RESISTIVE WALL MODE STABILIZATION

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Issue: Robust operation above the ideal MHD no-wall stability limit.

Operation above the ideal MHD no-wall stability limit and, therefore, resistive wall mode (RWM) stabilization are a prerequisite for the advanced tokamak (AT) path to a compact, more economically competitive, steady-state fusion reactor [1]. While the AT concept, which is based on a high value of normalized beta and on good alignment of the bootstrap current with the equilibrium current profile, relies on RWM stabilization, other operational scenarios, such as the hybrid scenario, can take advantage of operation above the no-wall limit in order to improve the fusion performance.

> **Passive RWM stabilization** is the most attractive solution. It has been observed in many devices and is linked to plasma rotation [2-6]. However, the rotation threshold is not well identified [7,8]. It is thought that kinetic effects that depend on the plasma rotation and distribution functions including fast particles are responsible for the observed RWM stability [9-12], but the present modeling still falls short of a quantitative description of the experiment [11,12], and the extrapolation to a reactor plasma is, therefore, still uncertain. In addition, a coupling of the stable RWM to other MHD modes such as edge localized modes (ELMs) and q=2 fishbones, which degrade performance or cause disruptions, has been observed [7,13] casting doubt on the robustness of passive RWM stabilization.
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> Reliance on passive RWM stabilization in a reactor *requires* sufficient understanding of the stabilization mechanism and of the coupling of a marginally stable RWM to other instabilities that might be present in a burning plasma.
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> **Active RWM stabilization using magnetic feedback** is a promising backup, if passive stabilization is not sufficient or not sufficiently robust for reactor operation above the no-wall limit. In tokamaks direct RWM feedback control has so far only been demonstrated transiently using either the current driven RWMs in Ohmically heated plasmas [14,15] or pressure driven RWM in neutral beam injection (NBI) heated high beta H-modes [16,17]. These results were transient due to a transient instability of the plasma in the current ramps in Ohmic plasmas or a complex stability boundary at high beta. Sustained RWM feedback control has, however, been demonstrated in modern reversed field pinch experiments, which rely on FB control to extend the discharge duration beyond the characteristic eddy current decay time of the conducting shell [18,19].
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> Reliance on RWM feedback control *requires* demonstration of sustained FB control in high beta plasmas and/or a sound understanding that the RFP results are transferable to a burning tokamak plasma. The feasibility of sustained RWM feedback control in a reactor has to be determined through validated feedback models.

> **Amplification of non-axisymmetric fields** including error fields and intentionally applied non-axisymmetric fields (e.g. resonant magnetic perturbations for ELM suppression) in high beta plasmas can lead to significant magnetic braking [20] and subsequent field penetration (locked mode) [21], which in turn leads to severe confinement degradation and often a disruption even if the RWM is stable. The amplification and hence the error field sensitivity can increase by up to an order of magnitude from high beta plasmas below the no-wall limit to wall-stabilized plasmas in the vicinity of the ideal wall limit [22]. The error field tolerance of high beta plasmas benefits from toroidal torque input, which in present day experiments is usually supplied by tangential NBI heating, but will be much less prominent in a self-heated reactor. While the amplification of the error field through the plasma increases the error field tolerance, it also limits the need for error field correction to the component that leads to the amplification.
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> Operation of a reactor in the wall-stabilized regime will *require* a reliable error field correction strategy.

An accurate evaluation of the potential for RWM stabilization is crucial for the prediction of fusion performance.

Requirements (for resolving issues)

Obtaining a sufficient understanding of **passive RWM stabilization** will require a quantitative measurement of passive stabilization to validate models that extrapolate to a reactor plasma. This has to include investigations of the sensitivity to parameters that will be different in a reactor such as rotation, the ratio of electron and ion temperatures and the fast particle content and distribution. Since the present efforts focus on linear stability models, the applicability of linear models has to be verified. In addition, the extrapolation of stabilizing effects to a reactor implies the need to reliably predict these quantities in a reactor.

Demonstration of **active RWM stabilization using magnetic feedback** in high beta plasmas requires above all a good understanding of passive stabilization and its limits. The understanding of passive stabilization is also needed to measure feedback performance and validate feedback models, which extrapolate to a reactor. Validated models can then be used to determine the specifications for the RWM observer, feedback coils, power supplies and the tolerable noise in a reactor. It is very desirable to validate advanced feedback schemes, which promise a substantial reduction of the power needed for RWM control [23]. The optimization should include the coupling to and possible integration with other magnetic control systems, such as the axisymmetric shape and position control as well as possible non-axisymmetric ELM control solutions.

In order to avoid the **amplification of non-axisymmetric fields** in high beta plasmas non-disruptive and efficient error field correction strategies need to be developed. Since the field errors are small and can depend on currents in other parts of the system, a direct measurement of the error field and an identification of its source can be difficult. Conventional error field detection schemes, therefore, rely on the effect of the error field on the plasma such as altering the density thresholds for the onset of locked modes in Ohmic plasmas [24]. However, a disruptive scheme is likely not acceptable for an reactor size machine. Alternative error field detection schemes using their amplification at high beta [25] or the enhanced drag are presently under investigation and need to be validated. An error field correction strategy for a reactor should be sufficiently flexible to react to varying error fields over a wide range of scenarios.

Elements of a research thrust

Much of the required research can be carried out in existing machines with enhanced capabilities. Medium-size tokamaks (or STs), such as DIII-D or NSTX, are well suited for the study of stability limits, since they tolerate frequent disruptions inherent to these experiments.

The required research thrust should include:

- Extended comparison of passively stable, high beta plasmas with improved kinetic models of RWM stabilization including fast particle effects.
    - Extend experimentally accessed parameter regime.
    - Improve linear modeling of RWM stabilization (e.g. by including finite resistivity, poloidal rotation).
    - Assess necessity for non-linear modeling of the interaction of non-axisymmetric perturbations with high beta plasmas.
    - Extend studies to the n=2, 3 RWMs, which could limit the attainable beta to values below the ideal MHD ideal wall limit even if the n=1 mode is stabilized.
- Enhanced diagnostics that can resolve quasi-static toroidal asymmetries (and extrapolate to a reactor, such as SXR emission or ECE measurements at multiple toroidal locations).
- Additional electron heating such as ECH to test the RWM stability with reactor relevant distribution functions with reduced rotation and fewer fast particles.
- Continued feedback experiments on current driven modes in tokamaks and RFPs for feedback model validation.
    - Inclusion of multiple unstable and stable modes.
- Develop real-time stability measurements and/or calculations.

Ultimately the knowledge has to be transferred to a burning plasma regime, which could be achieved by extending the ITER AT operational regime/capabilities. The current steady-state scenario uses only a small fraction of the potential performance gain through RWM stabilization. Preserving the AC and n=1 capabilities of the internal and possibly external non-axisymmetric coil sets would be a prerequisite for such an extension.

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