.

The macroscopic phenomena, which are the focus of this Contribution, on the other hand, can often be actively controlled. Therefore, both physics and control are equally important for many of the macroscopic perturbations in fusion plasmas. Moreover, being macroscopic, these perturbations are often sensitive to geometry, in particular to the magnetic geometry such as the field line curvature. For modelling and comprehensive understanding of these macroscopic instabilities, the interplay between physics, (magnetic) geometry and control, schematically described in Fig. 1, is crucial. This "triangle" interplay will be the special focus of this Contribution and will be exclusively discussed.



There are many different types of macroscopic instabilities, or modes, in fusion plasmas, including the vertical instability, the ideal kink modes – either internal or external or infernal, the resistive modes such as the tearing mode or the neoclassical tearing mode, the edge localized modes, the resistive wall mode, etc. This talk will give a basic introduction to some of these modes as the first part.

This will be followed by more detailed discussions on those instabilities, that are of particular concern for the future fusion reactor scale devices. These include the edge localized mode and the resistive wall mode, to which extensive theory and experimental efforts have been devoted during recent years, with significant progress being made. These up to date progress results, especially from the theory and modelling perspective, will be reported. In the following, we briefly illustrate the aforementioned "triangle" interplay for the resistive wall mode. Different kinds of interplay occur for the edge localized mode [1], which will be reported in the full Contribution.

The resistive wall mode (RWM) is essentially an external kink instability, driven either by the plasma current or pressure. For most of high performance fusion plasmas – for instance those of the advanced tokamaks - this mode is driven by the plasma pressure. The presence of a conducting wall, with finite conductivity, usually significantly reduces the growth rate of the mode (typically from microseconds time scale to milliseconds time scale), but without modifying the stability boundary. This means that, for long pulse or steady state discharges, the RWM will become a serious, and eventually the most dangerous instability at high beta, in the plasma. The macroscopic nature of the mode often prevents a strong non-linear saturation physics to self-stabilize the mode, as opposed to more local modes such as the tearing mode. On the other hand, the slow growth of the mode, combined with the fact that the mode is nearly "locked" to the wall (i.e. with nearly vanishing mode frequency in the laboratory frame), leads to a strong interaction between the mode and continuum waves (shear Alfven and sound waves) [2], and even more importantly, between the mode and drift motions of thermal/energetic particles in the plasma [3-4], opening effective energy dissipation channels that can eventually stabilize the mode. This passive stabilization mechanism may not be sufficiently robust (and certainly does not apply for current driven RWM), inviting for active control of the mode using magnetic coils [5], which, fortunately, is indeed technically achievable, thanks to the slow growth of the mode as well as the global external nature of the mode. Magnetic geometry plays important role in the RWM stability. In a realistic toroidal plasma, the mode is rich in poloidal harmonics, which are often strongly coupled between each other. The mode, even at low toroidal numbers n=1,2,3, can be strongly ballooning pushed by the high plasma pressure, rendering the average favorable curvature stabilization less effective. The wall stabilization on the mode is sensitive to the plasma shaping. In extreme cases of plasmas with negative triangularity, for instance, the wall stabilization becomes very weak [6].

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