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Impact of Resonant Magnetic Perturbations on ELM Mitigation and Impurity Transport in HL-3 H-mode Plasmas

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The ITER project aims to achieve fusion energy through a burning plasma, but this requires exhausting significant power via the thin scrape-off layer (SOL) outside the magnetic separatrix. Without proper control, the heat flux can exceed material limits, necessitating prior dissipation. Edge-localized modes (ELMs) and impurity transport are critical challenges for stable and efficient operation in tokamak fusion devices. Resonant magnetic perturbations (RMPs) have been demonstrated as an effective tool for ELM mitigation [1] and impurity transport modification [2] in various tokamaks, including HL-3.

In this study, we present the first experimental observations of ELM mitigation using n=2 RMPs on the HL-3 tokamak and investigate the accompanying changes in impurity confinement. The results are supported by simulations using the EMC3-EIRENE code, providing insights into the underlying mechanisms of RMP effects on plasma edge transport. HL-3 is a medium-sized tokamak with a major radius of 1.78 m and a minor radius of 0.65 m. The RMP system on HL-3 consists of 16 in-vessel coils arranged in an 8 × 2 (toroidal × poloidal) configuration, enabling flexible magnetic field spectra. During the 2025 experimental campaign, the n=2 RMP configuration was successfully commissioned, leading to significant ELM mitigation.

In a representative discharge (#12693), the plasma parameters included a toroidal magnetic field (B_t) of 1.12 – 1.13 T, a plasma current (Ip) of ~500 kA, and a line-averaged density (ne) ranging from 1.93 to 3.42 × 10^{19} m^{-3}. The transition to H-mode occurred at 1.05 s with auxiliary heating power of 1.8 MW. Upon applying n=2 RMPs at 1.2 s, the amplitude of the D_α signal decreased by 30%, and the ELM frequency increased approximately threefold, indicating effective ELM mitigation. These observations align with previous findings on other tokamaks, where RMPs alter the edge pressure gradient and current density, thereby destabilizing the peeling-ballooning modes responsible for ELMs.

TThe application of RMPs not only mitigates ELMs but also significantly impacts impurity transport, which is crucial for divertor heat load management. To study this effect, we performed simulations using the EMC3-EIRENE code for HL-3 H-mode plasmas with and without n=2 RMPs. Nitrogen gas was injected near the outer divertor strike point to simulate impurity seeding. With n=2 RMPs, the impurity radiation in the core plasma decreased by ~20% compared to the axisymmetric case, suggesting enhanced impurity transport toward the divertor region, where radiation is more uniformly distributed.

The experimental and modeling results demonstrate that n=2 RMPs effectively mitigate ELMs and modify impurity transport in HL-3. The formation of stochastic magnetic field regions and helical lobes near the separatrix plays a pivotal role in redistributing heat and particle fluxes, reducing peak divertor loads. These findings are relevant for ITER and future fusion reactors, where RMPs are a key component of ELM control schemes.

Further studies will focus on refining the understanding of turbulence and edge plasma conditions under RMPs, as well as exploring synergistic effects between RMPs and advanced divertor configurations (e.g., snowflake divertors) for improved performance..

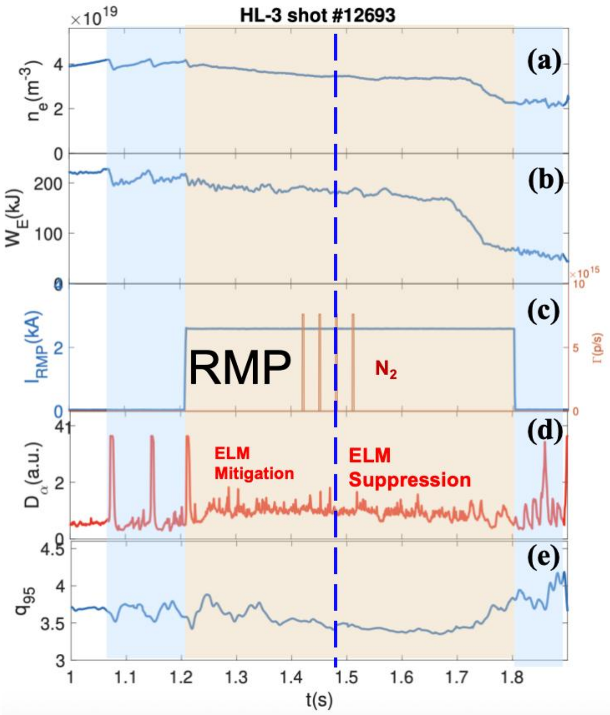

Figure 1. Time traces of plasma parameters and mitigation of ELMs by RMP on HL-3 discharge #12693. (a) Line averaged density n_e (blue solid) (b) stored energy W_E(blue solid), (c) RMP coil current I_{RMP} (blue solid) and impurity injection (orange solid), (d) divertor D_α light emission, (e) q_{95}.

References

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