Locked Mode Disruptions: Stability, Dynamics, Control

Francesco Volpe
Dept of Applied Physics and Applied Mathematics, Columbia University
New York, NY 10027, USA

Neoclassical Tearing Modes large enough to cause disruptions are also large enough to decelerate under the effect of the wall torque, and eventually lock to a residual error field. These locked modes with rotating precursors, as well as error-field penetration "born locked" modes, are among the most prominent causes of disruptions in present tokamaks, and a concern for ITER, where slow rotation is expected to favor locking. In fact, in ITER Neoclassical Tearing Modes are expected to start decelerating nearly immediately after forming and remain locked until saturation, unless they cause a disruption before. For these reasons, the prediction, avoidance and control of locked modes are a critical need for the prediction and avoidance of disruptions, as well as for forestalling the need for mitigation. Given their importance, two lectures will be dedicated to locked modes, starting with the linear and non-linear theory of island stability. We will then study how a magnetic island partly frozen in a rotating plasma interacts with the resistive wall, with static error fields and applied static or rotating fields, as well as with other modes. Stability and dynamics are coupled, in that the evolving island width affects island rotation, and vice versa, resulting for example in hysteresis in the locking process. A rigorous treatment of the full problem will be discussed, including single fluid effects and plasma shaping effects. Such treatment has the potential to answer open questions, for instance on slowly rotating, "quasi stationary" modes. On the other hand, simpler approaches suffice to explain simpler experimental observations, and are computationally less intensive, thus suitable for real time control. One such approach consists in treating the island as a rigid, radially thin set of slowly-evolving helical current filaments. This model allowed modeling the entrainment of the otherwise locked island by applied rotating fields. Simulations agree with present experiments, and were extrapolated to ITER and translated in current requirements for the control coils. The model also served as basis for a feedback controller of mode phase and rotation. Magnetic perturbations can also be applied in feedforward, or by a different feedback algorithm, originally intended for resistive wall modes. Results will be presented from all three approaches, and their merits and disadvantages discussed. Yet another approach is to apply static perturbations to cause the mode to lock with a specific phase, such that its O-point can be accessed by Electron Cyclotron Current Drive. This technique completely stabilized the locked mode and avoided the associated disruption. In parallel with further advances in locked mode control, it will also be important to improve our predictive capability of locking and locked mode effects, from mild degradations of confinement to severe disruptions. In this regard, large databases are proving useful in guiding the theory and identifying key physics parameters with good predictive capability. One of these is the ratio of internal inductance to edge safety factor –probably acting as a proxy for classical stability. Statistics were also acquired and partly interpreted about the timescales of mode locking, the surprisingly long "survival time" between locking and a "pre-thermal quench" growth, culminating in the actual disruption. Possible mechanisms will be discussed by which locked modes could initiate a thermal quench and thus a disruption.