MULTI-MACHINE STUDIES OF LOW-Z BENIGN TERMINATION OF RUNAWAY ELECTRON BEAMS AND EXTRAPOLATION TO ITER

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Tokamak disruptions pose a significant threat to the structural integrity of the vessel and plasma facing components (PFCs) due to the intense thermal and electromagnetic loads they generate. To mitigate these effects, Massive Material Injection (MMI) via gas or pellets is employed to disperse the energy over a broader area, leveraging the radiation efficiency of medium and high Z materials. However, this approach can inadvertently lead to the formation of runaway electron (RE) beams due to the sudden increase in plasma resistance and electric field [2]. Such beams, if unmitigated, could cause severe damage to PFCs on ITER, necessitating a reliable defense strategy for RE beam mitigation.

One promising approach, termed 'low-Z benign termination,' utilizes MMI of hydrogenic species to induce recombination and reduce the electron density of the companion plasma [2,3]. The technique then involves approaching low q-edge to trigger a fast-growing current-driven kink instability, which spreads the RE beam's energy over a large wetted-area and significantly reduces heat flux. Experiments conducted on ASDEX Upgrade (AUG), COMPASS, DIII-D, JET, and TCV [2,3,4] have refined the understanding of this process, demonstrating that achieving a low electron density is essential for a fast Alfvén velocity and a highly resistive companion plasma. These conditions are crucial for driving the rapid growth of the magnetohydrodynamic (MHD) instability at the final collapse, expelling confined REs before they can regenerate. A multimachine database consolidates these experimental results, while first-of-their-kind simulations provide new physics insights and support extrapolations to ITER.

Analysis of the multimachine database reveals a strong correlation between the neutral pressure required for recombination and both RE current density and impurity density (Figure 1). Experimental results show that as the companion plasma recombines, radiated power decreases, suggesting that neutral energy conduction is responsible for the reduction in electron temperature and subsequent recombination [4]. SOLPS simulations reproduce this trend, demonstrating that increasing neutral pressure leads to a decrease in core electron temperature and density, further highlighting the role of neutrals in transporting thermal energy away from the companion plasma (Figure 2).

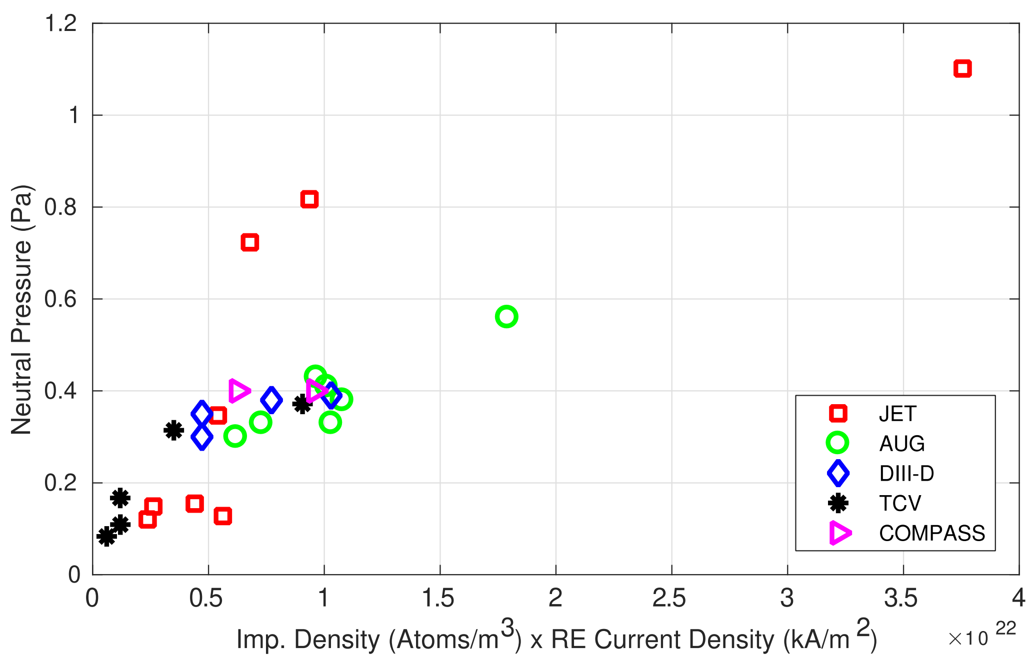

Figure 1 - Multimachine database showing the required neutral pressure to recombine the companion plasma, following an argon primary injection, as a function of RE current density and impurity density.

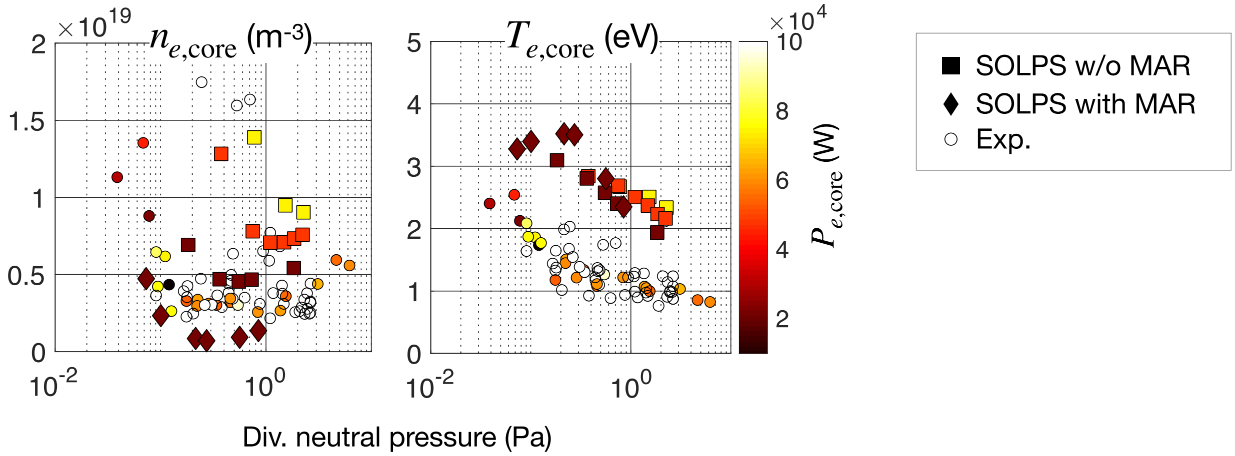

Figure 2 - SOLPS simulations of the companion plasma on TCV showing a decreasing electron density and temperature with increasing neutral pressure. Simulations conducted at fixed input powers ($P_{e,core}$) to the companion plasma from RE interactions.

Experimental results indicate that at neutral pressures on the order of several pascal, the efficacy of the benign termination technique significantly decreases [4]. This reduction is attributed to RE impact ionization, which increases the electron density of the companion plasma and consequently lowers the mode growth rate at the final collapse [5]. SOLPS simulations account for this effect by introducing an electron source term in the plasma core to model RE impact ionization. These represent the first comprehensive simulations to capture the full power balance between REs, the companion plasma, and neutrals. Comparison with experimental data shows strong agreement, providing key insights into the required neutral pressure range for ITER.

The final collapse has been experimentally investigated by approaching a low q-edge through plasma compression against the walls, plasma current ramps, and toroidal field variations. Systematic variation of the toroidal field at the time of collapse on TCV provided critical data for extrapolating to high-field machines. These experiments, combined with JOREK MHD simulations of AUG, JET, and TCV, have yielded deeper insights into the underlying dynamics, further refining the understanding of benign termination.

The combined datasets from these experiments provide a comprehensive scaling analysis, offering strong validation of this approach for ITER and future reactor-sized machines. The integration of experimental data with advanced modeling tools like SOLPS and JOREK has established a robust predictive framework for assessing the efficacy of this method on ITER.

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