Error Field Tolerance and Error Field Correction Strategies for ITER

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Tokamak plasmas are sensitive to external long-wavelength non-axisymmetric magnetic perturbations δB that are up to four orders of magnitude smaller than the axisymmetric magnetic field B. These non-axisymmetric fields typically arise from inevitable asymmetries in the coil configuration and are referred to as "error fields". Error fields can limit operation by inducing a locked mode, usually the $m/n = 2/1$ mode on the $q = 2$ surface, which leads to cessation of plasma rotation, confinement degradation or a disruption. Ohmically heated L-mode discharges at low density as well as slowly rotating discharges at high normalized plasma pressure $\beta \equiv 2\mu_0 \langle p \rangle / B^2$ are most susceptible to error fields. Even though the error field eventually penetrates the $q = 2$ surface, both scenarios are most sensitive to an externally applied field that best matches the kink mode structure, and not to the resonant component of the external field at the location of the $q = 2$ surface. The most robust characteristic of the error field tolerance in Ohmically heated L-mode plasmas across many devices is a linear dependence on the plasma density. In high β plasmas the error field tolerance increases with the plasma rotation. This can be understood by magnetic braking leading to a loss of torque balance. At sufficiently high values of β, external non-axisymmetric fields are increasingly amplified by the plasma, which enhances the braking and decreases the error field tolerance. The error field tolerance can be further reduced by the onset of other instabilities such as neoclassical tearing modes or resistive wall modes, which both depend on the plasma rotation. In the vicinity of the rotation threshold of either one of these instabilities, the error field tolerance approaches zero.

The most widely used technique to detect and correct error fields is based on the density dependence of the error field tolerance in Ohmically heated L-mode discharges. In a set of discharges with constant density, an increasing externally applied $n = 1$ field with three or more different toroidal phase angles is added to the error field until a locked mode occurs. Since the locking density depends only on the absolute value of the sum of the error field and the added $n = 1$ field, one can infer phase and amplitude of the coil currents that best correct the error field. An alternative detection and correction technique is based on the measurable plasma amplification of the error field in high β plasmas. Currents in external coils to correct the error field are considered optimized when no plasma amplification is detected. These currents can be readily found in real-time using a feedback algorithm.

In ITER the error field detection and correction has to be worked out in the initial Ohmic campaign. Since disruptions have to be avoided and β will be too low for a measurable amplification, new detection and correction techniques have to be developed. Two methods based on non-disruptive locked modes typically encountered at higher values of the safety factor are proposed. In one method magnetic feedback is used to minimize the amplitude of the locked mode. In the other method an externally applied $n = 1$ field rotates the locked mode in the toroidal direction. An error field would manifest itself by a dependence of the toroidal phase shift between externally applied field and the mode on the toroidal angle. Feasibility of these techniques and the applicability of the resulting correction currents to high β plasmas remains the subject of current research.

Work supported by the US Department of Energy under DE-FG02-04ER54761, DE-FC02-04ER54698k, DE-AC02-09CH11466, and DE-FG02-89ER53296.